

Development of Photovoltaic–Thermal Porous Solar Dryer

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Abstract

Drying is a key post-harvest process for preserving agricultural and herbal products. However, under humid tropical conditions, drying remains energy-intensive and limited in performance. This study presents the development and performance evaluation of a photovoltaic–thermal (PVT) solar dryer integrated with porous absorbers to enhance heat and mass transfer. The system consists of a 150 W PVT panel and a solar air collector equipped with porous steel mesh absorbers with porosities of 0.98 and 0.96, together with a non-porous reference configuration. Drying experiments were conducted in Thailand under tropical conditions at an air velocity of 0.1 m/s using kaffir lime leaves. The results show that porous integration increases the effective heat transfer area and thermal energy retention, resulting in a drying rate increase of up to 50% and a reduction in specific energy consumption (SEC) of up to 33.3% compared with the non-porous system. The configuration with a porosity of 0.96 provided the best overall performance. Overall, integrating porous materials into a PVT solar dryer significantly improves drying performance and energy efficiency.

Keywords: Solar Drying, Photovoltaic-Thermal (PVT), Porous Material, Kaffir Lime

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1. Introduction

The escalating global energy and environmental challenges have intensified the demand for sustainable technologies capable of reducing dependence on fossil fuels while maintaining process efficiency. Among renewable energy sources, solar energy is regarded as one of the most promising options due to its high potential, environmental benignity, and suitability for practical applications [1–3]. In particular, Thailand receives high levels of solar irradiation throughout the year, making solar thermal technologies especially attractive for agricultural processing and food preservation applications. Drying is a critical post-harvest operation that accounts for a substantial share of energy consumption in agricultural processing chains. Conventional open sun drying, although widely practiced, suffers from several limitations, including long drying times, contamination risks, and non-uniform product quality. Dryers provide better process control and hygiene; however, their high energy consumption and operating costs often restrict adoption, especially among small-scale farmers and rural communities. Consequently, numerous previous studies [4–6] have investigated solar-assisted drying systems as a sustainable alternative, as they are capable of reducing energy consumption without compromising product quality. In recent years, efforts to enhance the performance of solar dryers have focused on design optimization for forced convection and the integration of thermal energy storage

systems. Both sensible and latent heat storage materials, particularly phase change materials (PCMs), have been demonstrated to effectively improve drying continuity and system stability under fluctuating climatic conditions [7–9].

Recently, photovoltaic–thermal (PVT) systems have attracted increasing attention due to their capability to simultaneously generate electrical power and recover useful thermal energy from photovoltaic panels, thereby enhancing overall solar energy utilization. Previous studies [10–12] have confirmed that PVT-based solar dryers are able to supply electrical power to auxiliary components while concurrently providing thermal energy for the drying process, resulting in superior performance compared with conventional solar drying systems.

At the same time, the application of porous media in solar air collectors has emerged as an effective approach to enhance heat transfer by increasing the heat transfer surface area, intensifying convective heat exchange, and improving thermal energy retention. Previous studies [13–15] have reported that porous absorbers can enhance temperature uniformity and drying performance. However, excessively low porosity may lead to increased pressure drop across the airflow path, thereby deteriorating overall system performance. Despite these advances, the integration of photovoltaic–thermal (PVT) systems and performance enhancement through porous media has largely been investigated in a fragmented manner.

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To date, limited research has examined the combined effects of PVT systems and porous absorber characteristics within a single solar drying system, particularly under humid tropical climatic conditions, where ambient humidity strongly influences drying behavior and energy efficiency. Moreover, the influence of porous material porosity on the performance of integrated PVT-based drying systems remains insufficiently understood.

Therefore, this study aims to develop and experimentally evaluate a photovoltaic–thermal porous solar dryer that integrates waste heat recovery from photovoltaic panels with a porous absorber–enhanced solar air collector. Kaffir lime leaves were used as the drying material, and experiments were conducted under real tropical climatic conditions in Thailand to investigate temperature variation, drying rate, and specific energy consumption at different porosity levels.

