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Design and Performance Evaluation of a Large-Size PV/Thermal Hybrid Solar Tunnel Dryer for Arid Regions: A Study on Date Palm (*Phoenix dactylifera* L.)

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1. INTRODUCTION

Date palm (*Phoenix dactylifera* L.) is among the oldest cultivated fruit trees and plays a crucial role in the socio-economic sustainability of arid and semi-arid regions worldwide. The crop exhibits remarkable tolerance to extreme temperatures, intense solar radiation, and low relative humidity, particularly during the fruiting and ripening stages. Owing to its high carbohydrate content, dates are classified as high-energy foods, providing approximately 300 kcal per 100 g. Additionally, dates are nutritionally rich, being an excellent source of essential minerals such as iodine, iron, calcium, and potassium, while remaining low in fat content. In India, date palm cultivation is primarily concentrated in the north-western arid tracts, particularly in western Rajasthan and parts of Gujarat. Among the cultivated varieties, 'Khadrawi' has gained prominence as a commercially important cultivar due to its suitability for drying and conversion into *chhuhara* (dried dates). Over the past decade, date palm cultivation has expanded significantly in western Rajasthan, emerging as a promising cash crop for farmers in arid environments.

Despite its agronomic suitability, date palm production in arid regions faces serious post-harvest challenges. The most critical issue arises from the coincidence of the date ripening period with the onset of the southwest monsoon, typically in June. Exposure of ripening fruits to unexpected rainfall results in rapid microbial spoilage, fermentation, and physical deterioration. Field observations and regional estimates indicate that post-harvest losses due to rainfall-induced spoilage can reach up to 60%. To mitigate such losses, farmers often harvest fruits prematurely and sell them at low prices, thereby reducing economic returns. Drying immature or semi-ripened dates and converting them into value-added products is therefore essential for enhancing marketability, extending shelf life, and stabilizing farm income. However, the traditionally practiced open sun drying method suffers from several limitations, including non-uniform drying, long drying durations, exposure to dust and birds, deterioration in color and texture, oxidation of vitamins, and inconsistent product quality. These drawbacks necessitate the development of improved, hygienic, and energy-efficient drying technologies suitable for arid climatic conditions.

2. Scope of Solar Energy Utilization in Arid Regions

Solar energy represents the most abundant and environmentally benign renewable energy resource available in arid regions. India's desert ecosystem receives exceptionally high solar radiation, ranging from 6.0 to 7.4 kWh m^{-2} day^{-1}, with nearly 300 clear sunny days annually. This immense potential makes solar energy particularly suitable for agricultural processing operations such as drying, heating, and dehydration, which generally require low to moderate temperatures. The utilization of solar energy in agricultural processing not only reduces dependency on fossil fuels and grid electricity but also contributes to climate-resilient farming systems. Over the past three decades, ICAR–CAZRI, Jodhpur, has undertaken extensive research and development efforts to harness solar energy for domestic, agricultural, and industrial applications. These include solar cookers, water heaters, solar dryers, water purification systems, cold storage units, solar sprayers, and solar dusters. Recently, CAZRI has also initiated work on 105 kW capacity agrivoltaic systems, wherein solar photovoltaic (PV) panels are integrated with crop cultivation to enable dual land use for food and energy production. In this context, the integration of photovoltaic and thermal components in solar dryers offers an innovative pathway to improve drying efficiency, enhance temperature control, and ensure consistent performance under fluctuating climatic conditions.

3. Solar Drying Technology: Concept and Relevance

Drying is one of the oldest and most widely practiced methods of food preservation. By removing excess moisture, drying inhibits microbial activity, reduces enzymatic reactions, and extends the shelf life of perishable agricultural produce. Historically, drying was performed using natural sun exposure; however, such methods are highly dependent on weather conditions and lack process control. Modern solar drying systems aim to overcome the limitations of open sun drying by providing controlled drying environments that ensure faster moisture removal, uniform temperature distribution, and improved product quality. Solar dryers can be broadly classified into direct, indirect, and mixed-mode systems, operating under natural or forced convection. In arid regions characterized by high solar radiation and low relative humidity, natural convection solar dryers are particularly effective due to the strong buoyancy-driven airflow. Electrically operated mechanical dryers, although efficient, are often economically unviable in rural and remote arid areas due to high capital costs and unreliable electricity supply. Therefore, the development of large-capacity, naturally ventilated, solar-based drying systems represents a sustainable solution for post-harvest processing of date palm fruits.

