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Original Article

Determination of drying characteristics and airflow performance of a turbo-stove assisted solar dryer

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ABSTRACT

Food insecurity continues to affect many rural communities in the Philippines due to climate disruptions, poor postharvest systems, and inadequate food preservation methods. Solar drying offers a sustainable and low-cost solution to reduce postharvest losses, particularly for nutrient-rich yet highly perishable crops such as sweet potato leaves. This study designed and evaluated a twin-wall polycarbonate solar dryer with dimensions of 2.3m(width)x1.2m(height)x3m(length) integrated with a turbo-assisted stove (TSD) to enhance drying efficiency and thermal performance. Drying experiments were conducted using four configurations: open dryer (OD), closed dryer (CD), turbo-assisted stove dryer (TSD), and traditional sun drying (SD), with each dryer loaded with approximately 15kg of sweet potato leaves. When no load was present, the TSD exhibited the highest mean airflow rate of 1.14m³/s, followed by the CD (1.07m³/s) and OD (0.83m³/s). Under loaded conditions, the OD and CD recorded higher exhaust airflow rates of 0.54m³/s and 0.50m³/s, respectively, compared to 0.34m³/s for the TSD. The TSD achieved the highest and most consistent drying performance (40–60°C), with the bottom tray recording the peak rate of 358.91g H_2O/g dM·h, attributed to its proximity to the heat source. On average, the TSD attained the highest drying rate of 93.784g H_2O/g dM·h, which was significantly greater than that of OD (54.062), CD (44.339), and SD (38.067). In terms of moisture removal, sun and open drying methods retained the highest residual moisture, while the CD showed better efficiency, and the TSD consistently achieved the lowest moisture content due to its supplemental heat source and stable temperature conditions. Moreover, statistical analysis revealed a significant difference among treatments ($p < 0.0001$). Overall, the hybrid solar dryer demonstrated superior thermal performance, higher drying efficiency, and better product quality, making it a cost-effective and scalable postharvest solution for enhancing food preservation and food security in tropical rural areas.

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INTRODUCTION

Food insecurity is a global problem that most countries face in some form or another, leading to hunger, malnutrition, and unrest. In many affected countries, this trend is driven by increasing fragility linked to protracted conflicts or more frequent exposure to extreme weather conditions, heightening the risk of food crises (Gustafon & Vos, 2025). The Philippines, like many developing countries, faces issues regarding food security due to extreme weather events, supply chain disruptions, and geopolitical issues. Locally, typhoons are becoming stronger and more frequent; droughts and floods disrupt harvests; rural farmers lack the infrastructure (postharvest handling) to mitigate losses or improve food quality. The sun, being a limitless source of heat energy, offers great potential in food processing and preservation, especially to tropical countries such as the Philippines. This type of energy has led to the development and adoption of solar dryers as a practical method of harnessing solar energy to extend the shelf life of agricultural products.

Drying is a crucial method used to lower the moisture content of crops, retarding the spoilage process and aiding long-term storage. In addition to preservation, dried products offer improved safety, easier handling, and more economical transportation (Razak et al., 2021). Dryers are generally classified as natural (passive), mechanical (active), or hybrid systems depending on their energy source and operating principles (Fernandes & Tavares, 2024). Among the various drying techniques, natural dryers or open sun dryers remain the most commonly used in tropical regions because of their low cost and accessibility for smallholder farmers. However, their effectiveness depends heavily on ambient weather conditions, and the products are highly susceptible to contamination from dust, insects, rain, and other environmental factors, which often results in poor product quality and reduced economic returns for farmers. To address these limitations, advanced drying systems such as greenhouse and hybrid solar dryers have been developed. These technologies provide faster drying rates, improved energy efficiency, and better product hygiene, effectively reducing postharvest losses compared to conventional open-air sun drying methods (Udomkun et al., 2020).

Recent studies have explored various drying methods and system designs to improve the quality and efficiency of drying sweet potato products. Sweet potato leaves contain high levels of vitamins A, B, and C, iron, calcium, dietary fiber, and antioxidants (Sun et al., 2014; Nguyen et al., 2021; Stathers et al., 2018). These nutrients make it an interesting component for the consumer and the feed industry. However, due to their high moisture content and delicate nature, sweet potato leaves are highly perishable with no long-term storability without adequate processing (Laurie et al., 2024; Makori et al., 2020). Van Tai et al. (2023) evaluated the effect of different drying and storage conditions on the nutritional and antioxidant quality of purple sweet potato leaves. Their findings showed that controlled hot-air drying preserved higher levels of antioxidants and bioactive compounds than traditional sun drying, emphasizing the importance of temperature regulation during the drying process. Similarly, Sakouvogui et al. (2023) developed and tested a forced-convection solar dryer for drying sweet potatoes using locally available materials in Guinea. Their results demonstrated significant improvements in drying efficiency and product quality compared to open-air sun drying, highlighting the practicality of low-cost solar drying technologies for smallholder farmers.

Given the need for efficient, low-cost, and sustainable drying solutions in agriculture, this study presents the design and performance evaluation of a turbo-stove assisted solar dryer constructed using durable and locally available materials, specifically designed for drying sweet potato products. In this study, sweet potato leaves were used as the test material for assessing the dryer's performance since they are among the most nutritious and delicate among health-promoting, unsung, non-conventional vegetables. This research seeks a scalable solution to create a viable, improved postharvest handling method to enhance food security in rural settings.

MATERIALS AND METHODS

Design and Fabrication of Solar Dryer System

The design of the solar dryer (Figure 1) considered the availability, affordability, and durability of the materials. Fabrication was carried out at the PhilRootcrops Processing Laboratory, Visayas State University, Leyte, Philippines. The frame was constructed using angle bars, while the walls and roofing were made from twin-walled clear polycarbonate sheets for improved thermal insulation and light diffusion.

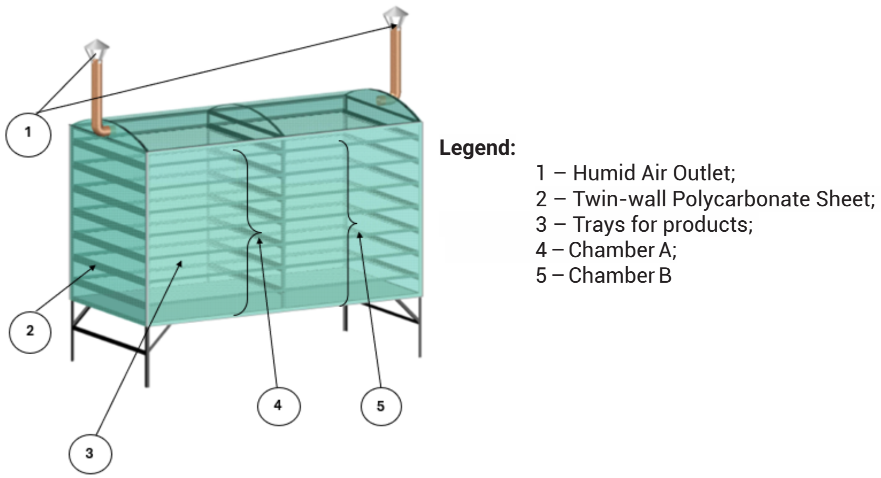

Figure 1. The perspective view of the solar dryer showing its main components.

