Journal of Natural Resource Conservation and Management
Vol. 7, No. 1, pp 1-7, 2026
doi: 10.51396/ANRCM.7.1.2026.1-7

Performance evaluation of a small scale solar tunnel dryer for drying tomato under subtropical climatic conditions

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Received : April 10, 2026
Revised : May 09, 2026
Accepted : May 10, 2026
Published : June 30, 2026

ABSTRACT

Drying of agricultural products is the most important unit operation after harvesting. It refers to the removal of moisture from the produce to obtain a desired level that will be safe for their storage. The major goal of the present study is to build a direct active type small-scale solar tunnel dryer and examine its performance in the Eastern Uttar Pradesh (U.P.) region. A small-scale solar tunnel dryer based on convection mode was developed at the Department of Renewable Energy Engineering, Mahamaya College of Agricultural Engineering and Technology, Ambedkar Nagar. Performance evaluation of the developed system was carried out in terms of moisture content and drying efficiency for drying tomato. During no load testing, maximum temperatures inside the dryer were found to be 60 ºC while during full load testing, maximum temperatures inside the dryer were found to be 57 ºC. Tomato slices were dried in the developed system from the initial moisture content of 95 % (wb) to the final moisture content of 15 % (wb) within 8 hours. The drying efficiency of the developed system was found 42 %.

Keywords: Solar Tunnel Dryer, Tomato drying, Efficiency of STD, Moisture Content

INTRODUCTION

India is the world's second-largest producer of fruits and vegetables, accounting for 12.6% and 14.0% respectively. Fresh fruits and vegetables account for over 76% of total production, with post-harvest losses ranging from 20-22%. Only 2-4% Industries prepare and preserve vegetables and fruits (Mathur and Chugh, 2021). The worldwide demand for sustainable food preservation has never been more pressing. In many underdeveloped countries, post-harvestlosses for perishable vegetables can vary from 20% to 50%, owing to insufficient storage and processing facilities (Faqeerzada *et al*., 2018). Open-sun drying is still the most popular conventional approach; nevertheless, it is affected by dust contamination, insect infestation, unpredictable weather, and UV-induced nutritional loss (Belessiotis and Delyannis, 2011). To address these issues, sun drying technology provides a sustainable and sanitary option that greatly enhances product quality and shelf life.

Solar tunnel dryers (STDs) have become one of the most efficient systems for large-scale, high-volume drying of agricultural products and fruits (Tesfaye and Habtu, 2022; Nukulwar and Tungikar, 2021; Kagande *et al*., 2012). Unlike standard box dryers, the tunnel layout uses a wide surface area for sun collecting and allows for continuous longitudinal airflow over the goods (Hossain and Bala, 2007). The essential idea is the greenhouse effect, in which short-wave solar radiation enters via a transparent cover and is absorbed by a dark inside surface, resulting in long-wave heat energy. The drying process is based on the simultaneous transmission of heat and mass. Thermal energy is delivered to the vegetable surface, providing the latent heat of vaporisation required for moisture removal. As air flows through the tunnel, its relative humidity drops while its temperature rises, resulting in a vapour pressure deficit that drives moisture from the vegetables' interiors to the surface (Tiwari, 2016).

Compared with conventional box and direct-type solar dryers, small-scale solar tunnel dryers are more attractive because of their simple and economical construction, higher drying capacity, and better utilization of solar energy. Recent studies have shown that small-scale solar tunnel dryers are particularly effective for high-moisture vegetables like chillies, tomatoes, and leafy greens (Natarajan *et al.*, 2022). These systems can achieve drying temperatures 15°C to 30°C higher than ambient air, reducing drying time by up to 50% compared to open-air methods (Prakash and Kumar, 2014). This paper focuses on the development and performance evaluation of a low-cost, small-scale solar tunnel dryer tailored for smallholder farmers, aiming to provide a balance between thermal efficiency and economic viability

Tomato (*Solanum lycopersicum L.*) is one of the most important vegetable crops grown worldwide. Ripe tomatoes contain many essential nutrients required for a balanced diet. Tomatoes are rich in water, natural sugars, dietary fibre, potassium, and vitamins such as A, B-complex, and C (Kumar *et al.*, 2022). Tomatoes are easily digestible and provide quick energy. Tomato is also considered a medicinal vegetable, as it helps in reducing blood pressure, improving digestion, preventing constipation, supporting heart health, and strengthening the immune system (Ali *et al.*, 2021). Tomato is a climacteric vegetable with a soft texture, which makes it highly prone to damage during harvesting, transportation, storage, and marketing. Due to their high moisture content, tomatoes are easily bruised and contaminated during handling. High temperature and relative humidity accelerate quality deterioration. Both qualitative and quantitative losses occur during storage due to moisture loss, vitamin degradation, pest and disease attacks, and physiological disorders (Wakene and Sharew, 2024). Dried tomato products are popular in many countries and are widely used in soups, sauces, and food preparations. Post-harvest losses of tomatoes can be significantly reduced through proper drying techniques (Wakene and Sharew, 2024). Therefore, there is good potential for tomato drying in tropical and subtropical regions.