2. Design Parameters

The theoretical design of the solar drying system is based on several simplifying assumptions. The temperatures of the absorber plate and the drying air are assumed to vary only along the flow direction. The glass cover and the frame of the solar collector are considered to absorb a negligible amount of solar radiation, while the remaining collector components are assumed to be adequately insulated to minimize heat losses. The solar collector consists of an absorber plate with a

selective coating, a transparent glass cover, and thermal insulation. The absorber plate is designed to satisfy the required operating temperature and airflow rate. The glass cover reduces convective and radiative heat losses, whereas the thermal insulation limits heat losses from the bottom and side surfaces of the collector, thereby enhancing overall collector efficiency. The solar radiation–receiving area is designed to match the airflow rate within the drying chamber and is calculated using Eq. (1).

$$A_c = \frac{mC_p(T_o - T_i)}{\eta} \quad (1)$$

The air mass flow rate is defined as:

$$m = \rho AV \quad (2)$$

where A_c is the solar radiation–receiving area of the solar collector (m^2), m denotes the air mass flow rate (kg/s), C_p is the specific heat capacity of air ($\text{kJ/kg}\cdot\text{K}$), T_o and T_i represent the outlet and inlet air temperatures of the solar collector ($^{\circ}\text{C}$), I is the solar irradiation (W/m^2), η denotes the solar collector efficiency, ρ is the air density (kg/m^3), A is the cross-sectional area of the drying chamber (m^2), and V is the air velocity inside the drying chamber (m/s).

The required electrical power of the photovoltaic panel is estimated using Eq. (3):

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$$P_{PV} = \frac{E_{use}}{T} \quad (3)$$

where P_{pv} is the required photovoltaic power (W), E_{use} is the required electrical energy (kWh), and T is peak sun hour of Thailand (h).

3. System Design and Construction

The solar collector was designed based on an air mass flow rate of 0.145 kg/s, corresponding to a maximum air velocity of 0.2 m/s. Previous studies [16-17] have reported that the recommended air velocity for solar drying applications lies in the range of 0.1–0.2 m/s. The design assumptions further included an average solar irradiation of 800 W/m², a 5 °C temperature rise across the solar collector, and an assumed solar collector efficiency of 0.7, which falls within the commonly reported range of 70–80% [18–19]. Using Eq. (1), the minimum required solar radiation–receiving area was calculated to be 1.303 m². Accordingly, the collector dimensions were selected as 0.75 × 1.85 m, providing an effective absorption area of 1.387 m², which exceeds the design requirement.

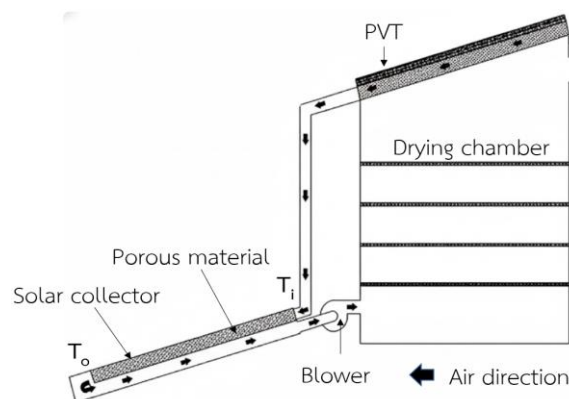


Figure 1. Schematic diagram of solar dryer



Figure 2. Photograph of solar dryer

The electrical subsystem was designed to meet a total energy demand of 0.5 kWh under a peak sun hour of 5 h. The required photovoltaic capacity to supply the fan load was estimated at 100 Wp; however, a 150 Wp photovoltaic panel was selected to enhance operational reliability and accommodate power fluctuations. Battery sizing was based on a nominal voltage of 12 V, a usable capacity of 60%, and an inverter efficiency of 80%, resulting in a minimum battery

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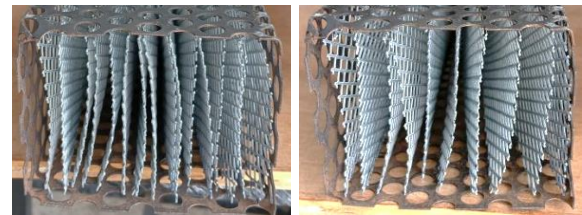
requirement of 12 V, 86.8 Ah. To comply with commercial specifications and ensure continuous operation, a 12 V, 100 Ah battery was adopted together with a 12 V, 15 A solar charge controller.

