

Research Article

Performance Enhancement of PVT-Porous Dryer under Humid Tropical Conditions

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ABSTRACT

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Drying remains one of the most energy-intensive processes in agriculture and food industries, accounting for significant energy costs and often compromising product quality under humid tropical conditions. This research investigates a photovoltaic–thermal (PVT) porous dryer designed to enhance drying efficiency and energy performance for kaffir lime leaves. The system integrates a 150 W photovoltaic panel with a double-pass solar collector and porous materials onto the absorber of three porosities (0.96, 0.97, and 0.98). Experiments were conducted under tropical conditions, with measurements of temperature distribution, moisture ratio (MR), drying rate (DR), and specific energy consumption (SEC). Data analysis employed two-way ANOVA and Tukey's HSD tests to evaluate statistical significance. Results indicated that drying occurred predominantly in the falling-rate period governed by internal diffusion. The incorporation of porous absorbers improved drying kinetics, reducing MR by 20–32% and increasing DR by 45–50% compared to the situation without porous material. Energy analysis revealed a 30–34% reduction in SEC, with the lowest value of 20.22 MJ/kg achieved at 0.96 porosity, corresponding to a 33.3% improvement. Statistical validation confirmed significant effects of airflow velocity ($p < 0.05$) and porosity ($p < 0.01$), identifying 0.96 as the optimal balance between air resistance and thermal contact. In conclusion, the PVT-porous dryer demonstrates strong potential as a sustainable and energy-efficient drying technology for herbal and agricultural products. Its ability to enhance drying rates while lowering energy consumption makes it particularly suitable for tropical regions where solar energy is abundant yet variable.

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1. Introduction

Drying represents a critical unit operation across various industries, including food processing, agriculture, and herbal product manufacturing. Its primary function is to reduce the moisture content of materials, thereby extending storage life, ensuring product stability, and preserving nutritional, functional, and sensory attributes (Kumar *et al.*, 2020). Beyond quality preservation, drying plays a central role in ensuring microbial safety and maintaining market competitiveness. However, it remains one of the most energy-intensive processes, accounting for approximately 10–25% of total industrial energy

consumption (Mujumdar, 2015; Tsotsas and Mujumdar, 2022). Consequently, advances in drying technologies are essential not only for enhancing process efficiency and improving product quality but also for addressing broader energy and environmental challenges. Nevertheless, drying is widely recognized as highly energy-intensive, requiring substantial energy input to achieve effective moisture removal. In many industrial sectors, drying accounts for approximately 10–25% of total energy consumption, underscoring its significant contribution to operational costs and environmental impacts. Consequently, improving the energy efficiency of drying systems is crucial not only for reducing production expenses but also for

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advancing sustainable industrial practices. Solar energy constitutes an abundant, renewable, and environmentally sustainable resource that is inherently inexhaustible and freely available. In light of escalating global challenges associated with climate change, largely attributable to the combustion of fossil fuels, alongside the rising costs of conventional energy, the transition toward solar energy has become increasingly imperative (Azis *et al.*, 2024; Senthil *et al.*, 2021). Solar energy, acknowledged as a clean, abundant, and renewable resource, presents a sustainable alternative for drying applications. However, its practical utilization is often constrained by inherent seasonal fluctuations and weather-dependent variations in solar radiation intensity. These limitations can result in inconsistent drying performance, particularly in humid tropical climates, thereby necessitating the development of integrated systems, such as photovoltaic–thermal (PVT) collectors, porous absorber materials, and phase change energy storage, to stabilize energy supply, enhance thermal efficiency, and ensure reliable drying outcomes. Solar dryers, by comparison, provide a more sustainable and cost-effective solution, particularly for agricultural materials (Rajarajeswari *et al.*, 2018; Teeboonma and Boonthum, 2019). Consequently, solar dryers have emerged as a cost-effective and environmentally sustainable alternative to conventional drying methods. Nevertheless, their efficiency remains relatively limited, as system performance is strongly influenced by the intermittency of solar radiation, particularly under unfavorable weather conditions. These inherent constraints highlight the need to incorporate performance-enhancing strategies, such as PVT integration for waste heat recovery, porous materials that incorporate an absorber for improved heat transfer, and thermal storage to stabilize energy availability, thereby ensuring consistent and efficient drying outcomes. Over the years, numerous researchers have investigated various strategies to enhance the efficiency of solar dryers. For instance, they designed and evaluated the performance of an innovative indirect free-convection solar dryer (Al-Jethelah *et al.*, 2021). Their results demonstrated substantial enhancements in drying performance, with thermal efficiency surpassing that of conventional systems by 68%, 39%, 49%, and 85%, respectively. Comprehensively investigated a double-pass hybrid PVT system for drying applications through theoretical modelling and experimental validation (Jadallah *et al.*, 2020). The system achieved outlet temperatures of up to 63°C and a peak overall efficiency of 85%, with maximum electrical and thermal outputs of 50.57 W and 389.37 W, respectively, at a flow rate of 0.031 kg/s. Their findings underscore the potential of PVT systems to enhance drying performance by leveraging both thermal and electrical outputs, while highlighting the importance of integrated waste-heat recovery for improved efficiency. Additionally, incorporating porous materials into solar collector absorber plates has been shown to enhance thermal efficiency and significantly stabilize

