

THERMAL PERFORMANCE OF A PHOTOVOLTAIC-THERMAL SOLAR DRYER INTEGRATED WITH HIGH-POROSITY STEEL MESH

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ABSTRACT

The growing global demand for sustainable, cost-effective drying technologies has driven significant advancements in solar drying systems. This study experimentally evaluated the performance of a solar dryer integrated with porous materials for drying kaffir lime leaves under tropical climatic conditions in Thailand to enhance thermal efficiency and drying effectiveness. The dryer incorporated a 150 Watt photovoltaic-thermal (PVT) panel, a double-pass solar collector, and porous materials with a porosity of 0.97 onto the absorber plate. Experiments were conducted at air velocities of 0.07, 0.09, and 0.10 m/s to investigate drying kinetics, including moisture ratio (MR), drying rate (DR), and specific energy consumption (SEC). The results revealed that moisture removal occurred primarily during the falling-rate period, governed by internal diffusion. The integration of porous materials enhanced drying performance, with DR improving by approximately 45-50% and SEC decreasing by 30-33%

compared to the case without porous materials. Statistical analyses using two-way ANOVA confirmed significant effects of air velocity ($p < 0.05$) and porous materials ($p < 0.01$), with porous materials identified as the dominant factor. Overall, the solar dryer incorporated with porous materials demonstrated faster drying, greater thermal stability, and improved energy efficiency.

KEYWORDS: Solar dryer, Porous materials, PVT, Thermal performance

1. Introduction

Solar energy represents an abundant, renewable, and environmentally sustainable energy source that is both inexhaustible and cost-free. Given the current global challenges associated with climate change, largely driven by the combustion of fossil fuels, as well as the escalating costs of conventional energy sources, the adoption of solar energy has become increasingly imperative [1-3]. The transition from fossil-fuel-based energy to renewable energy sources in production across both agricultural and industrial sectors plays a crucial role in mitigating global warming while simultaneously reducing production costs. Thailand and other ASEAN countries, situated near the equator, predominantly rely on agriculture, necessitating effective methods for preserving and processing agricultural products. A widely adopted preservation technique involves reducing the moisture content of agricultural commodities, a process that requires substantial heat. Among the available heat sources, solar energy presents a viable, low-cost alternative. Traditionally, farmers have relied on open-sun drying to reduce the moisture content of agricultural products. However, this method is susceptible to contamination from dust, insects, and other environmental pollutants. To address these concerns, many farmers have shifted towards using mechanical dryers, which offer greater control over drying conditions and product quality. Nevertheless, the high energy consumption associated with conventional drying systems significantly increases production costs. As a result, solar dryers have emerged as a more cost-effective and sustainable alternative. Despite their growing adoption, the efficiency of solar drying systems remains relatively low, and their performance is constrained by the intermittency of solar radiation, particularly during unfavorable weather conditions [4]. Over the years, numerous researchers have investigated various strategies to enhance the efficiency of solar dryers. For instance, Al-Jethelah et al [5] developed and analyzed the performance of an

innovative indirect free convection solar dryer. Their findings revealed that the thermal efficiency of the newly designed dryer exceeded that of conventional drying systems by 68%, 39%, 49%, and 85%, respectively, demonstrating significant improvements in drying performance. Manirathnam et al [6] conducted a study on enhancing the efficiency of solar dryers by integrating phase change materials (PCMs). The findings indicated that incorporating PCMs led to more stable temperatures in the drying chamber during periods of cloud cover. Additionally, the use of PCMs increased the overall efficiency of the solar dryer compared to conventional solar drying systems that do not use thermal energy storage. Udomkun et al [7] conducted a comprehensive qualitative study on the design variations of solar dryers and the key factors influencing their adoption across Asia and Africa. Their research assessed the economic, environmental, and social impacts of solar drying technologies, as well as the determinants affecting their widespread implementation. The findings indicated that while solar dryers offer a cost-effective solution, particularly for developing countries, their adoption is often hindered by the high initial investment required for implementation. Mohana et al [8] conducted a study on design and energy efficiency, highlighting existing gaps in developing cost-effective, energy-efficient solar dryers. Their research emphasized the economic and social benefits associated with solar drying technology. The findings indicated that while solar dryers present a sustainable alternative for agricultural and industrial applications, their widespread adoption remains constrained by certain limitations. Ismail et al [9] conducted a study on a double-pass solar air heater (DPSAH) incorporating lava rock as a porous medium. The integration of lava rock enhances the system's thermal storage capacity, making it a viable short-term thermal energy collector for solar drying applications. Additionally, the presence of lava rock increases convective heat transfer by expanding the heat transfer surface area and inducing turbulence in the airflow channel. A mathematical model based on energy balance equations was developed and numerically solved using MATLAB to evaluate the thermal performance of the collector under varying solar radiation intensities and wind speeds. Key design parameters considered in the study included collector size, air mass flow rate, and lava rock volume. The results demonstrated that the collector's optimal thermal efficiency ranged from 62% to 64% at solar intensities of 500 W/m² to 800 W/m², respectively, with an optimal air mass flow rate of 0.035 kg/s. Furthermore, an optimal porosity of approximately 89% was determined, balancing thermal efficiency and pressure drop. The collector was found to achieve an optimal output