A solar tunnel drying system suitable for hot and humid climatic conditions was designed and evaluated by (Schirmer *et al.*, 1996) for tomato drying in Thailand. The developed dryer was capable of handling nearly 2 kg of whole ripe tomatoes per drying batch, with the drying process completed within two to three days. During operation, the air temperature inside the dryer varied from 40 °C to 60 °C. The study reported that the dried tomato products obtained were of good quality, showing acceptable colour, texture, and flavour characteristics. Phoungchandang and Woods, (2000) developed a mathematical drying model for whole tomatoes. The predicted drying behavior showed good agreement with the experimental data, demonstrating the reliability of the model. The authors emphasised that reducing drying duration is important for improving the effectiveness of solar tunnel dryers. It was also found that fluctuations in drying air temperature due to changes in solar radiation intensity did not significantly influence the final quality of dried tomatoes. However, the overall thermal efficiency of the solar dryers was relatively low, indicating the need for design improvements such as the incorporation of movable reflectors to increase solar energy utilisation.

The present studies primary goal was to develop a small-scale solar tunnel dryer for vegetable drying. The dryer's objectives are to lower drying costs, enhance product quality, reduce post-harvest losses, and create a clean drying environment that inhibits the growth of microorganisms.

MATERIALS AND METHODS

Description of the solar dryer

A small-scale solar tunnel dryer was developed and tested for drying vegetables. The solar collector, tunnel-style drying chamber, air circulation system, and supporting frame are the main parts of the solar tunnel dryer. Fig. 1 depicts a schematic diagram of the solar tunnel dryer, while Table 1 lists the system's primary parts and specifications.

The dimensions of the solar collector are 1219 mm in length and 609 mm in width, resulting in a drying area of 0.56 m². A 200 micron-thick UV-stabilised polythene sheet was placed over the dryer to maximise solar radiation penetration while

Table 1. Specifications of the small-scale solar tunnel dryer for vegetables

Parameters	Specifications
Length of dryer	1219 mm
Width of dryer	609 mm
Area of dryer	0.56
Height of chimney	600 mm
Diameter of the chimney	55mm
UV-stabilised polythene	200 microns (thickness 1mm)
Numbers of tray	2
Tray size	570×570×25 mm
Material of the tray	Metallic net and Aluminium

Fig. 1. Small-scale solar tunnel dryer

minimising heat loss to the environment. The drying chamber was located directly beneath the transparent UV-stabilised polythene cover, allowing solar radiation to enter and heat the air inside the drier. The chamber was appropriately sealed to retain heat and provide adequate drying conditions. The drying chamber was designed to hold two horizontal drying trays. To achieve thorough moisture removal, the vegetable slices were distributed in thin, consistent layers across these trays. The trays were designed so that hot air could flow above and below them, resulting in consistent drying of the product. Each tray was made with an aluminium frame and a metallic net that allows hot air to flow freely through the drying material. The greenhouse effect caused by the polythene covering heated the drying air within the tunnel. Convection naturally carried warm air through the drying chamber. A chimney at the top of the dryer served to remove moisture-laden air from the chamber while allowing fresh air to enter from the input side. This continuous airflow increased drying efficiency and shortened drying time.

The drying chamber's design ensured efficient use of solar energy, homogeneous air circulation, and hygienic drying conditions. The covered construction kept dust, insects, and rain out, enhancing the quality of dried vegetables and lowering post-harvest losses.

Experimental procedure

For comparative performance evaluation, several trial runs were conducted under various drying conditions utilising a constructed small-scale solar tunnel dryer and conventional open sun drying. The experiments took place on bright sunny days in March 2026 at the Department of Renewable Energy Engineering, Mahamaya College of Agricultural Engineering and Technology, Ambedkar Nagar, India. To achieve experimental consistency, tomatoes (*Solanum lycopersicum* L.) with uniform maturation, size, and colour were obtained from the local market.