The PVT-porous drying system consists of a drying chamber equipped with a fan and a solar air-heating unit comprising a solar collector coupled with a photovoltaic-thermal (PVT) module. The overall system configuration and the fabricated prototype are illustrated in Figures 1 and 2.

4. Experimental Setup

The photovoltaic-thermal porous solar dryer (PVT-porous solar dryer) developed in this study operates as an active system and integrates a 150 W photovoltaic-thermal (PVT) panel. The PVT panel is mounted on the top of a cubic drying chamber fabricated from insulated steel sheets with dimensions of 1 m × 1 m × 1 m. An air duct connects the PVT unit to a dual-pass solar air collector with dimensions of 0.75 m × 1.85 m × 0.25 m. The solar air collector contains a 1.5 mm thick steel absorber plate, above which porous absorber materials are installed to enhance heat retention and heat transfer. The porous structures are fabricated from perforated steel sheets with a hole diameter of 10 mm and a thickness of 1.2 mm (2 PPI). The perforated metal sheets were assembled into hollow rectangular modules with dimensions of 100 × 90 mm and arranged across the width of the solar collector. Steel meshes were inserted

inside the hollow structures. Previous studies [15,20] have reported that this type of porous material exhibits high heat transfer effectiveness, with typical porosity values in the range of 0.96–0.98. Accordingly, two porosity levels, $\varepsilon = 0.96$ and $\varepsilon = 0.98$, were investigated in the present study. Heated air from the solar collector was supplied to the drying chamber through an air duct installed at the lower sidewall, driven by a fan. The system configuration and the arrangement of the porous absorber materials used in the experiments are illustrated in Figure 3.



(a) $\varepsilon = 0.96$

(b) $\varepsilon = 0.98$

Figure 3. Porous absorber material

The porosity of the porous material was calculated using Eq. (4):

$$\varepsilon = \frac{V_p}{V_t} \quad (4)$$

where V_p is the pore volume (m^3) and V_t is the total volume of the porous structure (m^3).

Experimental drying tests were conducted in Thailand under tropical climatic conditions

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during June and July 2025, between 9:00 a.m. and 4:00 p.m. Kaffir lime leaves were used as the drying material, with an initial sample mass of 200 g for each experiment. Moisture content was determined according to the standard AOAC (2019) method [21]. The hot air velocity inside the drying system was measured using a hot-wire anemometer. Air temperature was monitored using K-type thermocouples connected to a data logger, while the sample mass was measured using a load cell and a digital balance.

5. Data Analysis

The moisture ratio (MR) was evaluated by assuming negligible equilibrium moisture content and was defined as the ratio of the moisture content at any given time to the initial moisture content, as expressed in Eq. (5):

$$MR = \frac{M_t}{M_{in}} \quad (5)$$

where MR is the moisture ratio (–), M_{in} is the initial moisture content on a dry basis (d.b.), and M_t is the moisture content at time t (d.b.).

The moisture content at each time interval was then calculated using Eq. (6):

$$MC = \frac{w - d}{d} \quad (6)$$

where MC is the moisture content (d.b.), w is the wet mass at a given time (g), and d is the dry mass of the product (g).

The drying rate (DR), representing the mass of moisture removed per unit time, was determined using Eq. (7):

$$DR = \frac{\Delta w}{\Delta t} \quad (7)$$

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

The specific energy consumption (SEC), defined as the energy required to remove a unit mass of moisture, was calculated using Eq. (8):

$$SEC = \frac{3.6E}{w_i - w_f} \quad (8)$$

where SEC is the specific energy consumption (MJ/kg), w_i and w_f are the wet masses before and after drying, respectively (kg), and E is the total energy input (kWh).