temperature range of 41.7°C to 48.3°C, making it well-suited for agricultural and food drying applications. Moreover, compared with conventional DPSAH systems, integrating lava rock increased the average output temperature by more than 17.5%, highlighting its effectiveness in improving thermal performance. Sandali et al [10] conducted a qualitative study to enhance the efficiency of solar dryers by identifying key techniques and influencing factors that improve performance. Their analysis encompassed various efficiency parameters of solar drying systems (SDS), providing a comprehensive assessment of their operational effectiveness. The findings revealed that climatic conditions and solar radiation play a critical role in determining the efficiency of solar dryers. Furthermore, integrating solar panels for electricity generation, coupled with battery storage to provide heat during periods of insufficient sunlight, was identified as a viable strategy to enhance the overall efficiency and reliability of solar drying systems. Srivastava et al [11] conducted an experimental investigation of the thermal performance of a flat-plate solar collector and a solar dryer. Their study presented the performance characteristics of the solar collector and solar dryer integrated with a phase change material (PCM) storage system under quasi-steady-state conditions. The analysis was based on the system's fundamental energy balance, and a computational model was developed to predict various performance parameters of the solar drying system. To validate the thermal model, the study compared its predictions with theoretical calculations. Additionally, optimal values for both solar collector efficiency and dryer efficiency were determined using a genetic algorithm. A comparative assessment was conducted of the experimental, theoretical, and optimized efficiency values for the solar collector and dryer. Experimental trials were conducted over multiple days from June 2013 to March 2014, with specific observations recorded on March 24, 2014, to evaluate the system's empirical performance. The findings indicated strong agreement between the theoretical, experimental, and optimized efficiency values of the solar collector and dryer, reinforcing the reliability of the proposed model. Jadallah et al [12] conducted a comprehensive investigation into the performance of a dual-pass hybrid photovoltaic-thermal (PVT) solar cell system designed for drying applications. Their study encompassed both theoretical and experimental analyses, including the design, construction, and modeling of the system to simulate its output. The PVT heat collector extracts hot air that can be used as a heat source for drying processes. Key performance parameters, such as temperature distribution, useful heat, electrical power generation, and thermal efficiency, were evaluated

using MATLAB, specifically developed for this purpose. The findings indicate that the highest outlet fluid temperature achieved was 63 °C at a lower mass flow rate of 0.017 kg/s. Furthermore, at a higher mass flow rate of 0.031 kg/s, the system exhibited peak electrical, thermal, and overall efficiencies of 12.65%, 56.73%, and 85%, respectively. Additionally, the maximum electrical and thermal power outputs were recorded at 50.57 W and 389.37 W, respectively, at a mass flow rate of 0.031 kg/s. These results demonstrate the system's potential for efficient integration into drying applications, leveraging both electrical and thermal energy outputs. Singh et al [13] conducted a qualitative investigation into the advancement of solar dryer applications, with a particular emphasis on their utilization in both industrial and agricultural sectors. Their findings highlighted that solar dryers reduce fossil fuel consumption and hold significant potential to promote sustainability in these sectors. Similarly, Dadi et al [14] conducted a qualitative analysis of solar dryers, examining key design parameters and associated costs while emphasizing their advantages, including reduced post-harvest losses, enhanced product quality, and reduced environmental impact. The study concluded that, compared to conventional drying methods, solar dryers offer superior efficiency and product quality, making them a viable alternative for sustainable drying processes. Agrawal et al [15] conducted a comprehensive review of the research and development of solar dryers integrated with heat storage systems, focusing on the various heat storage materials used in these drying technologies. Their findings indicate that Phase Change Materials (PCMs) exhibit superior thermal energy storage efficiency, facilitating continuous drying operations. The incorporation of heat storage mechanisms significantly enhances the reliability of solar dryers, thereby expanding their applicability across diverse climatic conditions. Jha et al [16] conducted a comprehensive review of the design, applications, and simulation studies of hybrid solar drying technologies, with particular emphasis on systems integrating solar energy with supplementary energy sources. Their findings indicate that solar dryers integrated with heat pump systems exhibit superior efficiency and are particularly suitable for drying delicate agricultural products. Additionally, incorporating biomass as an auxiliary energy source in solar dryers offers a significant cost advantage, thereby enhancing the overall economic feasibility of the drying process. While solar dryers demonstrate adaptability and efficiency across diverse operational conditions, further advancements in system design and hygiene standards are needed to optimize their performance and broaden their applicability. Kamarulzaman et al [17] conducted a qualitative