The dryer consists of a main drying chamber, airflow system, and an integrated Yolanda Turbo Stove as a supplemental heat source. The entire dryer measured 2.3m in width, 1.2m in height, and 3m in length. Inside the drying chamber are two compartments equipped with six aluminum mesh trays supported by lightweight aluminum frames to promote uniform air circulation and efficient moisture removal. Each compartment has an upswing door for convenient loading and unloading of samples.

A chimney was installed above each chamber to facilitate natural convection airflow and to serve as an exhaust outlet for moist air and combustion gases. The dryer combines passive solar heating—utilizing direct sunlight transmitted through the polycarbonate cover—and supplemental biomass heating provided by the Yolanda Turbo Stove (Figure 2b).

The Yolanda Turbo Stove is a locally fabricated, biomass-fueled heat source made from repurposed scrap metal materials. It features a cylindrical steel combustion chamber with a perforated air intake plate at the base, which enhances primary air circulation and combustion efficiency. The "turbo" effect is created by natural draft airflow, producing a clean and steady flame without the need for blowers or electricity.

In this hybrid configuration, the stove is positioned at the center beneath the dryer, and the generated hot air is distributed upward through natural convection into both drying chambers in Figure 2A. This ensures uniform heat distribution and enables continuous operation during cloudy weather or nighttime.

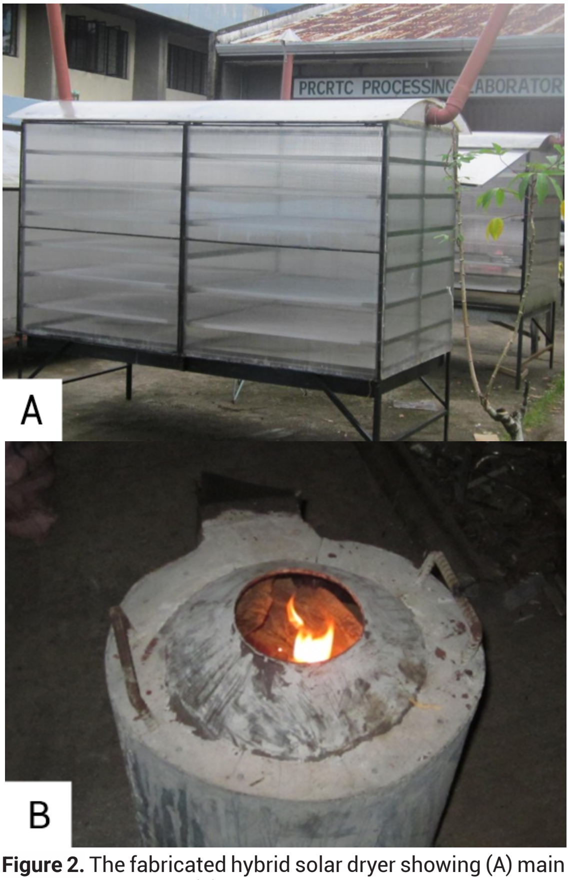

Figure 2. The fabricated hybrid solar dryer showing (A) main drying chamber and (B) the integrated turbo stove.

The solar dryer combines passive solar drying concepts and an inexpensive supplementary heating mechanisms and is thus a reasonable and practical option for smallholder farmers. The modular and scalable layout makes it suitable for all types of produce and leafy vegetables, like sweet potato leaves, root crops, herbs, and even medicinal plants.

Experimental Set-up and Procedure

Drying experiments were conducted over three successive days, denoted as Day 1 (D1), Day 2 (D2), and Day 3 (D3), under three different drying conditions: Open Dryer (OD), Closed Dryer (CD), Turbo Assisted-Stove Dryer (TSD), and traditional Sun Drying (SD). The solar dryer was positioned in an open field with no obstruction to sunlight to ensure consistent solar exposure.

All experiments followed the principles of thin-layer drying, wherein samples are spread in a single layer to ensure uniform drying. In this study, approximately 15kg of fresh sweet potato leaves were used per experimental run, with an initial moisture content of 94%. Leaves were sorted to remove damaged portions and evenly distributed across trays at different levels within the dryer. Each tray held a maximum load of 400–450g, corresponding to a loading density of 4.63kg m^{-2}, to maintain consistent drying conditions. The initial weight of each tray was recorded before drying commenced.

The internal temperature distribution and airflow rate at the exhaust outlet were recorded every fifteen (15) minutes, while sample weights were monitored every thirty (30) minutes to track moisture loss. To minimize heat loss during sampling, trays were removed quickly using pre-heated aluminum trays and insulated gloves, and the upswing doors of each drying chamber were opened only briefly. This procedure ensured that the internal temperature of the dryer remained stable throughout the experiment.

The performance of the fabricated solar dryer was evaluated both with and without load. For the no-load condition, the parameters assessed were internal temperature distribution, airflow, relative humidity, preheating time, and fuel consumption. Under loaded conditions, the same parameters were measured, along with the drying rate of sweet potato leaves placed at different tray levels: top tray (TT), middle tray (MT), and bottom tray (BT).

A comparative evaluation was also conducted to analyze the performance of the solar dryer under these three configurations against traditional sun drying. In the sun drying setup, sweet potato leaves were spread on the same type of trays used in the solar dryer and exposed directly to sunlight for moisture removal.

For both the drying kinetics and comparative study, fifteen (15) kilograms of sweet potato leaves were used with three replications per condition. The initial moisture content (wet basis) of the samples was determined using the convential oven-drying method.