Measurement uncertainties were evaluated for key parameters, including air temperature, air velocity, solar irradiance, and mass. The uncertainties associated with the K-type thermocouples, hot-wire anemometer, solar radiation meter, and weighing devices were $\pm 1.0^\circ\text{C}$, $\pm 5\%$, $\pm 5\%$, and $\pm 0.1\text{g}$, respectively.

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The individual uncertainties are summarized in Table 1.

Table 1: Individual uncertainties of measured parameters

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

The combined uncertainty was estimated using the root-sum-of-squares (RSS) method, as expressed in Eq. (9):

$$U_{total} = \sqrt{U_T^2 + U_V^2 + U_{SR}^2 + U_M^2} \quad (9)$$

where U_{total} is the combined uncertainty, and U_T , U_V , U_{SR} , and U_M represent the relative uncertainties of temperature, velocity, solar radiation, and mass, respectively.

The uncertainty associated with calculated parameters, including the drying rate and specific energy consumption, was evaluated using standard error propagation procedures based on the guide to the expression of uncertainty in measurement.

The combined uncertainty of the drying rate was determined to be $\pm 7\%$.

6. Results and Discussions

6.1 Temperature profile in the solar dryer

Experiments were conducted at an air velocity of 0.10 m/s between 9:00 a.m. and 4:00 p.m. to examine temperature distribution under different porous configurations.

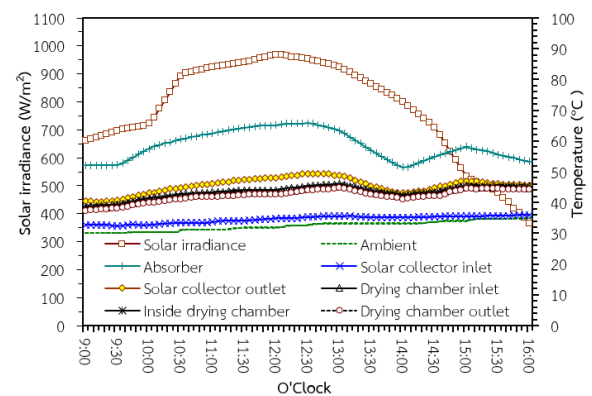


Figure 4. Temperature profile in the solar dryer without porous material

Figure 4 shows the temperature profile of the non-porous system. During the tests, solar irradiance ranged from 371 to 972 W/m², with an average of 764 W/m². The drying chamber temperature varied between 38 °C and 45 °C (average 42.7 °C), while the inlet air temperature ranged from 39 to 46°C (average 43.2 °C). Ambient temperature remained stable at 30–35 °C (average 32.6 °C). The absorber temperature was higher, ranging

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from 51 to 66 °C with a mean of 58.5 °C, whereas the solar collector inlet temperature varied slightly between 33 °C and 36 °C (average 34.6 °C).

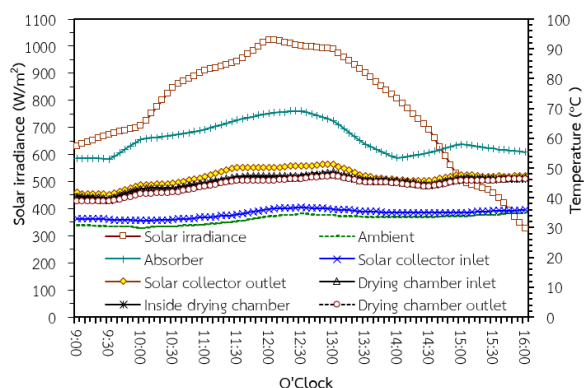


Figure 5. Temperature profile in the solar dryer with porous material ($\epsilon = 0.98$)

Figure 5 shows the temperature profiles for the porous configuration with a porosity of 0.98 at the same air velocity. Solar irradiance ranged from 332 to 1,028 W/m², with an average equal to the non-porous case (764 W/m²). The drying chamber temperature increased to 39–48 °C, with an average of 44.6 °C, while the inlet air temperature ranged from 40 °C to 48 °C (average 45.0 °C). Ambient temperature remained similar to the baseline, averaging 33.0 °C. The absorber temperature rose to 53–69 °C, with a mean of 60.0 °C, whereas the solar collector inlet temperature showed only a slight increase to 33–37 °C (average 34.9 °C).