study examining the technological advancements and design optimization of solar dryers. Their findings indicate that solar dryers exhibit high efficiency, low carbon dioxide emissions, and an economically favorable payback period of 0.5 to 4.6 years. Furthermore, solar drying technology is recognized for its cost-effectiveness, energy efficiency, and environmental sustainability. However, further advancements in design and optimization are necessary to enhance performance and reliability. Ramana et al [18] conducted a qualitative investigation to enhance the performance of solar dryers by optimizing the design of heat collectors and incorporating energy storage materials. Their findings demonstrated that a dual-purpose solar dryer, designed for both drying and heating applications and integrated with phase change materials (PCM), exhibited superior energy efficiency. Additionally, the study highlighted that implementing PCM not only reduced costs but also enhanced the overall investment value of the system. Luampon et al [19] investigated the use of stainless steel wire mesh as a porous material to enhance specific energy consumption (SEC) efficiency in a hot-air dryer. The experimental findings indicated that incorporating a hot-air recirculation duct resulted in a higher drying rate than in the system without recirculation. As the recirculation ratio increased, the drying rate improved, the drying time decreased, and the SEC was significantly reduced. These results highlight the potential of stainless steel wire mesh to enhance energy efficiency in a hot-air dryer. Kumar et al [20] conducted a comprehensive study on the influence of porous materials on the flow characteristics and temperature distribution within a passive solar air heater. The research examines the impact of flow resistance induced by a porous medium (representing agricultural products) at the outlet of a free-convection-based solar air heater. Both experimental and numerical approaches were employed to analyze these effects. The findings provide valuable insights into optimizing the design and efficiency of solar air heaters for agricultural drying applications.

Previous research has demonstrated that integrating porous materials into dryers can enhance their overall performance. Building upon these findings, this study aims to investigate the efficiency and effectiveness of solar dryers incorporating porous materials to optimize drying performance.

2. Methodology

2.1 Materials and method

In this study, a solar dryer was designed and functions as a passive system, incorporating a 150-Watt photovoltaic-thermal (PVT) panel with cooling fins on its back. The PVT panel is installed above the drying chamber, which is fabricated using steel sheets, insulated, and has inside dimensions of 0.9 m × 0.9 m × 1.2 m. The dryer is connected to a double-pass solar collector panel. The solar collector panel, measuring 0.75m wide, 1.75m long, and 0.25m high, features a 1.5 mm-thick steel absorber plate. To improve thermal performance, a porous material is made from perforated steel sheets with a 10 mm hole diameter and a 1.2 mm thickness, at 2 PPI, and cut and shaped into hollow rectangular boxes measuring 90 mm × 100 mm each. Porous materials are arranged along the length of the solar collector. These boxes span the width of the solar collector panel and are placed directly above the absorber plate. Porous material was fabricated using steel mesh, which was inserted into hollow rectangular enclosures to facilitate porosity measurements. In this study, the investigated porosity value was determined to be 0.97. A centrifugal fan transports the heated air from the solar collector panel to the drying chamber through a lower sidewall. Schematic diagrams, a photograph of the solar dryer, porous material, and measurement points utilized during the experiments are shown in Figures 1, 2, 3, and 4, respectively.

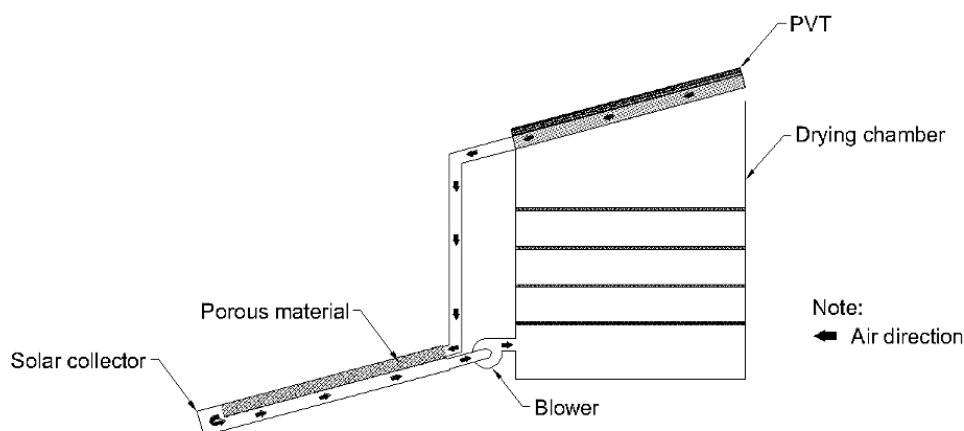


Figure 1 Schematic diagram of the photovoltaic-thermal solar dryer integrated with high-porosity porous material.



Figure 2 Photograph of the experimental photovoltaic-thermal solar dryer system.



Figure 3 High-porosity porous material configuration: assembled hollow rectangular modules (90mm × 100mm × 100mm) fabricated from perforated steel sheets.