air temperatures, even during periods of low solar radiation (Nima *et al.*, 2020; Murali *et al.*, 2020). Various studies have shown that combining porous materials with advanced solar panels can improve drying efficiency and energy efficiency, including investigating the effects of porous materials on flow resistance and temperature distribution in passive solar air heaters using experimental and numerical analyses (Kumar and Premachandran, 2020). Their study showed porous material significantly altered flow structure by reducing recirculation zones and improving flow uniformity; air temperature increased due to enhanced convective heat transfer; and the heat transfer coefficient and outlet air temperature improved compared to the non-porous configuration. While their findings offer valuable design insights, the combined application of PV waste heat recovery and porous materials in solar dryers remains underexplored. Examined the design and energy efficiency of solar dryers, identifying limitations in energy savings and cost-effectiveness (Mohana *et al.*, 2020). Their study emphasized the economic and social benefits of solar drying while noting that broader adoption remains constrained by several operational and developmental challenges. Highlighted that hybrid solar drying technologies, particularly PVT-porous systems and heat pump integration, improve efficiency and suitability for delicate products, while the utilization of biomass reduces costs (Jha and Tripathy, 2021). However, design refinements and enhanced hygiene standards remain necessary for optimization. A qualitative investigation into technological advancements in solar dryer design (Kamarulzaman *et al.*, 2021). Their findings indicated that solar dryers are efficient, environmentally sustainable, and characterized by low carbon emissions, with payback periods ranging from 0.5 to 4.6 years. Despite notable cost and energy savings, further design improvements are necessary to optimize performance. Furthermore, integrating heat-accumulating materials has been shown to improve system performance further. Hybrid PV-T solar collector using amorphous type of solar cells for solar dryer (Tarigan, 2020). Experimental results demonstrated its dual capability to generate heat and electricity, achieving air temperatures of 35–50°C and electrical outputs of 4–25 W under solar irradiance of 300–1000 W/m². The integrated generation of heat and power significantly enhanced overall drying efficiency. PVT-porous solar dryers integrating PVT systems achieve higher efficiency through combined heat and electricity generation, though at higher construction costs (Mirzaei *et al.*, 2022). Incorporating heat-storage materials further improved drying performance, uniformity, and environmental sustainability. Integration of porous materials enhances thermal retention and controlled heat release, while waste heat recovery improves absorber efficiency. These modifications in PVT-porous dryers significantly increase energy and exergy efficiencies, stabilize temperature profiles, and reduce performance fluctuations,

thereby advancing system reliability under variable solar conditions.

This study addresses the research gap by experimentally assessing the performance of a photovoltaic–thermal (PVT) porous dryer that couples solar energy utilization with waste heat recovery from a PV panel while integrating porous materials onto the absorber to enhance heat transfer. Conducted under humid tropical conditions in Thailand, the investigation demonstrates the system's potential for improving drying efficiency and energy recovery in solar-assisted drying applications.

2. Materials and Methods

2.1 Experimental setup

The PVT-porous dryer employed in this research is a passive system that incorporates a 150-watt solar panel with cooling fins on its backside, referred to as a PVT system. The panel is mounted atop the drying chamber, is constructed from steel sheets and insulated, and has dimensions of 1 m x 1 m x 1 m and contains 3 trays. An air duct connects the PVT system to a double-pass solar collector panel (DPSC) measuring 0.75 m in width, 1.85 m in length, and 0.25 m in height. The absorber plate within the solar collector is made from a 1.5 mm-thick steel sheet. The PVT, solar collector panel, and fan are connected via an air duct to deliver hot air into the drying chamber at its lower side wall. An 80 W forward-curved centrifugal fan is installed, and the airflow rate is modulated using a damper.