Figure 6 presents the temperature distribution for the porous configuration with

a porosity of 0.96. Solar irradiance ranged from 389 to 1,005 W/m², with an average of 770 W/m². This configuration produced the highest drying chamber temperature, ranging from 40 to 55 °C (average 47.6 °C). The inlet air temperature increased to 41–55 °C, with a mean of 48.0 °C. Ambient temperature remained stable at 31–33 °C (average 32.2 °C). The absorber temperature reached 53–68 °C, yielding the highest average value of 60.8 °C among all cases, while the solar collector inlet temperature remained nearly constant at 33–35 °C (average 34.0 °C).

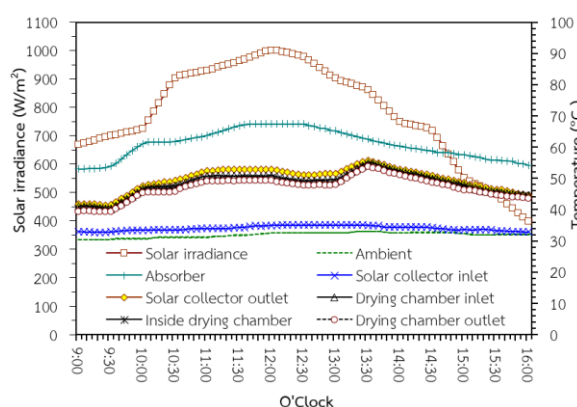


Figure 6. Temperature profile in the solar dryer with porous material ($\epsilon = 0.96$)

In summary, the experimental results demonstrate that the incorporation of porous materials significantly enhances heat retention and increases the air temperature within the drying chamber. This improvement is attributed to the increased heat transfer surface area provided by the porous structure, as well as its ability to store thermal energy.

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This thermal behavior directly leads to improved drying performance, as discussed in the following sections.

6.2 Effect of Porous Materials on Solar Dryer Performance

6.2.1 Effect of Porous Materials on Drying Time

Figure 7 shows the moisture ratio (MR) as a function of drying time at a fixed air velocity of 0.10 m/s for three configurations: non-porous, 0.96 porosity, and 0.98 porosity. In all cases, MR decreased continuously up to 420 min, indicating a dominant falling-rate drying regime controlled by internal moisture diffusion.

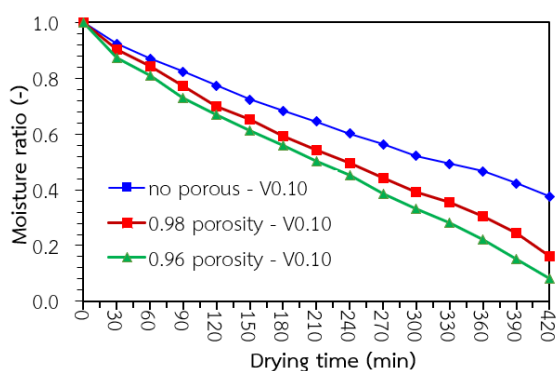


Figure 7. Moisture ratio versus drying time for different porous configurations

The incorporation of porous materials significantly accelerated drying. The 0.96 porosity configuration achieved the lowest final MR (0.13), compared with 0.19 for 0.98 porosity and 0.42 for the non-porous case. This improvement is attributed to the

increased heat exchange surface area, which leads to higher air temperatures within the drying chamber and promotes internal moisture vapor diffusion. As a result, the average drying rate increased by approximately 50%, from 7.71 g/h for the non-porous configuration to 11.57 g/h for the porous configuration with a porosity of 0.96. These results confirm that porous materials, particularly at lower porosity levels, significantly enhance drying efficiency while reducing drying time and energy demand. These findings are consistent with previous studies [22–24], highlighting the critical role of enhanced transport mechanisms in accelerating moisture removal.