4. Principle of the PV/Thermal Hybrid Solar Tunnel Dryer

The large-size PV/thermal hybrid solar tunnel dryer developed at CAZRI operates primarily on two fundamental principles: the greenhouse effect and natural convection. Short- and medium-wave solar radiation (<400 nm and 400–700 nm) penetrates the transparent polycarbonate cover and enters the drying chamber. Inside the tunnel, this radiation is absorbed by the blackened floor surface and the product itself, where it is converted into long-wave thermal radiation. Due to the selective transmission properties of the polycarbonate sheet, the long-wave radiation is trapped within the enclosure, resulting in a significant temperature rise—a phenomenon known as the greenhouse effect.

Simultaneously, the temperature difference between the inside of the tunnel and the ambient environment generates buoyancy-driven airflow. Cooler ambient air enters through strategically positioned inlet openings near ground level, gets heated upon contact with the warm floor and interior air, and rises upward while absorbing moisture from the product. The hot, moisture-laden air is finally expelled through a chimney located at the top of the tunnel.

The integration of photovoltaic elements provides auxiliary electrical power for monitoring instruments and offers potential for future expansion to forced convection or hybrid operation modes.

5. Design and Construction of the Solar Tunnel Dryer

A large-size, walk-in, tunnel-type PV/thermal hybrid solar dryer was designed and fabricated at the Solar Yard of ICAR–CAZRI, Jodhpur, for drying fruits and vegetables under arid climatic conditions. The dryer consists of a semi-cylindrical metallic frame fabricated using mild steel (MS) support pipes and angles to ensure structural stability and durability under high wind conditions typical of desert regions. The overall base area of the dryer is 640 × 300 cm. The entire structure is covered with a 6-mm thick UV-stabilized, double-filter, solid multilayer polycarbonate sheet. This material was selected due to its high solar transmittance, mechanical strength, resistance to ultraviolet degradation, and long service life under extreme climatic conditions. The floor of the dryer is made of cement concrete and painted black to enhance solar radiation absorption. Internally, the drying chamber is divided into multiple tiers of perforated drying trays arranged vertically to maximize drying capacity while ensuring adequate airflow around the product (Fig 1).

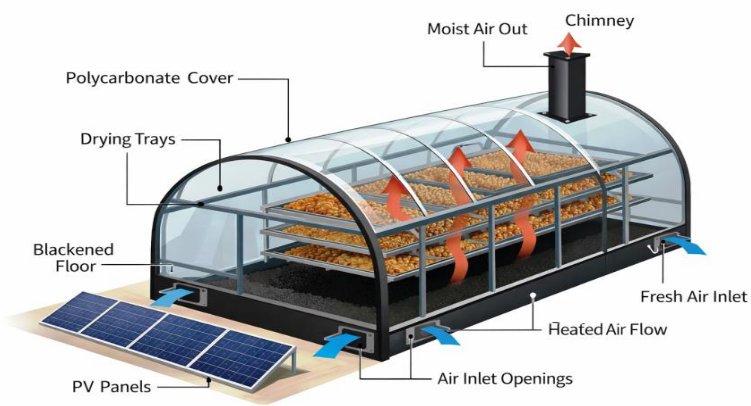

Fig. 1 Schematic diagram of large-size tunnel-type PV/thermal hybrid solar dryer

To achieve maximum exposure to southern solar radiation, the longitudinal axis of the tunnel was oriented in the east–west direction. Two uniformly sized air inlet openings were provided near ground level along the southern periphery of the tunnel to facilitate fresh air entry. A chimney installed at the apex of the tunnel enables efficient removal of hot and humid air. A door of dimensions 182 × 76 cm was installed at the upper end of the tunnel to allow easy loading and unloading of produce (Fig.2).

Fig. 2 Actual installation of large-size tunnel-type PV/thermal hybrid solar dryer at solar yard

6. Working Principle and Thermal Behavior

During operation, solar radiation incident on the polycarbonate cover passes into the tunnel and is absorbed by the floor and the product. As the internal temperature rises, a pressure and density gradient is established between the inside and outside air. This gradient induces natural convection airflow without the need for external power input. The drying air flows upward across the trays, ensuring continuous contact with the date fruits. The gradual removal of moisture occurs primarily during the constant-rate drying period, followed by a falling-rate period as moisture diffusion from the interior of the fruit becomes the controlling mechanism.

The thermal performance of the dryer is governed by solar radiation intensity, ambient temperature, relative humidity, airflow rate, and loading density. The hybrid design ensures stable thermal conditions even under moderate fluctuations in external weather parameters.