The porous material was placed onto the absorber plate, which was fabricated from perforated steel sheets with a thickness of 1.2 mm, 2 PPI, hole diameters of 10 mm, and a pitch of 3 mm. These perforated steel sheets were precisely cut and assembled into hollow, rectangular enclosures measuring 100 mm in width by 90 mm in height. Steel meshes were placed within hollow rectangular enclosures to determine porosity values of 0.98, 0.97, and 0.96. Figures 1, 2, and 3 illustrate the schematic diagram, a photograph of the PVT-porous dryer, and the structure of porous material. The porosity was systematically adjusted by varying the number of stacked steel mesh sheets, yielding porosity values of 0.98, 0.97, and 0.96 for 10, 18, and 22 mesh layers, respectively.

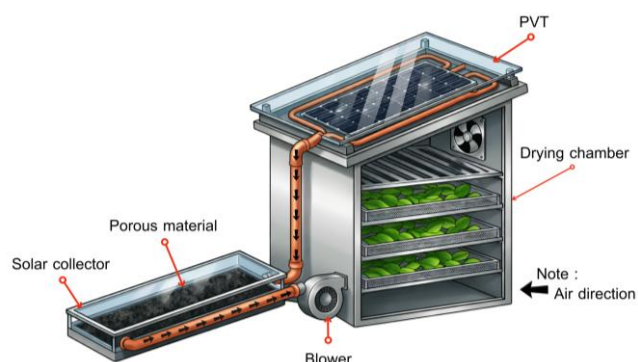


Figure 1 Schematic diagram of the PVT-porous dryer.



Figure 2 Photograph of the PVT-porous dryer.

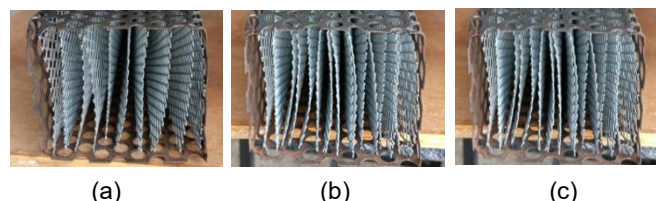


Figure 3 Porous material structure: (a) 0.98 porosity; (b) 0.97 porosity; (c) 0.96 porosity.

The porosity of the porous material was determined by weighing a representative sample, converting its mass to the corresponding solid volume using the steel density, and calculating the ratio of the solid volume to the total available volume above the heat collector plate.

The experiments were conducted under tropical weather conditions in Thailand on 9th June and 27th July 2025, from 9:00 a.m. to 4:00 p.m. Kaffir lime leaves were used as the drying sample, with an initial weight of 200 g per trial and a moisture content of 170% d.b. Using fresh whole kaffir lime leaves, select leaves that are of similar size and age. In solar drying of kaffir lime leaves, the moisture ratio (MR) is employed as an indicator of moisture content, with values maintained below 0.5. The AOAC (2019) standard was used to determine the product's moisture content (AOAC International, 2019). The selected air velocity represents the lowest feasible airflow that ensures proper solar dryer performance without excessive fan energy consumption. The hot air velocity inside the PVT-porous dryer was measured using a hot-wire anemometer with a range of 0 to 20 m/s, a tolerance of ± 0.03 m/s ($\pm 5\%$), and a resolution of 0.1 m/s. Temperature data were recorded using K-type thermocouples connected to a data logger with an accuracy of $\pm 1^\circ\text{C}$. The weight of the dried product was measured using a load cell capable of handling 1–20 kg with an accuracy of ± 0.1 g and a digital scale with a maximum capacity of 500 g and a resolution of 0.1 g. Figure 4 illustrates the measurement points utilized during the experiments.

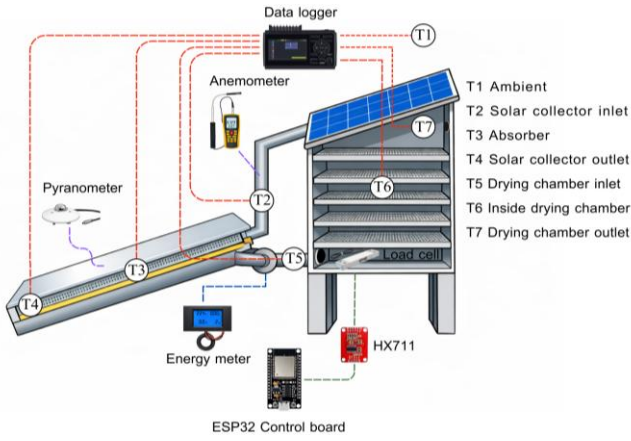


Figure 4 Measurement points utilized during the experiments.

2.2 Analysis

Porosity is calculated as the proportion of void volume relative to the total volume of a material. It represents a critical parameter for characterizing fluid retention and flow behavior in porous material, as expressed in Equation (1) (Bear, 1972).

$$\mathcal{E} = \frac{V_p}{V_t} = 1 - \frac{V_s}{V_t} \quad (1)$$

where $\mathcal{E}$ is porosity, V_p is the volume of the pore (m^3), V_t is the total volume (m^3), and V_s is the volume of the solid (m^3).