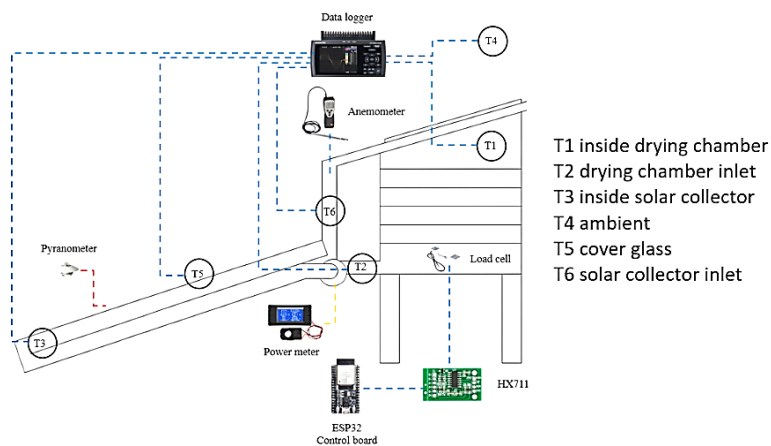


Figure 4 Instrumentation and measurement point locations for the experimental solar dryer system.

The experimental investigation of the solar dryer was conducted in Thailand under tropical climatic conditions during June and July 2025, between 9:00 a.m. and 4:00 p.m. Kaffir lime leaves were used as the drying sample, with each trial commencing with an initial mass of 200 g. The moisture content of the samples was evaluated in compliance with the AOAC (2019) standard. The velocity of hot air within the solar 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 readings were obtained using K-type thermocouples connected to a data logger with an accuracy of ± 1 °C. Additionally, the mass of the dried samples was monitored using a load cell capable of measuring weights from 1 to 20 kg, and a digital scale with a maximum capacity of 500 g and a resolution of 0.1 g. Porosity ($\mathcal{E}$) of porous material is then calculated using Eq. (1).

$$\mathcal{E} = \frac{V_p}{V_t} = 1 - \frac{(m_s / \rho_s)}{V_t} \quad (1)$$

When V_p = volume of pores (m^3)

m_s = mass of solid (kg)

ρ_s = density of solid (kg/m^3)

V_t = total volume of material (m^3)

2.2 Analysis

The moisture ratio is an estimate of the moisture content, assuming the equilibrium moisture content is negligible. It is calculated by comparing the moisture content at a given time to the initial moisture content, as shown in Equation (2).

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

When MR = Moisture ratio

M_{in} = Initial moisture content

M_t = Moisture content each time interval

Moisture content refers to the proportion of moisture contained in the product relative to its dry weight. The dry weight of the sample was determined by drying a portion of the product in a hot-air oven at 103 °C for 72 hours, following the AOAC (2019) standard [21]. These recorded values were then used to determine the moisture content at each time interval, as outlined in Equation (3).

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

When MC = Dry basis moisture content at each time interval (d.b.)

w = Wet weight of product at each time interval (g)

d = Dry weight of product (g)

The drying rate quantifies the amount of moisture removed over a specific period and is defined in Equation (4).

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

When DR = Drying rate (g/h)

Δw = Mass of evaporated water (g)

Δt = Time interval (h)

Specific energy consumption is the energy required to remove a specific quantity of moisture from the material and is calculated using Equation (5).

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

When SEC = Specific energy consumption (MJ/kg)

w_i = Wet weight before drying (kg)

w_f = Wet weight after drying (kg)

3 Results

An experimental analysis was performed without incorporating porous materials at air velocities of 0.07, 0.09, and 0.10 m/s from 9:00 a.m. to 4:00 p.m. The study provided crucial insights into solar radiation levels and temperature distributions across the dryer's components. Solar radiation values ranged from 371 to 1,001 W/m², with an average of 766.1 W/m². The temperature in the drying chamber ranged from 36 °C to 45 °C, with a mean of 41.1 °C. The inlet temperature to the drying chamber fluctuated between 36 °C and 46 °C, with an average of 41.5 °C. The absorber plate temperature ranged from 49 °C to 66 °C, with an average of 56.6 °C. Ambient temperatures ranged from 29 °C to 35 °C, with a mean of 32.4 °C. Additionally, the solar collector inlet temperature varied from 32 °C to 36 °C, with an average of 34.2 °C. These findings are illustrated in Figures 5-7.