7. Evaluation of Dryer Efficiency

The thermal efficiency (η) of the solar tunnel dryer was calculated using the following relationship:

$$\eta = \frac{ML}{A\int_0^{\theta} H_T \, d\theta} \times 100$$

where:

η = thermal efficiency of the solar dryer (%)

A = effective absorber area (m^2)

H_T = solar radiation incident on a horizontal surface ($J\ m^{-2}\ h^{-1}$)

L = latent heat of evaporation ($J\ kg^{-1}$)

M = mass of moisture evaporated (kg)

θ = drying duration (h)

This expression represents the ratio of useful energy utilized for moisture evaporation to the total solar energy incident on the dryer surface during the drying period.

8. Performance Evaluation for Drying Date Palm Fruits

The performance of the developed solar tunnel dryer was evaluated by drying freshly harvested date palm fruits with an initial moisture content ranging from 65 to 80% (wet basis). Drying trials were conducted during June 2024 under arid climatic conditions at Jodhpur. For comparative assessment, open sun drying experiments were conducted simultaneously. During no-load conditions, the stagnation temperature inside the dryer reached 71–75°C, indicating effective heat trapping and absorption. When loaded with 250 kg of fresh dates, the average temperatures recorded were 49–69°C in the upper trays, 46–68 °C in the middle trays, and 44–63°C in the lower trays. The average solar radiation during the experimental period varied from 430 to 940 $W.m^{-2}$, while the mean ambient temperature was approximately 39.5°C. Moisture reduction curves revealed that the solar tunnel dryer reduced moisture content from 65% to 25% within six days, whereas open sun drying required nearly eight days to achieve similar moisture levels. The final moisture content of dates dried in the solar tunnel dryer ranged between 20% and 26% (wet basis), which is suitable for safe storage (Fig. 3). The overall thermal efficiency of the dryer was calculated to be 36.6%. Higher efficiency was observed during the initial drying stages due to higher moisture evaporation rates, followed by a gradual decline as the moisture content decreased below 54% (Fig. 4).

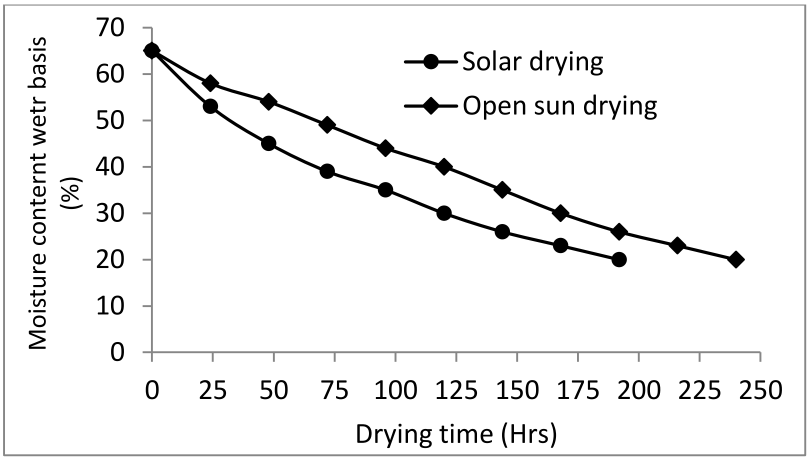

Fig.3 Changes in date palm moisture content and drying time under solar dryer and open sundrying

Fig. 4. Date palm drying in a large-size tunnel-type PV/thermal hybrid solar dryer

9. CONCLUSIONS AND IMPLICATIONS

The performance evaluation of the large-size tunnel-type PV/thermal hybrid solar dryer developed at CAZRI, Jodhpur, for drying dates (*Phoenix dactylifera* L.) was found to be highly successful. The main conclusions are:

Drying efficiency: The solar dryer reduced moisture content from 65% to 25% in only six days, compared to eight days required under open sun drying, indicating a time saving of about 25%.

Temperature management: The internal temperature of the dryer (44–69°C) remained significantly higher than ambient temperature (39.5°C). The no-load stagnation temperature reached 71–75°C, confirming efficient heat absorption.

Thermal efficiency: The average thermal efficiency of the dryer was 36.6%. Higher efficiency was observed during the initial drying stages, which declined as moisture content decreased (particularly below 54%).

Quality and storage: Achieving a moisture level of 25% within six days is ideal for safe long-term storage. The enclosed structure also protects the product from dust and external contaminants, resulting in better quality.

Overall, the developed solar tunnel dryer represents a practical, scalable, cost-effective and climate-resilient solution for post-harvest processing of date palm and other agricultural commodities in solar-rich arid environments.