The moisture ratio (MR) is commonly used to approximate moisture content, assuming the equilibrium moisture content is negligible. It is calculated by comparing the moisture content at a given time with the initial moisture content, as expressed in Equation (2).

$$MR = \frac{M_t}{M_{in}} \quad (2)$$

where MR is the moisture ratio, M_{in} is the initial moisture content, and M_t is the moisture content at each time interval.

The dry weight was determined by preparing a representative sample and drying it in a hot-air oven at 103°C for 72 hours, in accordance with AOAC (2019) standards. These values were subsequently applied to calculate the moisture content at each interval using Equation (3) (AOAC, 2019).

$$MC = \frac{w - d}{d} \quad (3)$$

where MC is dry basis moisture content at each time interval (D.B.), w is wet weight of product at each time interval (g), and d is dry weight of product (g).

The drying rate quantifies the rate of moisture removal per unit time and serves as a fundamental indicator of mass transfer efficiency in drying processes. In solar drying systems, it reflects the combined effects of heat and mass transfer mechanisms, and is mathematically defined in Equation (4) (Mujumdar, 2015).

$$DR = \frac{\Delta w}{\Delta t} \quad (4)$$

where DR is drying rate (g/h), Δw is mass of evaporated water (g), and Δt is time interval (h).

Specific energy consumption (SEC) represents the energy required to remove a unit mass of moisture from the material and is determined using Equation (5) (Fudholi *et al.*, 2010). This parameter is widely employed to evaluate the energy efficiency of drying systems, as lower SEC values indicate more efficient utilization of input energy.

$$SEC = \frac{3.6E}{w_i - w_f} \quad (5)$$

where SEC is specific energy consumption (MJ/kg), E is power of fan motor (W), w_i is wet weight before drying (kg), and w_f is wet weight after drying (kg).

Measurement uncertainties were evaluated for key parameters, including air temperature, velocity, solar irradiance, and mass. The associated uncertainties were $\pm 1.0^\circ\text{C}$ for K-type thermocouples, $\pm 5\%$ for the hot-wire anemometer, $\pm 5\%$ for the solar radiation meter, and ± 1 g for the scale. A summary of the individual uncertainties is presented in Table 1. The overall combined uncertainty was calculated using the root-sum-of-squares (RSS) method (JCGM, 2008).

$$\frac{\Delta R}{R} = \sqrt{\left(\frac{\Delta T}{T}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta M}{M}\right)^2} \quad (6)$$

where R is the calculated result, T , I , V , and M are measured parameters (air temperature, solar irradiance, velocity, mass), and Δ is the respective uncertainties.

Table 1 Individual uncertainties for each measured parameter.

Parameter	Device	Uncertainty
Temperature	K-type Thermocouple	$\pm 1^\circ\text{C}$
Air velocity	Hot Wire Anemometer	$\pm 5\%$
Solar radiation	Solar radiation meter	$\pm 5\%$
Scale	Digital scale and load cell	± 0.1 g

The total uncertainty of the calculated parameters, including drying rate and specific energy consumption, was assessed using error propagation methods in accordance with the Guide to the Expression of Uncertainty in Measurement (GUM). The combined uncertainty was $\pm 7\%$.

3. Results and Discussion

An experimental investigation conducted without porous materials at air velocities of 0.07, 0.09, and 0.10 m/s revealed notable variations in solar radiation and temperature profiles

within the dryer. Solar radiation ranged from 371 to 1,001 W/m², with an average of 776 W/m². The drying chamber temperature ranged from 36°C to 45°C, with an average of 41°C while the inlet air temperature ranged from 36°C to 46°C, with an average of 42°C. The absorber plate temperature fluctuated between 49°C and 66°C, with an average of 57°C. Ambient temperatures ranged from 29°C to 35°C, with an average of 32°C, and the solar collector inlet temperature ranged from 32°C to 36°C, with an average of 34°C. These results (as shown in Figures 5, 6, and 7) provide essential insights into the thermal behavior and energy dynamics of the PVT-porous dryer under varying air velocities.

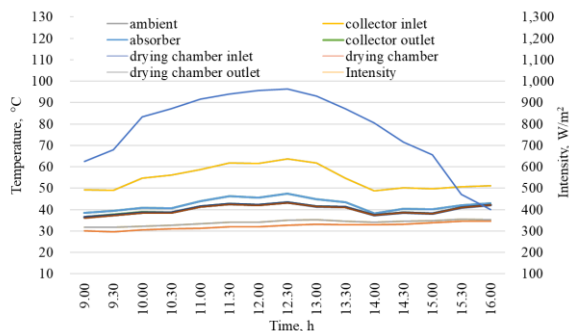


Figure 5 Temperature profile in the dryer without porous material at 0.07 m/s.