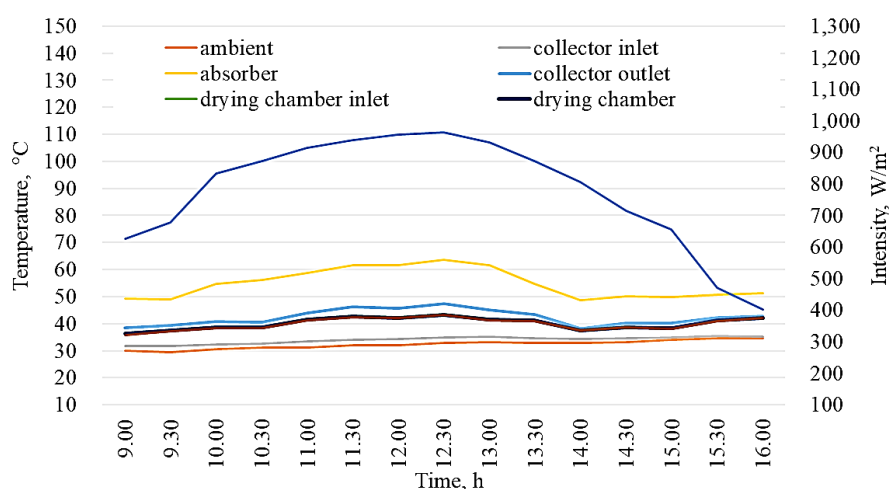


Figure 5 Diurnal temperature profiles and solar radiation intensity for solar dryer without T porous material at air velocities of 0.07 m/s.

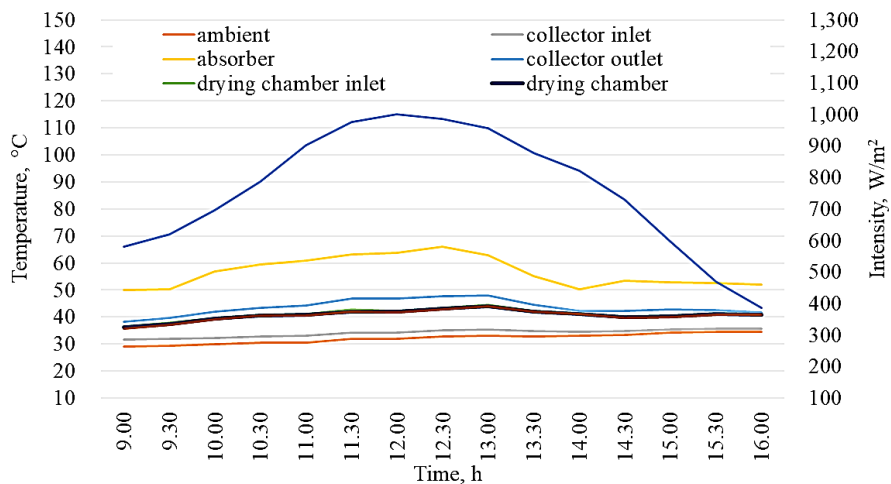


Figure 6 Diurnal temperature profiles and solar radiation intensity for solar dryer without porous material at air velocities of 0.09 m/s.

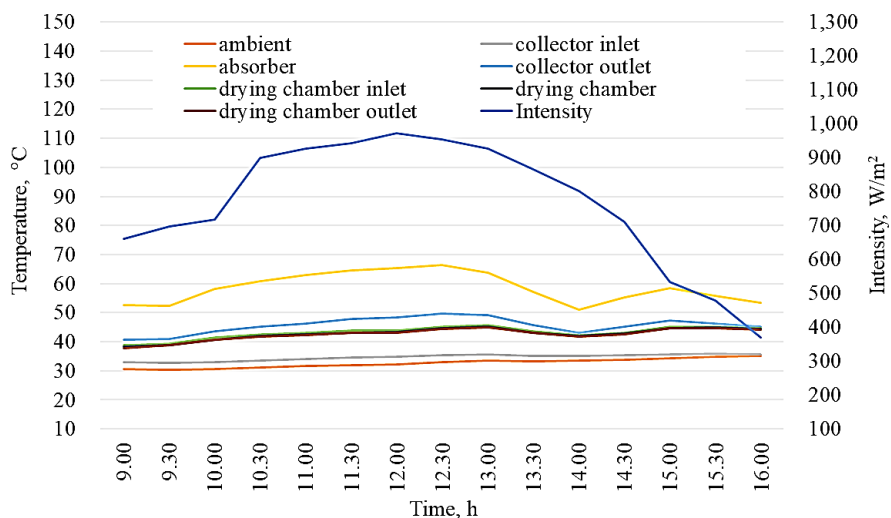


Figure 7 Diurnal temperature profiles and solar radiation intensity for solar dryer without porous material at air velocities of 0.10 m/s.

The experimental assessment of the solar dryer, incorporating porous materials with a porosity of 0.97, reveals significant improvements in thermal performance. Solar radiation levels ranged from 411 to 1,022 W/m², with an average of 778.9 W/m². The drying chamber temperature ranged from 37 °C to 50 °C, with a mean of 44.1 °C. Drying chamber inlet

temperature ranged from 38 °C to 51 °C, averaging 44.5 °C. The absorber plate temperature fluctuated between 50 °C and 68 °C, with an average value of 58.5 °C. Ambient temperatures ranged from 31 °C to 33 °C, with a mean of 31.9 °C. Solar collector inlet temperature ranged from 32 °C to 35 °C, with an average of 33.5 °C. These results indicate that integrating porous materials into the absorber plate enabled sustained higher air temperatures than without porous materials. The improvement in thermal stability is illustrated in Figures 8-10.