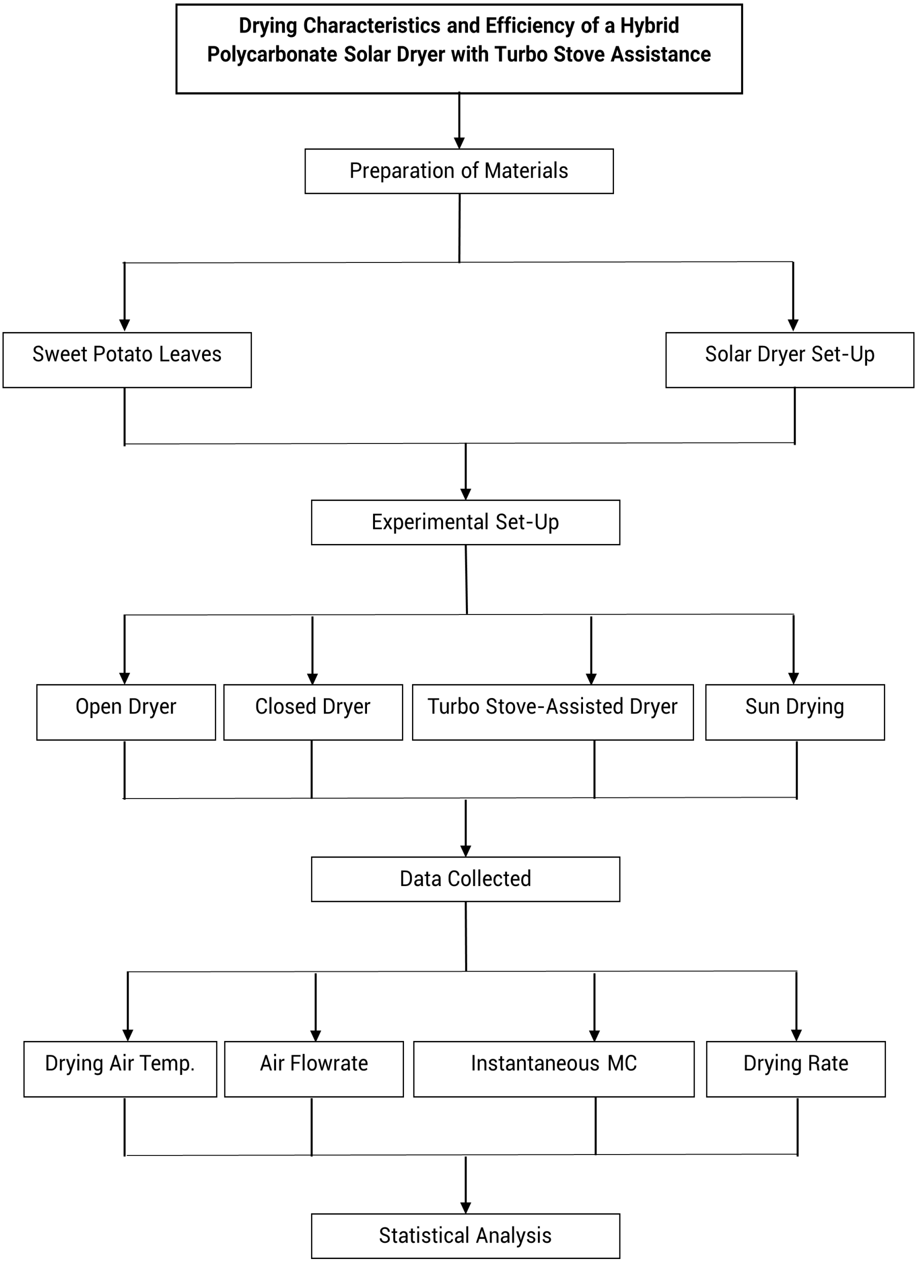

Figure 3. Framework of the Study

Data Gathered

The following data were collected during the experiment to evaluate the performance of the solar dryer under different operating conditions. The inside temperature (°C) of the dryer was measured at the top, middle, and bottom layers under all three dyers: OD, CD, and TSD, both with and without load. The ambient temperature (AT) (°C) was also recorded for comparison with the sun-drying method. The airflow rate (m^3/s) of the drying air inside the dryer under the three conditions was measured at the exhaust outlet using a mechanical airflow meter to assess the ventilation performance. The moisture content (%) of sweet potato leaves was monitored throughout the drying process, along with the corresponding drying time (hr) and drying rate (g H_2O/g dM·h) to determine the rate of moisture removal. Additionally, the preheating time (min) of the turbo stove was recorded to determine the duration required to reach the target reference temperature of 50°C before initiating the drying process.

Drying Kinetics

The initial moisture content of sweet potato leaves was evaluated on dry basis (db) using Equations (1) (Eltawil et al., 2018):

$$MC_{db} = \frac{W_i - W_f}{W_f} \tag{1}$$

where W_i and W_f denotes initial and final weights of the sample, respectively.

The mass of water removed at any time during the drying process was determined using Equation (2) (El-Sebaii et al., 2002):

$$W_t = \frac{M_0 - M_f}{100 - M_f} x W_i \tag{2}$$

where M_0 and M_f are the initial and final moisture content of the sweet potato leaves, respectively.

The instantaneous moisture content MC_t of the sweet potato leaves at any given time (t) during the drying process was calculated using equation (3):

$$MC_t = \frac{W_i - W_f}{W_f} \tag{3}$$

The drying rate (DR) indicates the amount of moisture removed per unit time and directly affects the drying efficiency and final product quality. It was calculated using Equation (4) (Goud et al., 2019):

$$DR = \frac{M_{t+dt} - M_t}{dt} x W_i \tag{4}$$

Where, *DR*= drying rate (kg $H_2O \cdot kg^{-1}$ dry matter·min^{-1})

M_t = moisture content at time t (kg $H_2O \cdot kg^{-1}$ dry matter)
M_{t+dt} = moisture content at time $t + dt$ (kg $H_2O \cdot kg^{-1}$ dry matter)
dt = time interval between measurements (min)
W_i = initial dry weight of the sample (kg)

In addition, the airflow rate was measured at the exhaust layer of the dryer under all three conditions. The volumetric airflow rate (m_{air}) was calculated using the following equation:

$$m_{air} = V_{air} x A \quad (5)$$

Where, m_{air} is the volumetric airflow rate (m^3 s^{-1}), V_{air} is the air velocity, and A is the cross-sectional area of the exhaust window (m^2)

This airflow rate served as a key factor influencing drying kinetics, particularly in determining the rate of moisture removal and drying efficiency across treatments.

RESULTS

Drying Air Temperature Distribution

The thermal distribution within the solar dryer was evaluated under three configurations: CD, OD, and TSD. Temperature measurements were taken at fifteen-minute intervals during both unloaded and loaded conditions over a three day period (D1, D2, and D3). For each condition, the temperature at the top, middle and bottom tray (TT, MT, and BT) was monitored to assess spatial variability and airflow performance.

Closed Dryer Condition

Under no-load conditions (Figure 4A), the CD exhibited the highest temperature gradient, with the TT reaching up to 58.55°C, while the MT and bottom BT measured 48.27°C and 45.31°C, respectively. The AT during this period averaged 33.50°C. These temperature values were obtained between 9:00AM and 3:30PM, highlighting the stratification of heat within the drying chamber. Heavy rainfall during the afternoon of Day 2 and Day 3 prevented data collection for those times.

When the dryer was loaded (Figure 4B), a decrease in average tray temperatures was observed. The TT, MT, and BT recorded 56.88°C, 49.57°C, and 40.42°C, respectively, while the AT averaged 29.67°C.

Open Dryer Condition

In OD, the absence of an enclosure resulted in a lower and less stable temperature profile (Figures 5A and 5B). Under no-load conditions, the TT, MT, and BT reached average temperatures of 48.62°C, 36.69°C, and 35.96°C, respectively. When loaded, these values fluctuated to 52.84°C, 38.36°C, and 33.24°C. The recorded temperature range across all trays varied between 33°C and 53°C, indicating notable fluctuations throughout the drying period.