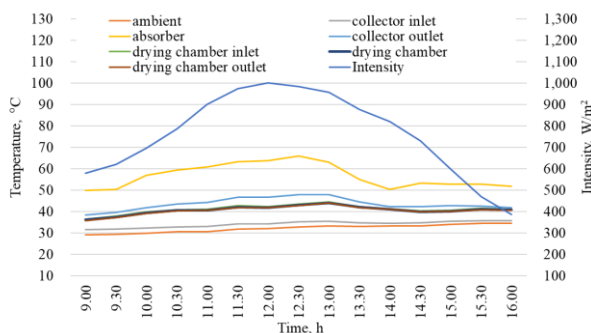


Figure 6 Temperature profile in the dryer without porous material at 0.09 m/s.

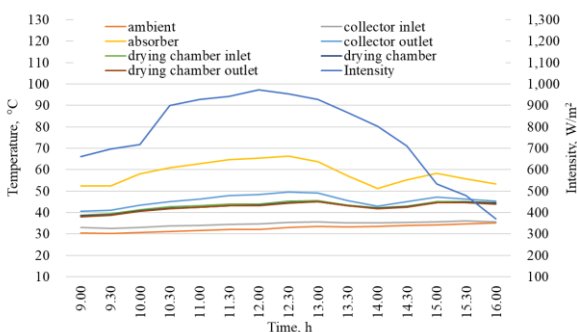


Figure 7 Temperature profile in the dryer without porous material at 0.10 m/s.

The experimental analysis of the solar dryer system incorporating 0.98 porosity porous materials on the absorber plate at air velocities of 0.07, 0.09, and 0.10 m/s demonstrated significant enhancements in thermal performance. Solar radiation values ranged from 332 to 1,015 W/m², with an

average of 763 W/m². The drying chamber temperature ranged from 38°C to 47°C, with an average of 41°C, while the inlet air temperature to the chamber ranged from 38°C to 47°C, with a mean of 41°C. The temperature on the absorber plate fluctuated between 47°C and 66°C, with an average of 55°C. Ambient temperatures ranged from 30°C to 34°C, with an average of 33°C. The inlet temperature to the solar collector ranged from 32°C to 37°C, with an average of 34°C. These results are illustrated in Figures 8, 9, and 10.

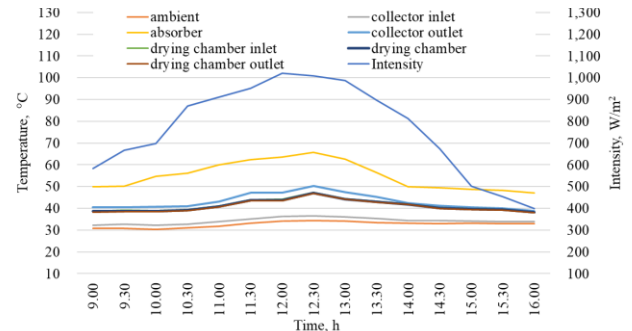


Figure 8 Temperature profile in dryer with 0.98 porosity porous at 0.07 m/s.

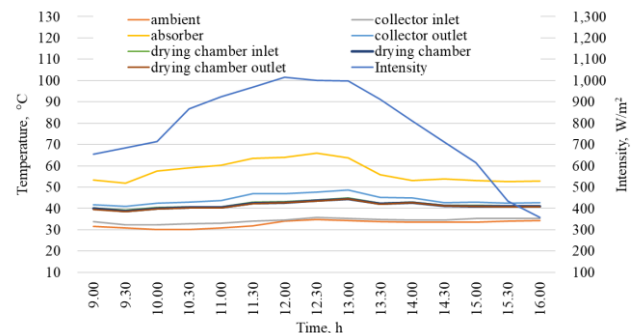


Figure 9 Temperature profile in dryer with 0.98 porosity porous at 0.09 m/s.

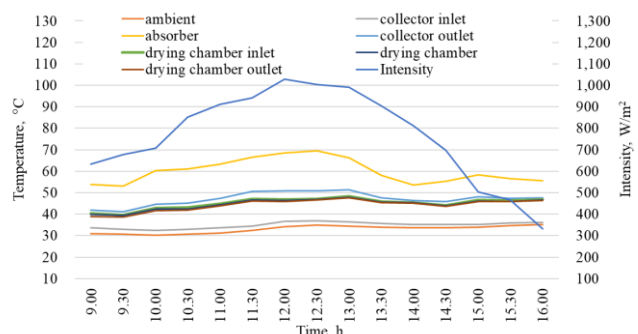


Figure 10 Temperature profile in dryer with 0.98 porosity porous at 0.10 m/s.

