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Analysis of Hybrid Photovoltaic Thermal (PV/T) Integrated Solar Dryer: An Experimental Validation

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Abstract

In this study, a hybrid photovoltaic thermal (PV/T) integrated solar dryer has been designed, developed, and experimentally analyzed to evaluate its performance in real-world climatic conditions. The system incorporates a UV-stabilized sheet mixed-mode tent house structure, installed on the rooftop of a building located in Bhilai, Chhattisgarh, India. The dryer is equipped with a thermal collector directly connected to the drying chamber to enhance heat transfer efficiency. Experiments were conducted in the month of November using 5 kg of methi (fenugreek leaves) as the test crop. The drying chamber included two perforated trays for uniform drying. Key atmospheric parameters such as ambient temperature, relative humidity, wind speed, and solar irradiance were continuously monitored. The PV/T system not only supplied the necessary thermal energy for drying but also generated electrical power for auxiliary components if required. Two perforated trays were installed in the drying chamber to ensure even airflow and steady drying of the product layers. Throughout the studies, important operational and environmental factors, including solar irradiance, wind speed, relative humidity, and ambient temperature, were continuously tracked to evaluate system performance. The PV/T module produced electrical power that could be used for auxiliary parts like fans or monitoring equipment, in addition to thermal energy for moisture removal. The dried product retained the desired color, texture, and aroma, suggesting exceptional quality, and the experimental findings showed good moisture reduction and drying. Overall, the results validate PV/T-integrated solar dryers' technological viability and promise as an energy-efficient and sustainable solution for agricultural drying applications in semi-urban and rural settings. The results demonstrated efficient drying performance, with the final product retaining desirable color, texture, and aroma, indicating a high-quality outcome. This experimental validation highlights the feasibility and effectiveness of PV/T-integrated solar dryers for sustainable agricultural processing in semi-urban settings.

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INTRODUCTION

Solar drying is an energy-efficient, eco-friendly method of preserving agricultural produce. Traditional drying techniques are often time-consuming and susceptible to contamination and degradation of product quality. Hybrid photovoltaic thermal (PV/T) technology presents an integrated solution by combining electricity generation with heat capture, improving overall system efficiency [1]. By simultaneously producing electricity and absorbing thermal energy from solar radiation, hybrid photovoltaic thermal (PV/T) technology offers a sophisticated and integrated approach to get around these restrictions. PV/T-based solar dryers greatly improve overall system efficiency and dependability by effectively utilizing both the electrical and thermal components of solar energy. While the produced electricity can power auxiliary systems like fans, sensors, and control units, guaranteeing consistent drying and better process control, the recovered thermal energy is efficiently employed for drying applications. Previous studies have demonstrated the benefits of PV/T systems in water heating and air heating applications, but limited research is available on their integration into solar dryers in semi-urban Indian contexts [2]. *Kasuri methi*, botanically known as *Trigonella corniculata* L., is a distinctive variety of fenugreek widely cultivated and consumed in India. It is primarily valued for its unique aroma and flavor, and its leaves are commonly dried and used as a spice in various regional cuisines. This plant is herbaceous and bushy in nature, and it exhibits slow growth during its vegetative period, remaining in a rosette condition for most of its early development. The plant eventually produces bright yellow to orange flowers and develops smaller, sickle-shaped pods compared to common fenugreek (*Trigonella foenum-graecum*). These traits make it particularly suitable for both fresh consumption and post-harvest drying for extended use [3].

The increasing interest in green leafy vegetables in recent years is largely due to their high nutritional value and associated health benefits. *Kasuri methi* is a rich source of vital nutrients, including essential vitamins, minerals, and dietary fiber [4]. Fresh leaves yield approximately 35 kcal per 100 g and comprise approximately 86.1% moisture, 4.4% protein, 0.9% fat, 1.1% fiber, 6.0% carbohydrates, and 1.5% ash content. Moreover, fenugreek leaves have an excellent micronutrient profile. They provide carotene (2.34 mg), thiamine (0.04 mg), riboflavin (0.31 mg), nicotinic acid (0.8 mg), and vitamin C (52.0 mg) per 100 g of the edible portion [5]. These compounds play an important role in supporting immune function, preventing oxidative stress, and contributing to the overall health of the host. *Kasuri methi* is valued for its nutritional benefits and phytochemical components, including flavonoids, alkaloids, and saponins, which exhibit various pharmacological properties, such as anti-inflammatory, antidiabetic, and antioxidant effects. The inclusion of dried *methi* leaves in the human diet can enhance the flavor and therapeutic value of daily meals. However, post-harvest handling, especially dehydration, plays a critical role in preserving the quality and shelf life of *Kasuri methi*. Improper drying techniques can lead to significant losses in color, aroma, texture, and nutritional content. Therefore, pre-treatment methods are often employed to minimize degradation during the drying process. Among the various methods, blanching is widely used because of its effectiveness in enzyme inactivation and microbial load reduction. Blanching helps preserve the characteristic green color of the leaves by inhibiting the action of polyphenol oxidase and chlorophyllase, which are responsible for browning and pigment breakdown.