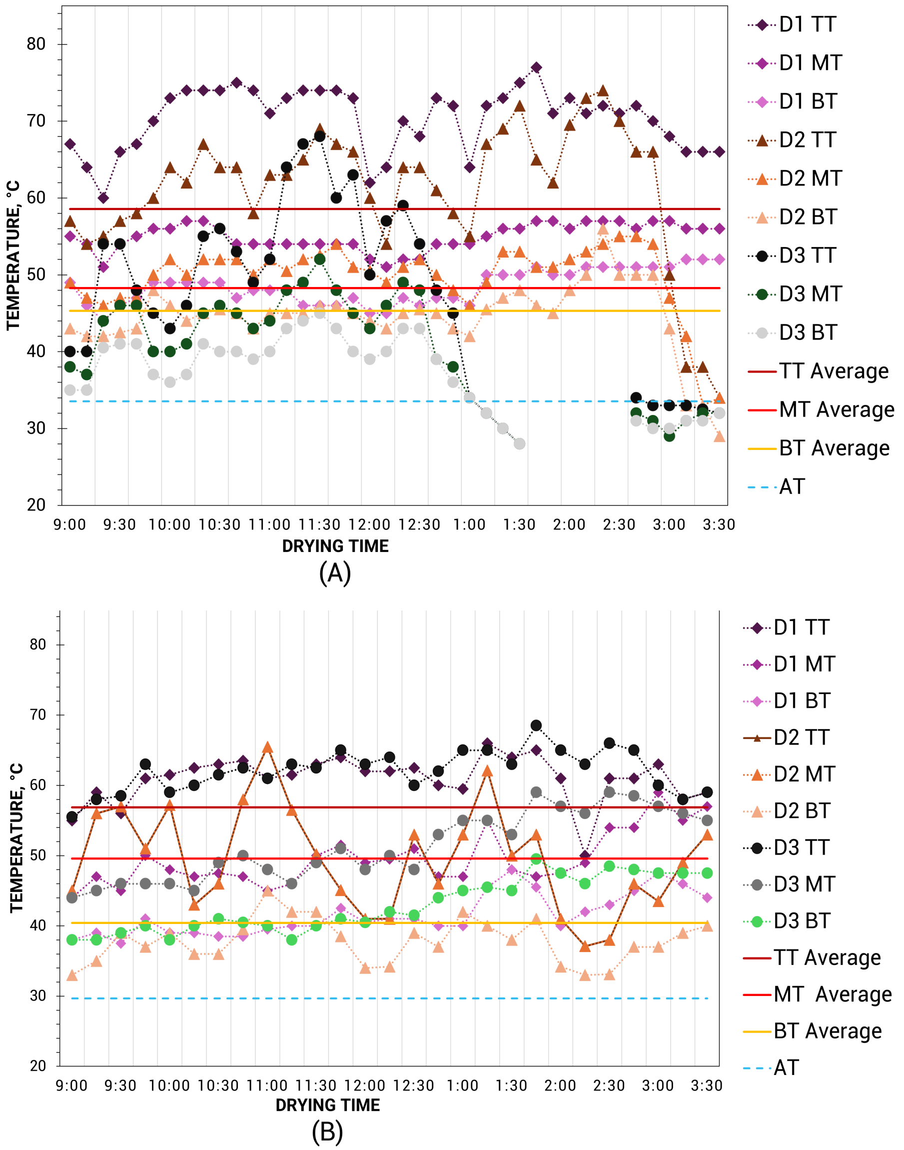

Figure 4. Air drying temperature profiles of CD: (A) without load; (B) with load

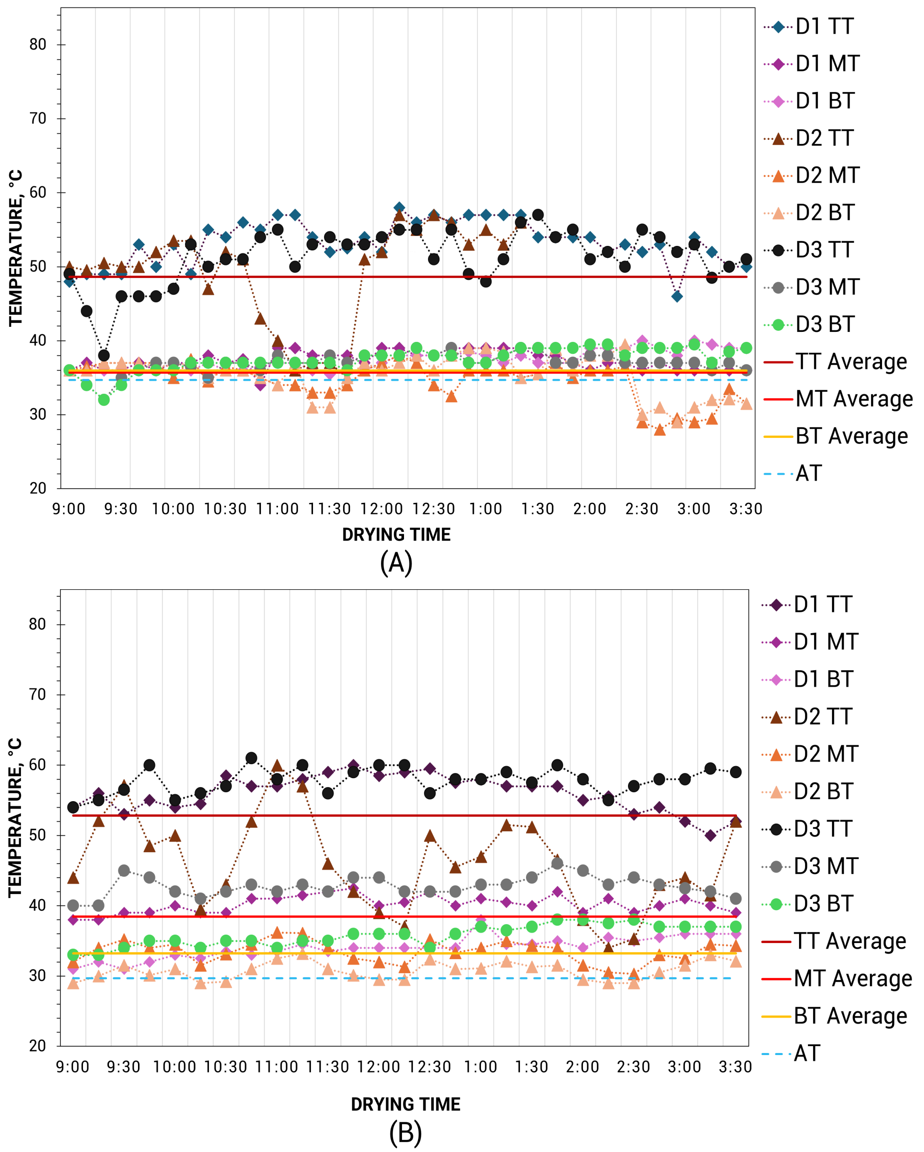

Figure 5. Air drying temperature profiles of OD: (A) without load; (B) with load; 9.00AM-3.30PM

Turbo-Stove Assisted Dryer

The addition of the turbo stove as a supplementary heat source significantly improved temperature uniformity within the dryer, particularly during nighttime operation (Figures 6A and 6B). Under no-load conditions, the TT, MT, and BT attained average temperatures of 49.8°C, 50.02°C, and 52.49°C, respectively. With load, the corresponding average temperatures were 48.99°C, 49.45°C, and

52.41°C. The overall temperature range recorded during both conditions was approximately 49–53°C. These nighttime readings, obtained between 7:00PM and 1:00AM, highlight the dryer's capability to sustain sufficient thermal levels even in the absence of solar input.