The experimental analysis of the solar dryer system incorporating 0.97 porosity porous materials on the absorber plate at air velocities of 0.07, 0.09, and 0.10 m/s demonstrated significant enhancements in thermal performance. Solar radiation values ranged from 411 to 1,022 W/m², with an average of 779 W/m². The drying chamber temperature ranged from 37°C to 50°C, with an average of 44°C, while the inlet air temperature to the chamber ranged from 38°C to 51°C, with a

mean of 45°C. The temperature on the absorber plate fluctuated between 50°C and 68°C, with an average of 59°C. Ambient temperatures ranged from 31°C to 33°C, with an average of 32°C. The inlet temperature to the solar collector ranged from 32°C to 57°C, with an average of 34°C. These results are shown in Figures 11, 12, and 13.

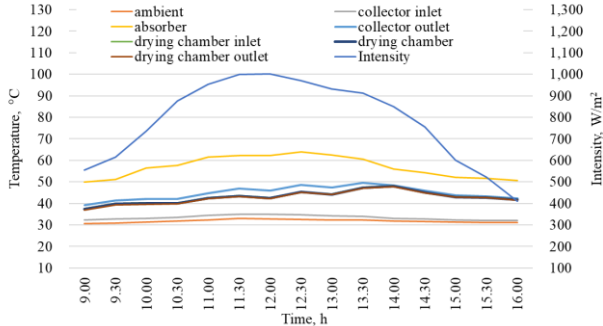


Figure 11 Temperature profile in dryer with 0.97 porosity porous at 0.07 m/s.

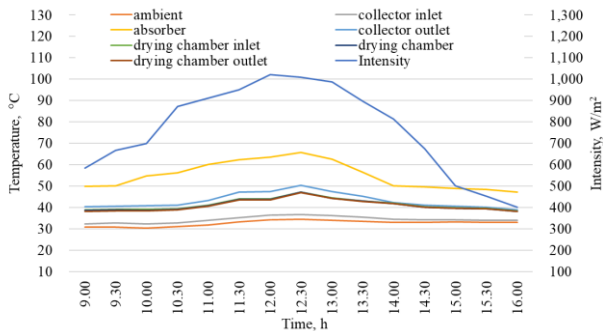


Figure 12 Temperature profile in dryer with 0.97 porosity porous at 0.09 m/s.

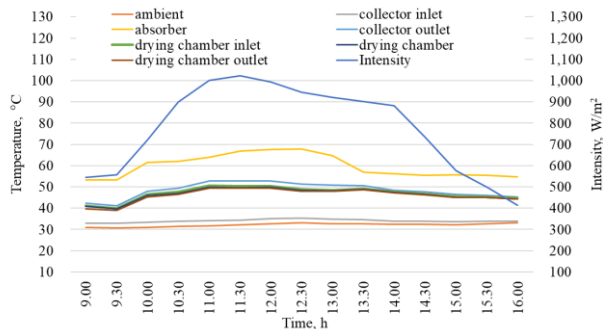


Figure 13 Temperature profile in dryer with 0.97 porosity porous at 0.10 m/s.

The experimental analysis of the solar dryer system incorporating 0.96 porosity porous materials on the absorber plate at air velocities of 0.07, 0.09, and 0.10 m/s demonstrated significant enhancements in thermal performance. Solar radiation values ranged from 357 to 1,008 W/m², with an average of 768 W/m². The drying chamber temperature ranged from 38°C to 55°C, with an average of 45°C while the inlet air temperature to the chamber ranged from 39°C to 55°C, with a mean of 45°C. The temperature on the absorber plate fluctuated between 50°C and 68°C, with an average of 59°C. Ambient temperatures ranged from 30°C to 33°C, with an average of

32°C. The inlet temperature to the solar collector ranged from 31°C to 35°C, with an average of 34°C. These results are shown in Figures 14, 15, and 16.

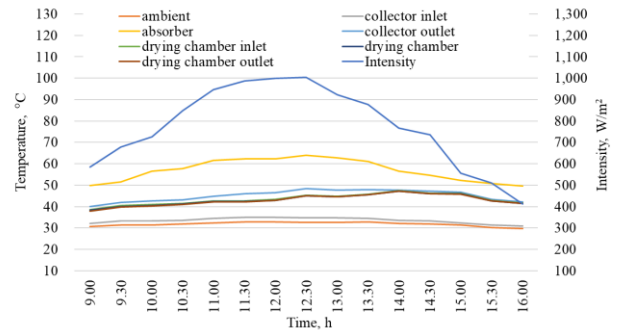


Figure 14 Temperature profile in dryer with 0.96 porosity porous at 0.07 m/s.