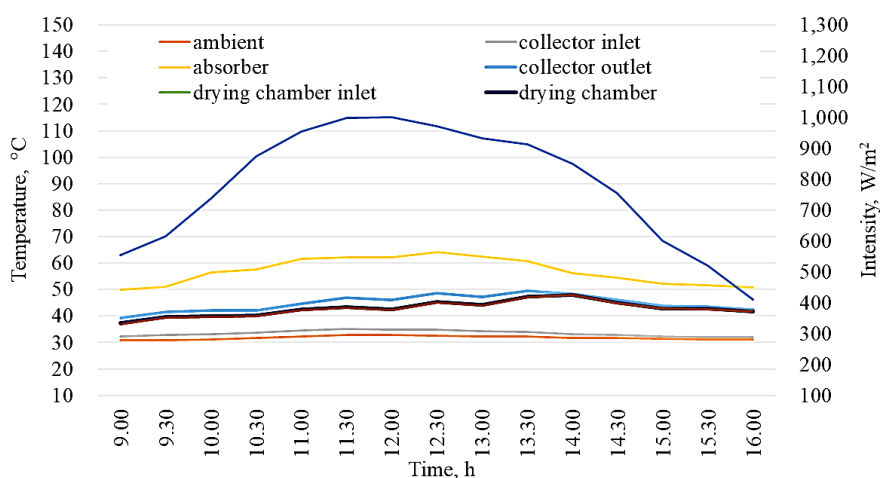


Figure 8 Diurnal temperature profiles and solar radiation intensity for solar dryer with porous material at air velocities of 0.07 m/s.

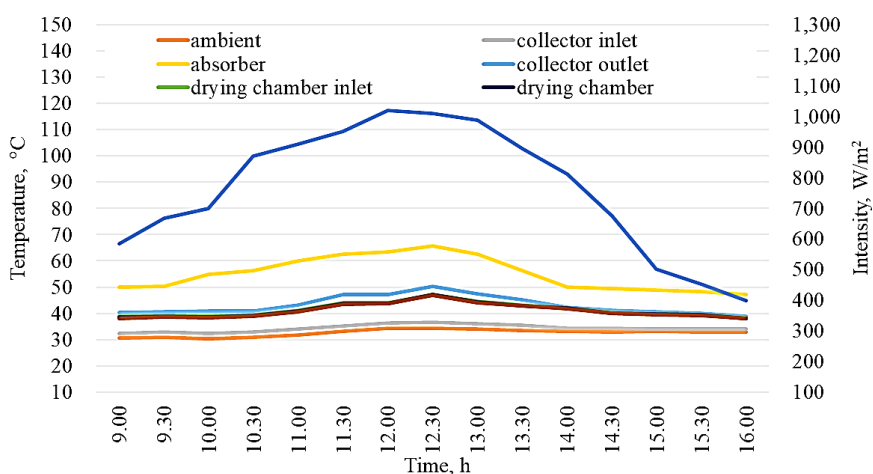


Figure 9 Diurnal temperature profiles and solar radiation intensity for solar dryer with porous material at air velocities of 0.09 m/s.

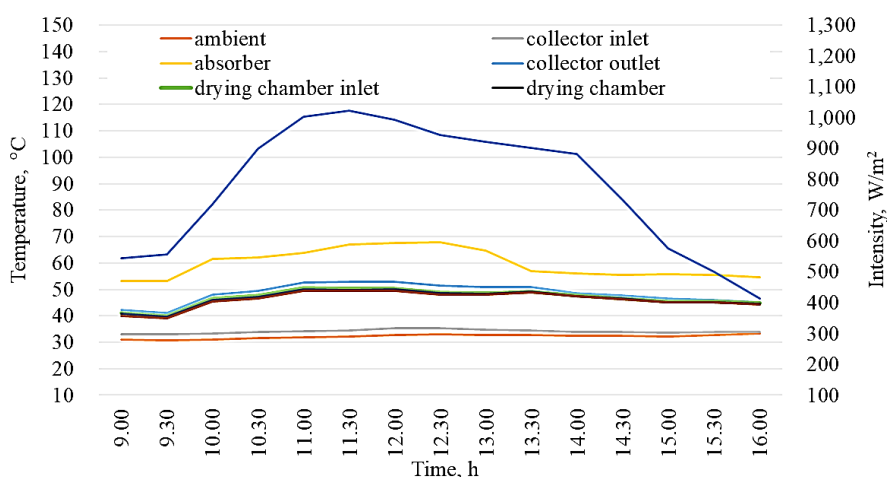


Figure 10 Diurnal temperature profiles and solar radiation intensity for solar dryer with porous material at air velocities of 0.10 m/s.