6.2.2. Effect of Porous Materials on Drying Rate

Figure 8 shows the drying rates of kaffir lime leaves at an air velocity of 0.10 m/s for three configurations: the non-porous system and porous systems with porosities of 0.98 and 0.96. The configuration with a porosity of 0.96 achieved a higher drying rate than that with a porosity of 0.98.

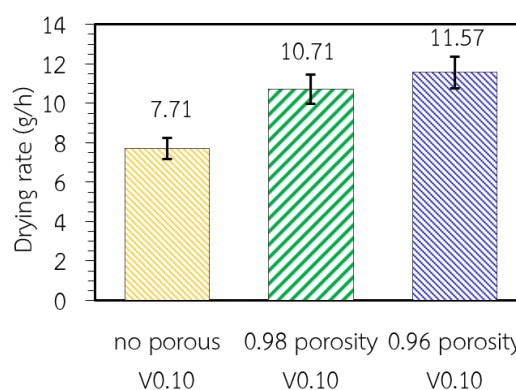


Figure 8. Drying rate under different porous material configurations.

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These results indicate that maximum porosity does not necessarily yield the best drying performance, as the structure with a porosity of 0.98 contains an excessive void fraction, which reduces the effective surface area available for heat exchange. These findings are consistent with previous studies [22–23, 25], which reported that porous material structures can significantly enhance drying performance.

6.2.3. Effect of Porous Materials on Specific Energy Consumption

Figure 9 shows the specific energy consumption (SEC) at an air velocity of 0.10 m/s for three configurations: the non-porous system and porous systems with porosities of 0.98 and 0.96. The incorporation of porous materials clearly reduced SEC.

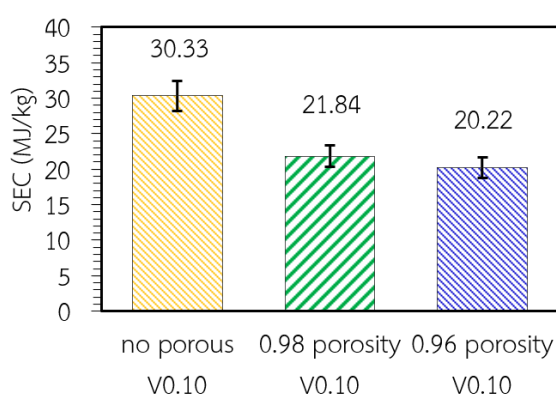


Figure 9. Specific energy consumption for different porous configurations

The non-porous configuration exhibited the highest SEC of 30.33 MJ/kg, while SEC decreased to 21.84 MJ/kg and 20.22 MJ/kg for

porosities of 0.98 and 0.96, corresponding to reductions of 28.0% and 33.3%, respectively.

The lowest SEC obtained at a porosity of 0.96 indicates that, although this configuration requires higher fan power due to increased pressure drop compared with the 0.98 porosity case, it enables greater moisture evaporation for the same drying duration. Consequently, the porosity of 0.96 resulted in the minimum SEC. These findings are consistent with previous studies [26–27] and highlight the importance of optimizing porous structure characteristics for the development of energy-efficient and sustainable solar drying systems.

7. Conclusions

This study successfully developed and experimentally evaluated a PVT solar dryer integrated with porous absorbers under tropical climatic conditions. The results indicate that porous integration significantly improved drying performance and energy efficiency. Compared with the non-porous configuration, the average drying rate increased by approximately 50%. A porosity of 0.96 provided the best overall performance. In addition, specific energy consumption was reduced by up to 33.3%. These findings confirm that the PVT–porous solar dryer is an effective and energy-efficient solution for agricultural drying in humid tropical environments.

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