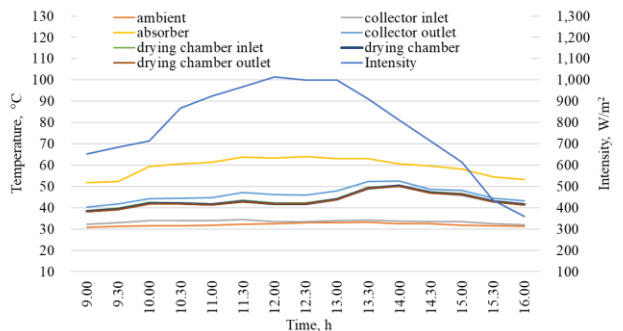


Figure 15 Temperature profile in dryer with 0.96 porosity porous at 0.09 m/s.

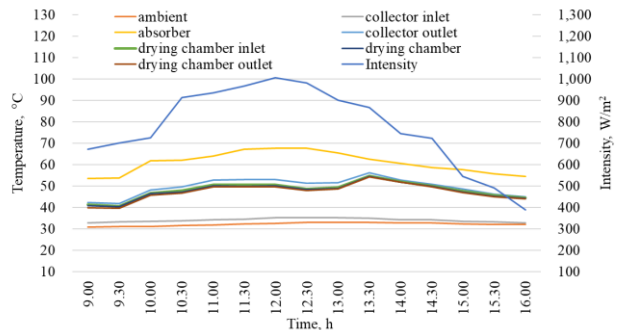


Figure 16 Temperature profile in dryer with 0.96 porosity porous at 0.10 m/s.

Figure 17 shows the variation of moisture ratio (MR) with drying time for kaffir lime leaves at air velocities of 0.07, 0.09, and 0.10 m/s without and with porous materials (0.96, 0.97, and 0.98). Figure 18 shows kaffir lime leaves after drying. In all cases, MR decreased continuously during the 420 min drying period, confirming that drying was dominated by the falling-rate stage controlled by internal diffusion. Incorporating porous materials enhanced drying efficiency, with final MR values of 0.15–0.20 compared to 0.22–0.25 without porous material, representing a 20–32% improvement. The 0.96 porosity consistently yielded the lowest MR values, suggesting an optimal balance between air resistance and thermal contact. Drying constants (k) derived from the exponential model

increased by 10–20% with porous absorbers, peaking at 0.96. A reduction in porosity facilitates a more uniform distribution of thermal energy across the heat transfer area and intensifies airflow turbulence, thereby enhancing convective heat transfer and improving mass transfer and overall drying performance compared with higher-porosity configurations. Two-way ANOVA confirmed significant effects of air velocity ($p < 0.05$) and porosity ($p < 0.01$) while Tukey's HSD validated differences across porosity levels. These results corroborate earlier findings (Das *et al.*, 2020; Messai *et al.*, 2022) and advance understanding by confirming the optimization of porosity, with 0.96 identified as the most effective configuration.

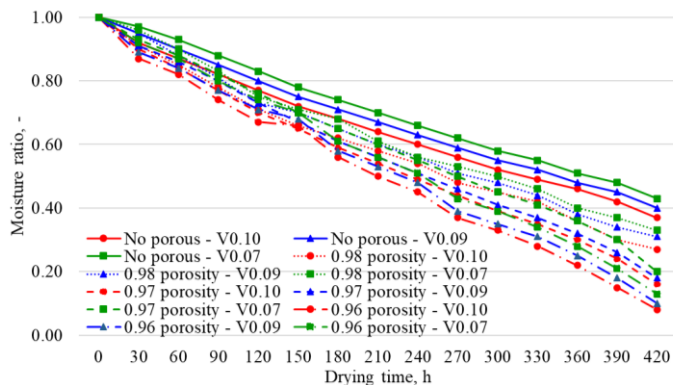


Figure 17 Moisture ratio in each experiment with and without porous material.



Figure 18 Dried kaffir lime leaves.