Figure 11 presents 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 under two conditions: with and without porous materials. In all cases, MR decreased continuously over the 420 min drying period, indicating that moisture removal predominantly occurred during the falling-rate period, governed by internal diffusion. The incorporation of porous material accelerated moisture reduction across all velocities. MR decreased continuously under all test conditions. The system with porous materials consistently produced lower MR values, achieving 12–25% improvement over the non-porous configuration. Increasing air velocity reduced MR, although porous material reduced sensitivity to velocity by stabilizing heat distribution. Air velocity also contributed significantly to drying kinetics. Increasing the velocity from 0.07 to 0.10 m/s reduced MR by 10–12% without porous materials, whereas with porous materials, the reduction was 8–9%. This suggests that while velocity enhances external convection, porous structures reduce the sensitivity of air velocity by stabilizing thermal conditions and improving heat distribution. This demonstrates that integrating porous materials with higher air velocities significantly enhances moisture-removal efficiency, thereby improving drying performance [22].

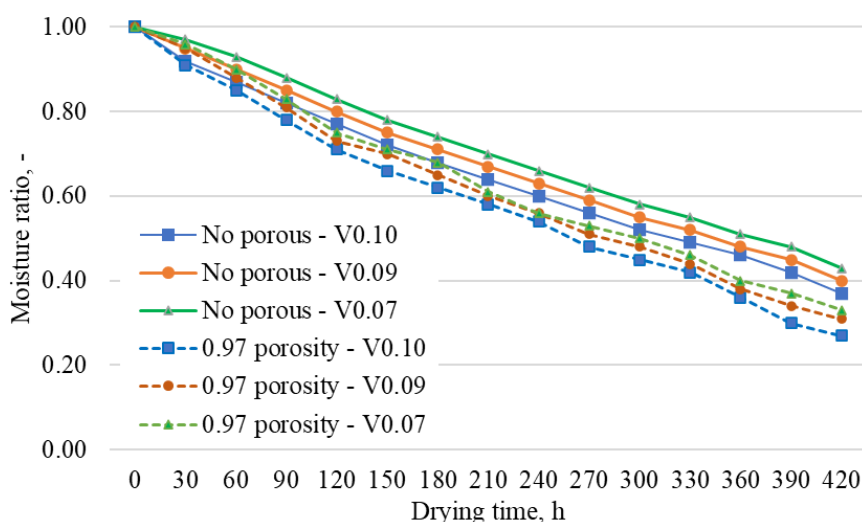


Figure 11 Moisture ratio (MR) versus drying time for kaffir lime leaves at three air velocities with and without porous material integration.

Figure 12 illustrates the effect of air velocity and incorporates 0.97 porosity porous materials on the drying rate of kaffir lime leaves. In the porous configuration, drying rates increased gradually with air velocity, from 6.86 g/h at 0.07 m/s to 7.71 g/h at 0.10 m/s, representing a 12% increase. In contrast, the inclusion of porous materials substantially enhanced performance, yielding drying rates of 10.28, 10.71, and 11.14 g/h at the respective velocities. At 0.07–0.10 m/s, drying rates without porous material ranged from 6.86–7.71 g/h. With porous material, rates increased to 10.28–11.14 g/h—an enhancement of 44.5–49.9%. These findings confirm that porous media intensify turbulence and increase heat-transfer surfaces, resulting in faster moisture removal. These results indicate that porous material accelerated drying by nearly 50%, with greater benefits at lower velocities, consistent with theoretical drying relationships and previous research [23]. The error bars in Figure 12, representing standard deviations, highlight the reliability of the experimental data. Overall, the integration of porous materials enhanced turbulence, increased heat transfer surface area, and stabilized thermal conditions, resulting in faster moisture removal.

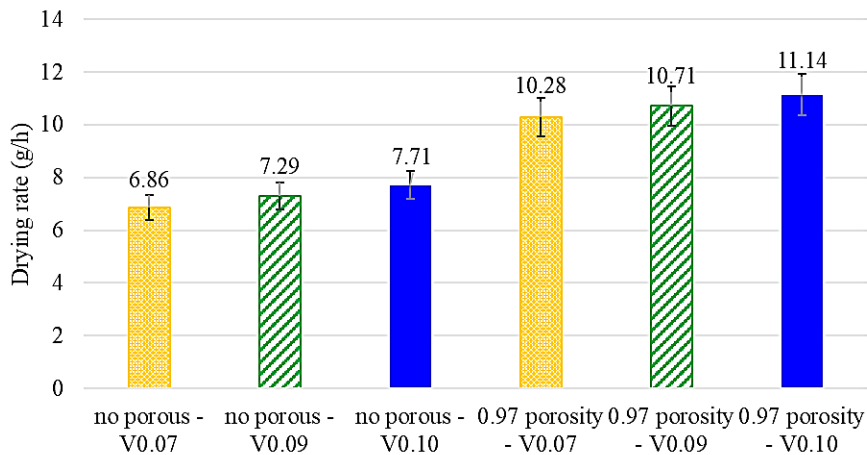


Figure 12 Effect of air velocity and porous material integration on average drying rate of kaffir lime leaves.