Furthermore, pretreatments help soften plant tissues, facilitating uniform moisture removal and shortening the overall drying time. This step is particularly essential for the drying of leafy vegetables, as they are highly perishable and prone to enzymatic and microbial spoilage if not processed correctly. The application of appropriate pre-treatment also leads to improved rehydration characteristics of the dried product, which is important for its culinary application. Advanced solar drying systems, especially hybrid photovoltaic thermal (PV/T) dryers, offer an energy-efficient and sustainable method for processing *Kasuri methi* while retaining its nutritional and sensory attributes [6]. When combined with proper pre-treatment, these systems can significantly improve the quality of dried *methi*, making it more appealing to both domestic and commercial markets. *Kasuri methi* is a nutritionally rich and culturally significant herb in India. Proper pre-treatment and drying techniques, especially in combination with renewable energy-based technologies, offer a viable solution for reducing post-harvest losses, maintaining product quality, and adding economic value to this important leafy vegetable, Moringa.

Experimental Setup

A mixed-mode hybrid solar dryer was innovatively designed and fabricated for experimental validation, utilizing a UV-resistant polycarbonate sheet mounted securely over a galvanized metallic frame. This structure was shaped in the form of a tent to maximize solar heat retention and facilitate natural airflow [7]. The transparent polycarbonate covering allows ample solar radiation to enter the chamber while minimizing heat losses, thus creating an ideal environment for drying leafy vegetables like *methi*. The system integrates a hybrid photovoltaic thermal (PV/T) module, which was strategically positioned facing due south to align with the geographical location (latitude 21.2°N, Bhilai, India). The PV/T panel was mounted at an optimal tilt angle of approximately 25°, ensuring maximum exposure to incident solar radiation throughout the day. This orientation enhances both the thermal and electrical efficiency of the system.

The key components of the dryer include: A glazed flat-plate thermal collector with a surface area of 1.5 m², which absorbs solar radiation and transfers heat to the circulating air. The collector supports both natural convection and forced convection (when powered) to heat and channel the air into the drying chamber efficiently [8]. A photovoltaic panel rated at 100 Wp, integrated with the thermal collector, is capable of generating sufficient electrical power to operate auxiliary components such as a direct current (DC) fan or environmental sensors. This dual functionality not only improves the overall energy conversion efficiency but also makes the system self-sustaining in off-grid conditions. The drying chamber houses two perforated stainless-steel trays, which are designed to distribute the drying material evenly. The perforations enhance vertical airflow, ensuring uniform drying across all layers of the crop by allowing heated air to pass through the material with minimal resistance [9].

The experimental trials were conducted in November at a rooftop test site in Bhilai, Chhattisgarh. This period was selected to represent the moderate winter conditions typical of central India. Figure 1 shows the experimental setup.

The average solar irradiance during the experiments varied between 450 and 700 W/m², providing favorable conditions for solar drying [10]. A total of 5 kg of fresh *methi* leaves were uniformly spread over the trays to ensure consistent exposure to the heated air stream. Observations and measurements were recorded at regular hourly intervals to monitor parameters such as ambient temperature, chamber temperature, humidity levels, solar radiation, and weight loss of the drying material. These data were used to evaluate the performance and efficiency of the PV/T-assisted solar dryer. Table 1 shows the average solar irradiance level and wind speed data for a particular day.

Table 1. Solar irradiance and wind speed data for a particular day.

Time (hours)	Wind speed (m/s)	Solar irradiance level (W/m^2)
9:00	1.3	378.4
9:30	1.6	448.7
10:00	2.1	538.4
10:30	2.3	582.3
11:00	1.7	614.8
11:30	2.8	643.2
12:00	3.2	680.5
12:30	1.9	720.4
13:00	2.7	672.4
13:30	2.3	584.5
14:00	1.6	510.6
14:30	1.4	458.2
15:00	2.1	361.7
15:30	1.8	322.4
16:00	1.4	238.6
16:30	2.3	181.4
17:00	2.2	76.02

RESULTS AND DISCUSSION

A PV/T-based solar dryer was used to dry fenugreek leaves. The experiments were performed on 21st November 21, 2024, in Bhilai, Chhattisgarh, India. The coordinates of the location are 21.1938°N, 81.3509°E. The experiments were performed from 9:00 AM to 05:00 PM on the particular day. As observed from the input data, the highest and lowest solar irradiance levels recorded were 720.4 W/m^2 and 76.02 W/m^2, respectively. The ambient temperature ranged between 24°C and 30°C.

Figure 2 shows the input solar irradiance level along with the wind speed. The solar radiation intensity level reached its highest value at approximately 12:30 PM, after which its value decreased until the end of the day.

The drying chamber was connected to the outlet of the PV/T system. The heated air from the PV/T system was inserted into the drying chamber to dry the *methi*. Figure 3 shows the temperature difference between the inlets and outlets of the channel. The chamber temperature remained 10–15°C higher than the ambient temperature, with the thermal collector contributing significantly to the preheated airflow.

Figure 1. Experimental setup of PV/T-assisted solar dryer.