Figure 19 shows the drying rate of kaffir lime leaves at air velocities of 0.07, 0.09, and 0.10 m/s without and with porous materials (0.96, 0.97, and 0.98). Without porous material, drying rates increased from 6.86 g/h at 0.07 m/s to 7.71 g/h at 0.10 m/s, reflecting a modest 12% improvement. By contrast, incorporating porous material onto the absorber plate significantly enhanced performance, yielding 9.86–11.57 g/h, equivalent to a 45–50% improvement. Among the porous cases, a porosity of 0.96 consistently yielded the highest drying rates, indicating an optimal porosity threshold that balances air resistance and heat transfer. Two-way ANOVA confirmed significant effects of air velocity ($p < 0.05$) and porosity ($p < 0.01$), while Tukey's HSD test verified significant differences across groups. These results are consistent with earlier reports that porous media improve thermal performance and drying efficiency (Mirzaei *et al.*, 2022; Safri *et al.*, 2020; Coban *et al.*,

2021). The present study advances knowledge by identifying 0.96 porosity as the most effective configuration.

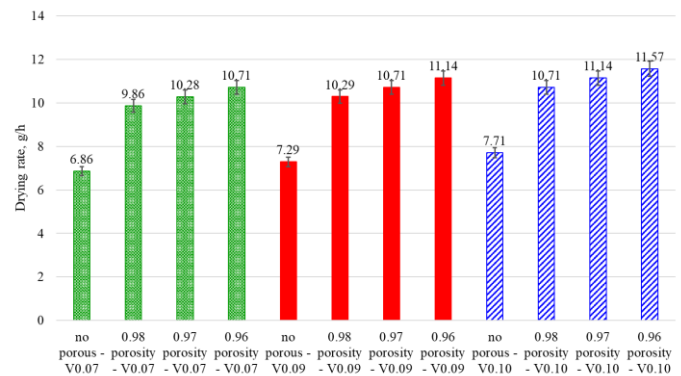


Figure 19 Drying rate in each experiment.

Figure 20 illustrates the specific energy consumption (SEC) of kaffir lime leaves under air velocities of 0.07, 0.09, and 0.10 m/s without and with porous materials (0.96, 0.97, and 0.98 porosity). Without porousness, SEC decreased from 34.13 MJ/kg at 0.07 m/s to 30.33 MJ/kg at 0.10 m/s, representing about an 11% improvement with velocity. In contrast, incorporating porous materials significantly reduced the SEC to 20.22–23.74 MJ/kg, corresponding to approximately 30–34% energy savings compared with the value without porous materials. The relative improvement with the maximum reduction was observed at 0.10 m/s for a porosity of 0.96 (33.3%). Among porous levels, 0.96 consistently achieved the lowest SEC, suggesting an optimal porosity that balances turbulence enhancement with effective heat transfer. Two-way ANOVA confirmed significant effects of air velocity ($p < 0.05$) and porosity ($p < 0.01$), with Tukey's HSD test verifying statistical differences across configurations. The reduced sensitivity of SEC to air in porous configurations indicates improved thermal stability. These results align with earlier reports (Mohammad *et al.*, 2025), while the present study advances understanding by identifying 0.96 porosity as the most energy-efficient configuration.

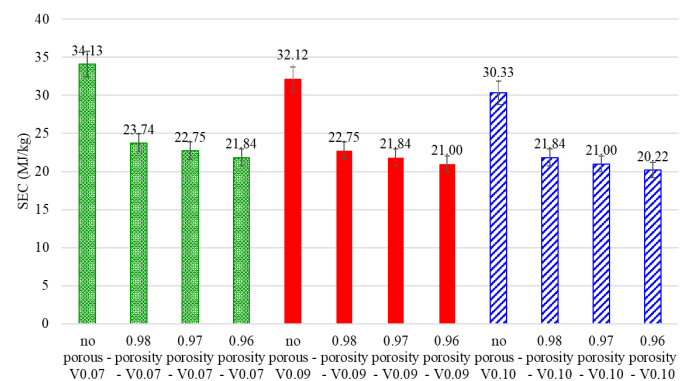


Figure 20 Specific energy consumption in each experiment.

4. Conclusion

This study experimentally demonstrated that a photovoltaic–thermal (PVT) dryer integrating porous materials onto the absorbers significantly improves drying performance and energy efficiency for kaffir lime leaves under humid tropical conditions. The results confirmed that drying was dominated by the falling-rate period, governed by internal diffusion. The use of porous materials reduced final moisture ratios by approximately 20–32% and enhanced drying rates by 45–50% compared to the case without porous materials. Specific energy consumption decreased by 30–34%, with the lowest value achieved at a porosity of 0.96, corresponding to a 33.3% reduction. Statistical analysis confirmed that both air velocity and porosity exerted significant effects, with 0.96 representing the optimal balance between air resistance and thermal contact. These findings establish the PVT-porous dryer as a sustainable and energy-efficient alternative for agricultural drying applications. Future studies should address scalability, economic feasibility, and performance under diverse climatic conditions.

5. Acknowledgments

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