Figure 13 presents the variation of specific energy consumption (SEC) under different airflow velocities (0.07, 0.09, and 0.10 m/s) for solar air heater configurations with and without porous material. Without porous materials, the SEC decreased with increasing air velocity. Without porous media, SEC values ranged from 34.13 to 30.33 MJ/kg. With porous media, SEC drastically improved, ranging from 22.75 to 21.00 MJ/kg, representing a 30–33% reduction. This study demonstrated that integrating porous materials (porosity 0.97) into a passive solar dryer significantly improves drying performance and energy efficiency when drying kaffir lime leaves. Drying rate improved by 45–50%, while specific energy consumption decreased by 30–33%. Porous materials increased turbulence, enhanced thermal distribution, and reduced sensitivity to airflow variations. Statistical analysis confirmed porous media as the dominant factor influencing drying performance. The porous-integrated solar dryer offers an effective, sustainable solution suitable for agricultural applications in tropical climates. Additionally, this configuration enhanced the drying rate, which aligns with established drying kinetics [24]. Consequently, this approach effectively reduced the specific energy consumption of the drying process, indicating improved energy efficiency under these conditions. The error bars in Figure 13 (standard deviations) further validate the reliability of the experimental results.

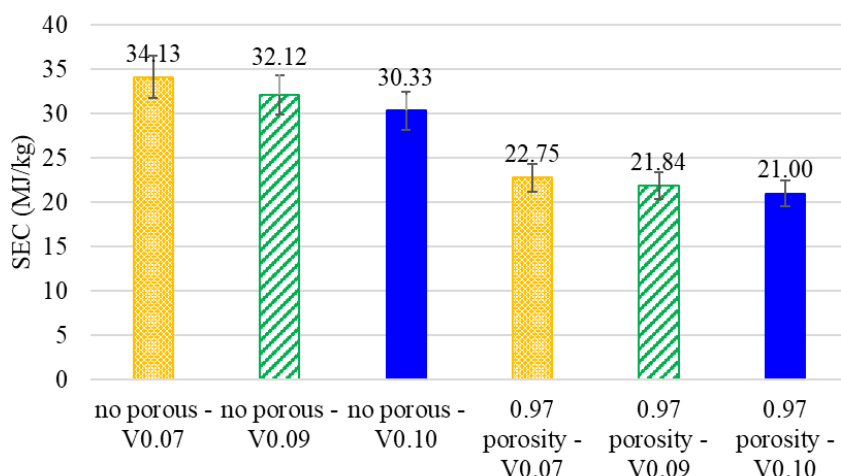


Figure 13 Specific energy consumption (SEC) for solar drying of kaffir lime leaves with and without porous material integration.

4 Conclusions

This study experimentally evaluated the performance of a solar dryer integrated with porous materials for drying kaffir lime leaves under tropical conditions. The findings clearly demonstrated that incorporating 0.97 porosity porous materials and a velocity of 0.07–0.10 m/s significantly enhanced the thermal and drying performance of the dryer compared with the configuration without porous materials. The results revealed that moisture removal predominantly occurred during the falling-rate period, governed by internal diffusion. The integration of porous materials accelerated drying kinetics, yielding approximately from 6.86–7.71 to 10.28–11.14 g/h (45–50%) improvements in drying rate across air velocities of 0.07–0.10 m/s. Similarly, the specific energy consumption (SEC) decreased from 30.3–34.1 to 21.0–22.8 MJ/kg, competitive with literature, 58–65% vs conventional, confirming the dryer's enhanced energy efficiency. The improved performance can be attributed to increased turbulence, enhanced heat transfer surface area, and stabilized thermal conditions within the solar collector, which collectively promoted faster moisture diffusion and more efficient utilization of solar energy. Moreover, integrating porous materials reduced the dryer's sensitivity to air velocity, indicating that drying performance was primarily controlled by internal mass transfer rather than external convection. In summary, the study highlights the solar-porous dryer as an energy-efficient, sustainable, and practical technology for agricultural drying applications. By

reducing drying time, improving energy efficiency, and enhancing product quality, the dryer offers a promising solution for advancing renewable energy integration in post-harvest processing, particularly in regions reliant on solar-based agricultural practices.

Acknowledgement

This research was supported by the Department of Mechanical Engineering, Faculty of Engineering, Ubon Ratchathani University.

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Article History:

Received: October 24, 2025

Revised: April 10, 2026

Accepted: April 11, 2026