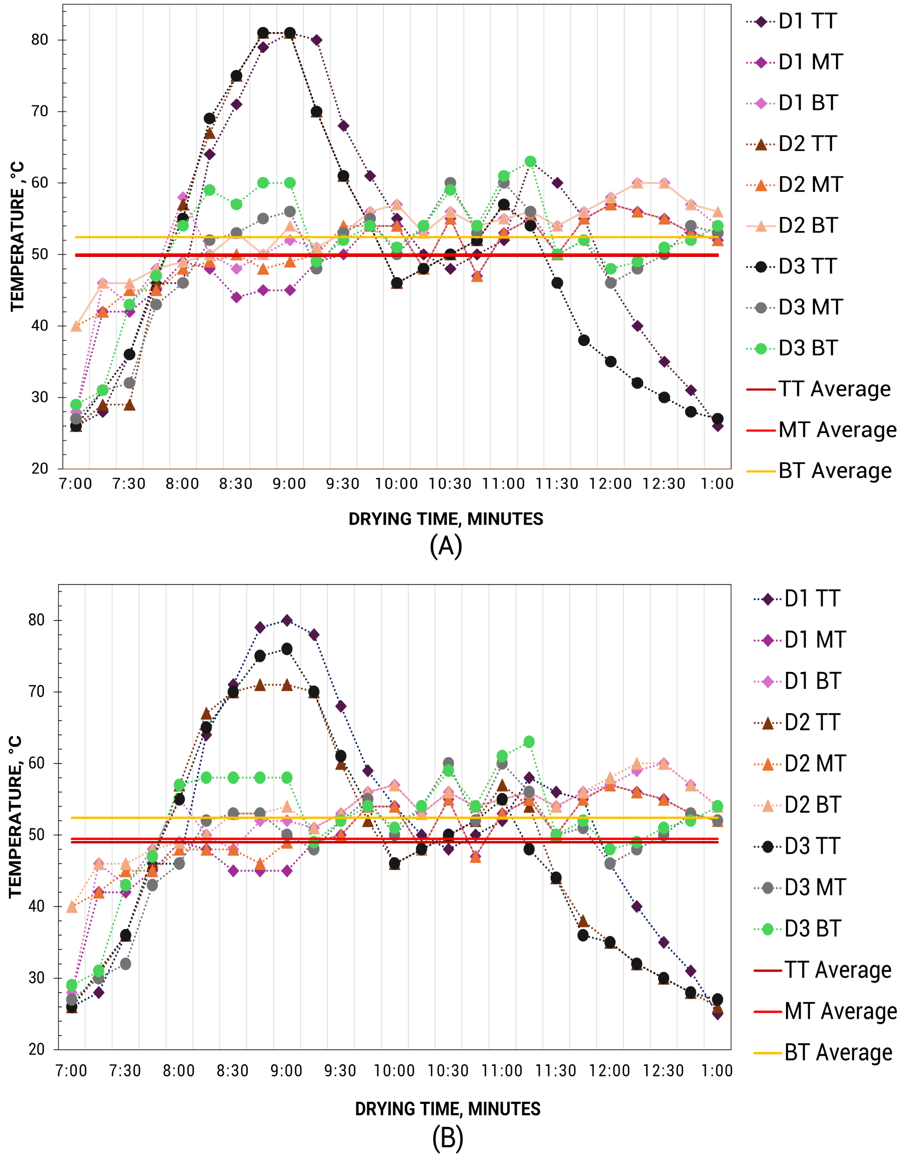

Figure 6. Air drying temperature profiles of TSD: (A) without load; (B) with load; 7.00PM-1.00AM.

Airflow Rate

Airflow rate is a critical factor in drying performance, as it influences the removal of moisture vapor from the drying chamber. Figure 7 presents the mean airflow rates measured at the exhaust layer for the three dryer configurations under both loaded and unloaded conditions.