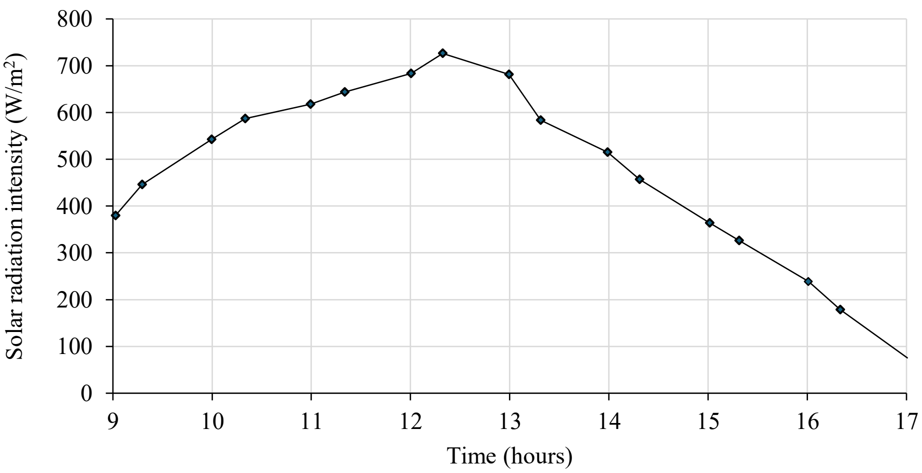

Figure 2. Variation in solar radiation intensity with time.

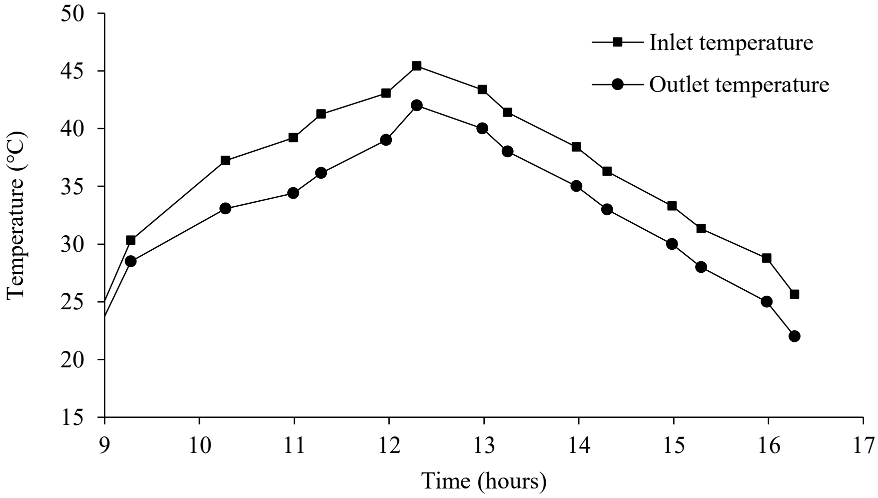

Figure 3. Temperature difference at the inlet and outlet of the PV/T collector.

Figure 4. (a) Open sun drying, (b) PV/T-based solar drying.

The PV/T-based solar dryer was capable of absorbing moisture from the fenugreek leaves compared to open sun drying. In 6 h of drying, using the PV/T-based solar dryer, the moisture content was reduced by up to 90%, whereas using open sun drying, the moisture content was reduced by up to 73%. Figures 4(a) and (b) shows the actual images of fenugreek leaves after 6 h of drying.

The initial moisture content of *methi* seeds was approximately 85% (wet basis). After approximately 6 h of continuous drying, the final moisture content was reduced to below 10%, which is suitable for storage. The natural green color, distinctive scent, and tolerable texture of the dried *methi* were retained, indicating good physical quality and minimal degradation of heat-sensitive nutrients and bioactive substances. There were no indications of external contamination, microbial development, or discoloration during the drying process, indicating that the enclosed PV/T-integrated solar dryer offered hygienic drying conditions. The drying rate followed a typical falling rate curve. Dried *methi* retained its green color and aroma, indicating minimal nutrient loss. No microbial growth or external contamination was observed, confirming the hygienic drying. The PV panel produced ~0.35–0.5 kWh of electricity per day, which could be used to operate a small fan or light, thereby enhancing the system functionality. The photovoltaic module produced between 0.35 and 0.5 kWh of electrical energy daily, in addition to thermal performance. To improve airflow homogeneity, system usability, and general functioning, this electrical output is adequate to run auxiliary components such as a lighting system or a tiny ventilation fan. These outcomes show how well the PV/T-integrated sun-drying system works to remove moisture effectively, preserve product quality, and offer extra electrical advantages.

CONCLUSION

The experimental validation of the hybrid PV/T-integrated solar dryer demonstrates its potential for effective and sustainable drying of agricultural products. The integration of thermal and electrical outputs enables efficient use of solar energy, ensuring higher drying temperatures, shorter drying times, and improved product quality. The system is suitable for decentralized deployment on rooftops in urban and rural areas, providing a cost-effective solution for small-scale farmers and entrepreneurs. Future work can include automation, thermal storage integration, and testing with other crops.

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