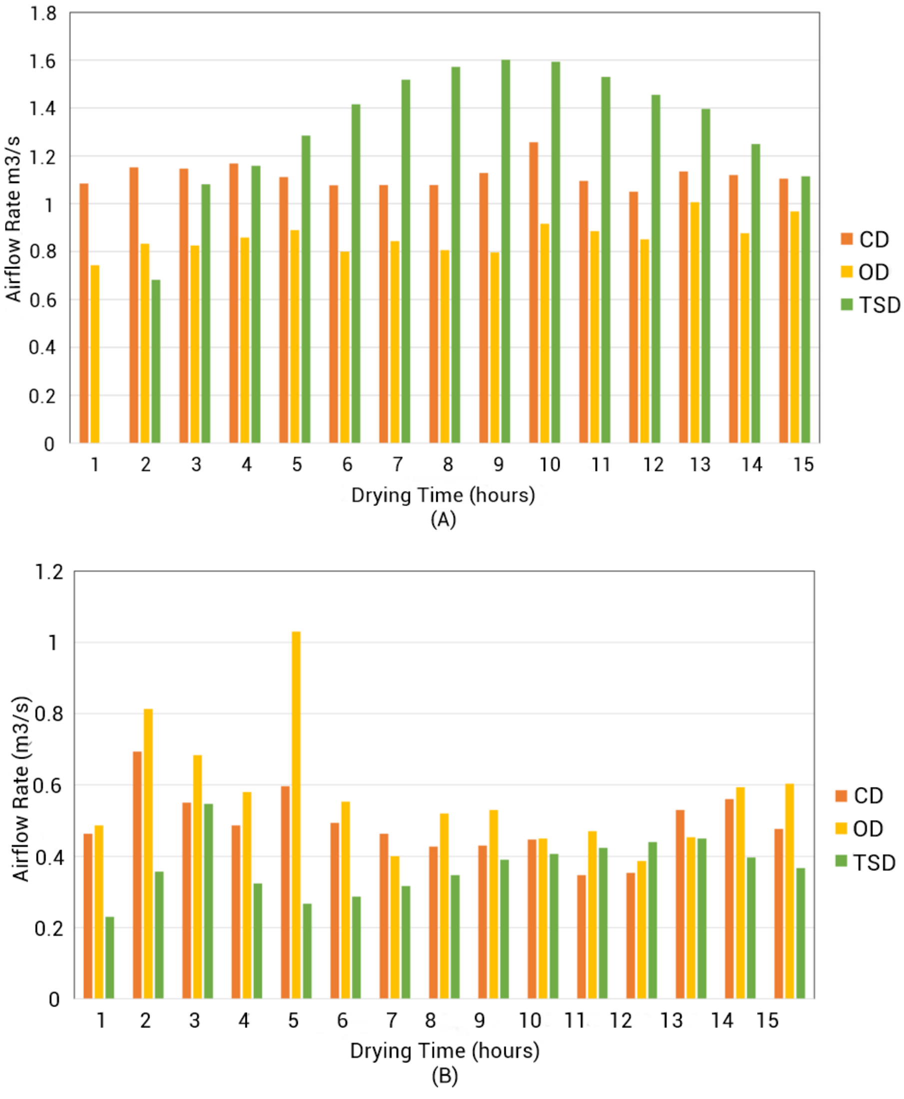

Figure 7. Mean airflow rate at the exhaust layer of the three (3) dryers: (A) without load; (B) with load

When no load was present, the TSD exhibited the highest airflow rate among the three dryers, with a mean value of 1.14 m^3/s, followed by the CD with 1.07m^3/s, and the OD with 0.83m^3/s. Conversely, under loaded conditions, the OD and CD recorded higher exhaust airflow rates, averaging 0.54m^3/s and 0.50m^3/s, respectively, while the TSD exhibited a reduced airflow rate of 0.34m^3/s.

Drying Characteristics of the Samples

The drying behavior of fresh sweet potato leaves in the three drying systems: OD, CD, and TSD was evaluated based on instantaneous moisture content and drying rate. These parameters were used to assess the moisture removal efficiency and overall drying performance of each system over time.

Instantaneous Moisture Content (IMC, %)

The variation of the moisture content in the samples throughout the drying process is presented in Figure 8. This figure compares the average instantaneous moisture content observed in the three solar dryers and in traditional sun drying.

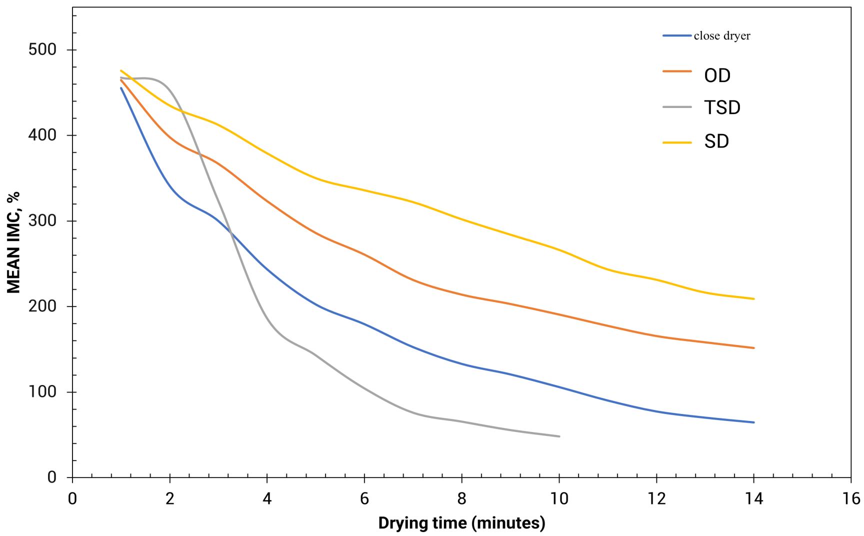

Figure 8. Instantaneous moisture content of sweet potato leaves under different drying systems

The SD exhibited the highest residual moisture content throughout the drying period. The OD followed a similar pattern, showing relatively higher moisture levels due to insufficient heat retention and lack of controlled airflow. In contrast, the CD demonstrated better moisture removal efficiency, while the TSD consistently recorded the lowest moisture content across the drying duration.

Drying Rate

The drying rate, expressed as the mass of moisture removed per hour (g H_2O/g dM·h), reflects how efficiently the drying system extracts moisture from the sample. The drying rate curves for each configuration are presented in Figures 9, while a comparative summary is provided in Figure 10.

Airflow Rate

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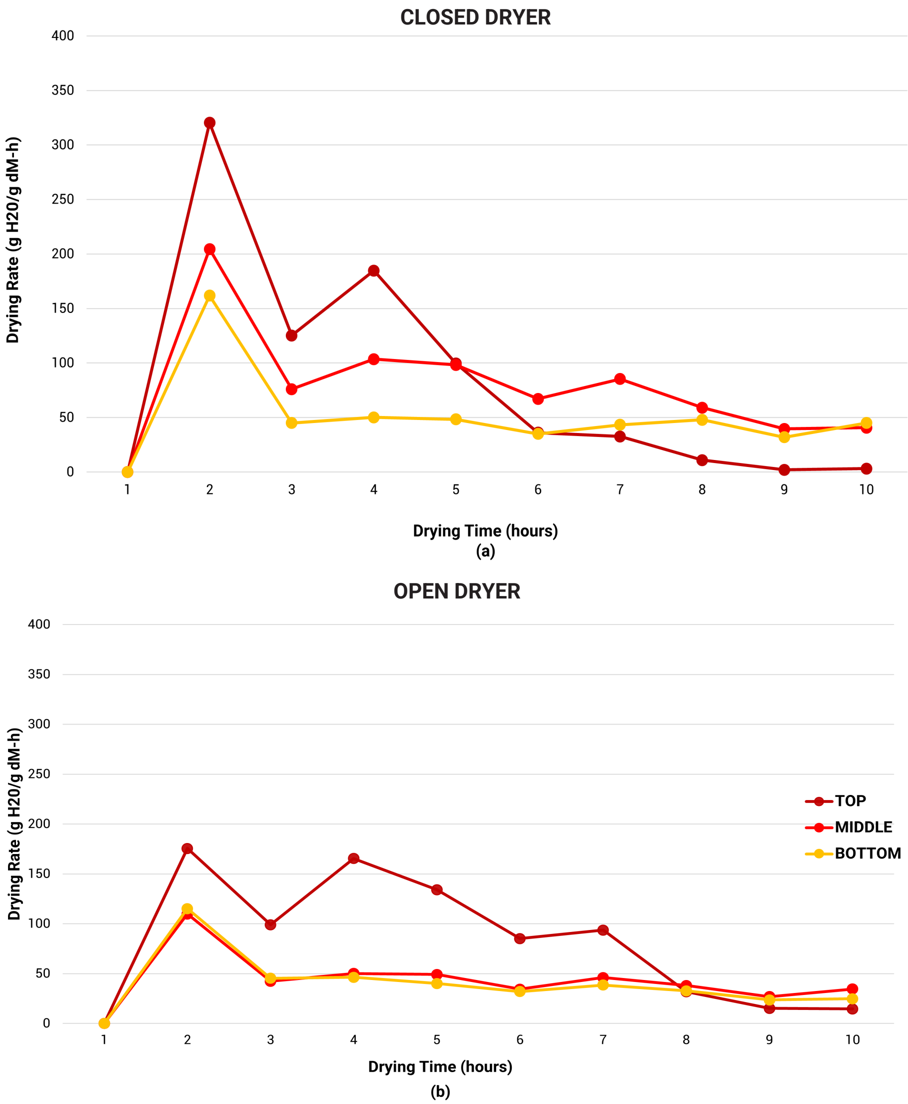
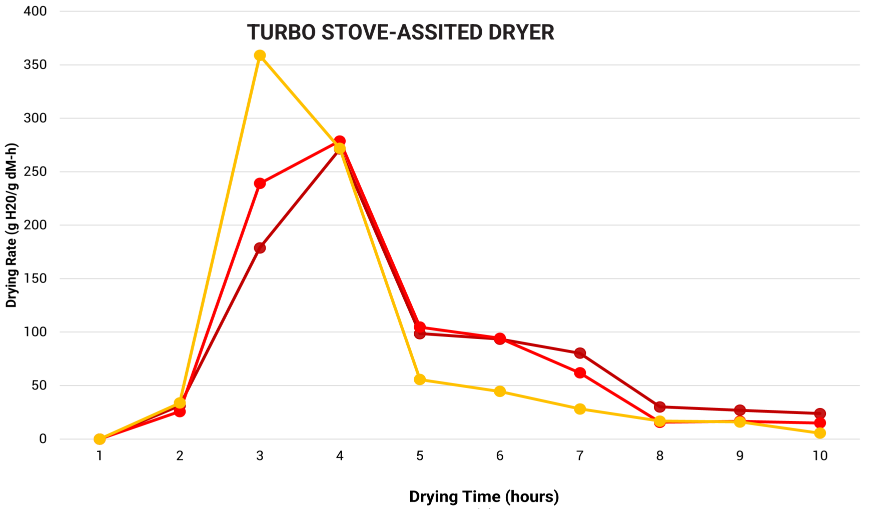


Figure 9. Mean drying rate vs drying time for each dryer (a = CD, b = OD, c = TSD)



(c)

Figure 9. continued

a. Closed Dryer

In CD, the TT initially exhibited the highest drying rate of 320.30g H_2O/g dM·h, with noticeable fluctuations during the first 3.5h. The drying rate then stabilized, indicating a transition to the falling-rate period of drying. The MT showed a more gradual and steady moisture removal, reaching a near-constant drying rate around 6.5h. In contrast, the BT maintained a relatively inconsistent and lower drying rate throughout the drying process, likely due to reduced exposure to heat and limited airflow.

b. Open Dryer

In OD, the TT recorded the highest initial drying rate of 175.48g H_2O/g dM·h, as it was directly exposed to solar radiation. However, the drying rate declined gradually as the drying process progressed. The MT and BT exhibited lower and slower moisture removal, indicating limited vertical heat transfer. Overall, the OD demonstrated less efficiency than the CD.

c. Turbo Stove-Assisted Dryer

The TSD exhibited the most consistent and highest drying rates among all dryers. The BT achieved the peak drying rate of 358.91g H_2O/g dM·h, attributed to its proximity to the turbo stove heat source. The TT and MT also recorded high and stable drying rates, suggesting effective and uniform heat distribution within the dryer chamber.

d. Comparative Analysis

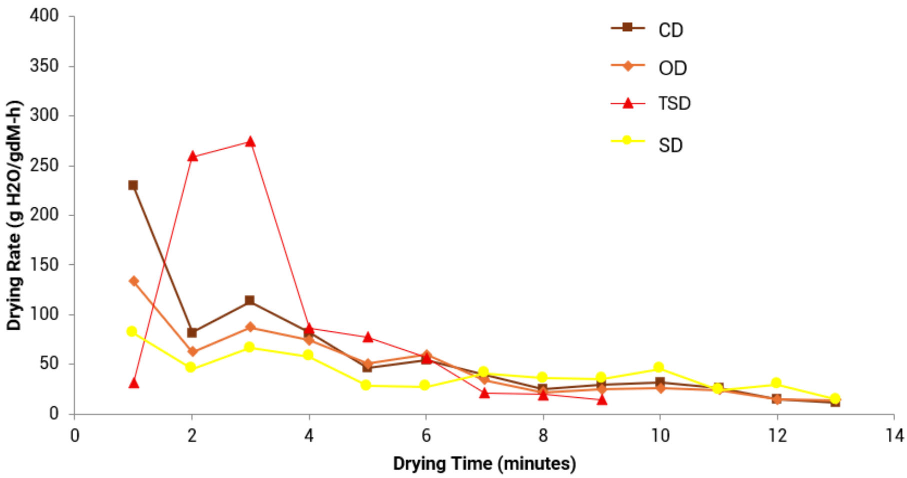


Figure 10. Comparative drying rates among the three dryers and sun drying.

The TSD demonstrated the highest moisture removal rates across all tray levels, outperforming the other drying systems. The CD followed in performance due to its enclosed design, which minimized heat losses and maintained higher internal temperatures. Meanwhile, the OD and SD exhibited the lowest drying rates, with values fluctuating based on time of day and weather conditions. Across all systems, the drying rate declined over time, reflecting the typical falling-rate drying behavior observed in leafy vegetables such as sweet potato leaves.

Statistical Analysis

Statistical analysis revealed that the drying method had a highly significant effect on the average drying rate of sweet potato leaves ($p < .001$), as summarized in Table 1.

Table 1. One-Way Analysis of Variance (ANOVA) of the Average Drying Rates of Sweet Potato Leaves under Different Drying Treatments

Source of Variation	Sum of Squares	df	Mean Square	F-value	*p*-value
Treatment	84562.91837	3	28187.63946		
Block	34995.66072	14	2499.690056	101.99**	< .0001
Experimental Error	33163.7728	120	276.3648	9.04**	< .0001
Sampling Error	76033.05233	42	1810.31077		
Total	228755.4042	179			

***** Note:** p < .01, highly significant at 1% level of significance.*

To determine which treatment pairs differed significantly, a post-hoc comparison was conducted using Tukey's Honestly Significant Difference (HSD) test. As presented in Table 2, the Closed Dryer with Turbo Stove (T3) achieved the highest average drying rate (93.784g H_2O/g dM·h), which was significantly greater than that of the closed dryer (T1), open dryer (T2), and sun drying (T4).

Table 2. Tukey's HSD Test Results for the Average Drying Rates under Different Treatments

Treatment	Dryer Configurations	Average Drying Rate ($g\ H_2O/g\ dM \cdot h$)
T3	TSD	93.784a
T4	OD	54.062b
T1	CD	44.339c
T2	SD	38.067c

Note: *Means with the same letter are not significantly different at the 5% level.*

DISCUSSION

The performance of the three drying systems: OD, CD, and TSD demonstrated clear variations in temperature distribution, airflow behavior, and overall drying performance. These differences highlight how airflow control, enclosure design, and supplemental heating influence the drying characteristics of sweet potato leaves.

In CD, the TT consistently exhibited the highest temperatures due to its direct exposure to solar radiation through the transparent polycarbonate cover. The temperature gradient observed between trays reflects the natural stratification of heat, typical in chamber-type solar dryers with limited forced air movement. When loaded with sweet potato leaves, the overall chamber temperature decreased because the product's thermal mass absorbed heat and stabilized internal fluctuations. This explains why the loaded condition exhibited more uniform temperature profiles than the unloaded condition, where air heated more rapidly without material to absorb and redistribute energy.

The OD, on the other hand, exhibited a lower and less stable temperature range of 33–53°C, falling below the optimal drying temperature of 50–60°C recommended for leafy crops such as sweet potato leaves. The absence of an enclosure led to significant heat loss from wind exposure and ambient air mixing, resulting in poor thermal containment and prolonged drying durations. This outcome aligns with Rocha et al. (2011), who reported that open drying systems are thermally inefficient and unsuitable for crops requiring stable temperatures for quality preservation and uniform moisture removal.

The TSD demonstrated the most stable and elevated temperature distribution, maintaining optimal drying conditions even during periods of low solar radiation. The Yolanda Turbo Stove provided a steady source of biomass-derived heat, effectively sustaining temperatures between 49°C and 53°C across trays during nighttime drying. The BT exhibited the highest temperature, indicating that heat from the stove was efficiently retained and transferred upward by natural convection. However, this also suggests the potential for localized overheating at the lower tray level, which may risk thermal degradation of temperature-sensitive materials, highlighting the need for improved airflow balancing and chamber design.

The enhanced airflow observed in the TSD under no-load conditions can be attributed to the additional thermal energy from the turbo stove, which strengthened buoyancy-driven airflow and increased natural convection inside the chamber. The greater temperature gradient between the air inlet and exhaust created higher pressure differentials, leading to faster air movement. However, when loaded with sweet potato leaves, the airflow decreased due to obstruction caused by trays and samples, which limited air circulation. The higher humidity inside the chamber and restricted ventilation pathways further reduced airflow, suggesting that the integration of an auxiliary heat source must be complemented by optimized vent design and air passage to maintain drying efficiency.

The observed differences in moisture reduction among the drying systems further emphasize the impact of airflow regulation and supplemental heating. The OD's exposure to ambient conditions resulted in greater temperature fluctuations and lower drying uniformity, leading to slower moisture removal. The CD minimized heat losses and maintained higher internal temperatures conducive to faster drying. Meanwhile, the TSD obtained consistent heating, reducing drying time and enhancing moisture removal efficiency.

Within the CD, tray position and airflow distribution also influenced drying behavior. The TT achieved a higher initial drying rate due to its proximity to hot air and better circulation near the exhaust vent, promoting faster surface moisture evaporation. The MT showed a more balanced drying profile, suggesting a stable thermal environment. Conversely, the BT recorded more inconsistent drying rates, likely due to weaker convection currents and cooler air pockets forming at lower levels. For SD, fluctuating drying rates reflected dependence on changing weather conditions, underscoring the limitations of uncontrolled natural drying methods.

Similarly, the OD's drying rate was highly dependent on direct solar exposure, with the TT benefiting most from radiant heat. The lack of a controlled airflow mechanism and heat containment led to a gradual decline in drying rate as moisture removal slowed, particularly in the lower trays. Although the OD performed slightly better than SD, its efficiency remained limited by environmental variability and insufficient heat retention compared to enclosed systems.

The TSD showed the most consistent and rapid drying behavior, with the BT achieving the peak drying rate due to its proximity to the heat source. The combined use of solar and biomass-derived heat maintained elevated and stable chamber temperatures, resulting in enhanced drying uniformity and reduced total drying time. However, the consistently higher BT temperature suggests the need for airflow control improvements to prevent localized overheating and ensure even moisture removal.

Overall, the superior performance of the TSD can be attributed to the synergistic effect of solar and biomass energy, which maintained an elevated and stable drying environment even under fluctuating solar intensity. The use of twin-wall polycarbonate sheets also contributed to improved heat retention and insulation, consistent with the findings of Tan and Cinto (2014), who emphasized that insulation and light transmittance are key factors in solar dryer efficiency.

Nonetheless, a heat imbalance was noted within the drying chamber during the turbo stove operation, as the concentration of heat near the lower and central sections resulted in non-uniform temperature distribution with some areas approaching ambient levels. This observation supports similar findings by Fudholi et al. (2014), who reported that multi-tray solar dryers often suffer from inadequate thermal homogenization due to uneven airflow and suboptimal chimney design. This highlights the need for design refinement to enhance air distribution and maintain consistent product quality across tray levels.

While this study focused on drying characteristics and airflow behavior, the determination of drying efficiency was not included due to the lack of complete energy balance data, such as solar radiation intensity, heat input, and biomass fuel consumption. Future studies are recommended to integrate a detailed energy and exergy analysis to compute drying efficiency and thermal utilization. This would provide a more comprehensive assessment of the system's overall performance and contribute to the further optimization of hybrid solar dryers for high-moisture-content crops like sweet potato leaves.

CONCLUSION

The performance evaluation of the different drying systems revealed that airflow control, heat retention, and supplemental heating significantly influence the drying behavior of sweet potato leaves. Among the tested dryers, the TSD demonstrated the best overall performance, achieving the highest and most consistent drying rates due to the combined effect of solar and biomass-derived heat. This hybrid system effectively maintained the optimal drying temperature range of 50–60°C, reducing drying time and enhancing moisture removal efficiency even under fluctuating weather conditions.

In contrast, the OD and SD methods were more affected by ambient variations, resulting in unstable temperatures, weaker airflow, and slower drying. The CD also performed well but showed slight temperature variations across trays, emphasizing the importance of uniform heat and airflow distribution for product quality. The observed decrease in drying rate over time across all systems is consistent with the typical falling-rate drying phase observed in leafy vegetables, where internal moisture diffusion becomes the limiting factor.

Overall, the findings confirm that hybrid solar dryers with integrated biomass heating and proper airflow design can significantly enhance drying performance, thermal efficiency, and product consistency. Future improvements should focus on optimizing airflow pathways, vent design, and heat distribution to prevent localized overheating and further improve uniform drying within the chamber.

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Author Contributions

MGCS: Writing – original draft preparation, Writing – review and editing, Conceptualization, Data Gathering, Data curation, Visualization, and Validation. MACA: Writing – original draft preparation, Writing – review and editing, Data curation, Visualization, and Validation. RS: Data Gathering, Visualization, and Validation. DLS: Supervision and Validation. HCM: Review and Validation.

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Availability of Data and Materials

The data will be made available upon request.

Ethical Considerations

Not Applicable.

Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work reported in this paper.

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