Before each experimental run, the solar tunnel dryer was run at no load for about an hour to stabilise the internal air temperature and airflow pattern. This preheating phase guaranteed that the product dried steadily before it was loaded. The tomatoes were properly rinsed in clean water to remove surface impurities before being cut into consistent thicknesses ranging from 3 to 5 mm with a stainless-steel knife. To guarantee uniform exposure to the drying air, the sliced samples were evenly spread in a single layer on aluminium trays lined with metallic mesh. Each testing batch contained around 2 kg of tomato slices placed into the dryer.

For comparison, control tomato slices were stacked in a single layer on trays and placed next to the dryer under open sun drying conditions. Drying began soon after loading, usually at 09:00 h, and continued until the samples achieved a safe final moisture content suited for storage. The weight reduction of samples in both the solar tunnel dryer and open sun drying was measured at hourly intervals using an electronic weighing scale. Temperature measurements of the ambient air and the air inside the dryer were taken with thermocouples placed at strategic spots. During the drying process, the intensity of sun radiation was monitored at regular intervals using a solar power meter. All observations were made during the day, between 09:00 h and 16:00 h. The moisture content of tomato slices was measured using the oven-drying method. Representative samples were dried in a hot air oven at a controlled temperature until a consistent weight was produced. Moisture content was determined based on the starting and end sample weights. After drying, the dried tomato samples were removed from the dryer, cooled to room temperature in shady settings, and stored in airtight polyethene bags for further examination.

Determination of moisture content and drying efficiency

Moisture Content

This ratio is defined as the quotient of the difference between the initial weight and final weight of the product, divided by the initial weight of the product (Lingayat *et al.*, 2017).

$$\text{Moisture Content} = \frac{W1 - W2}{W1} \times 100 \quad \text{...Eq.1}$$

Where,

W_1 = Weight of sample before drying, kg

W_2 = Weight of sample after drying, kg

Drying efficiency

This ratio, defined as the heat utilized by the dryer divided by the heat supplied to the dryer, is expressed as a percentage and calculated using the following formula (Sharma, 2015).

$$\eta = \frac{Q}{A \times I} \times 100 \quad \text{...Eq.2}$$

Where,

η = efficiency of the drying system

Q = Total quantity of heat required for drying, J

A = collector area, m^2

I = solar insolation (W/m^2)

RESULTS AND DISCUSSION

Performance evaluation

The performance of the developed small-scale solar tunnel dryer was evaluated by analysing the rise in air temperature inside the drying chamber with respect to the ambient air temperature, along with the corresponding variation in solar radiation intensity, under both no-load and full-load conditions.

Table 2. Variation of ambient temperature, temperature inside dryer and solar radiation under no-load condition

Time (h)	Ambient Temp. (°C)	Temp. inside dryer (°C)	Solar radiation (W/m^2)
09:00	32	35	350
10:00	35	45	550
11:00	37	51	800
12:00	39	58	1050
13:00	41	60	950
14:00	40	57	750
15:00	38	52	550
16:00	37	46	400

Performance evaluation under no-load condition

Under no-load conditions, the empty solar tunnel dryer was run to study the heat collection capability of the collector and the resulting temperature build-up inside the drying chamber. As shown in Table 2 and Fig. 2, the temperature inside the dryer increased progressively with the increase in solar radiation during the forenoon, reaching a maximum of 60 °C at 1:00 PM, and a minimum of 35 °C at 9:00 AM. The ambient air temperature during the same period varied between a minimum of 32 °C (at 9:00 AM) and a maximum of 41 °C (at 1:00 PM).

The difference between the temperature inside the dryer and the ambient temperature increased with the rise in solar radiation, reaching a maximum value of about 19 °C above ambient near solar noon. The solar radiation increased from a minimum of about 350 W/m^2 at 9:00 AM to a maximum of about 1050 W/m^2 at 12:00 noon, and decreased gradually thereafter. The close correspondence between the solar radiation curve and the dryer-air temperature curve indicates that the UV-stabilised polythene cover effectively transmitted and trapped the incoming solar radiation, while the dark interior surfaces of the tunnel absorbed it and converted it into thermal energy, raising the temperature of the air inside the chamber considerably above the ambient level. The natural draught created by the chimney further assisted in the continuous circulation of the heated air within the dryer.

Performance evaluation under full-load condition

The full-load test was conducted with the dryer loaded with freshly sliced tomatoes spread in a thin layer on the trays, in order to evaluate the collector's thermal response under actual operating conditions.

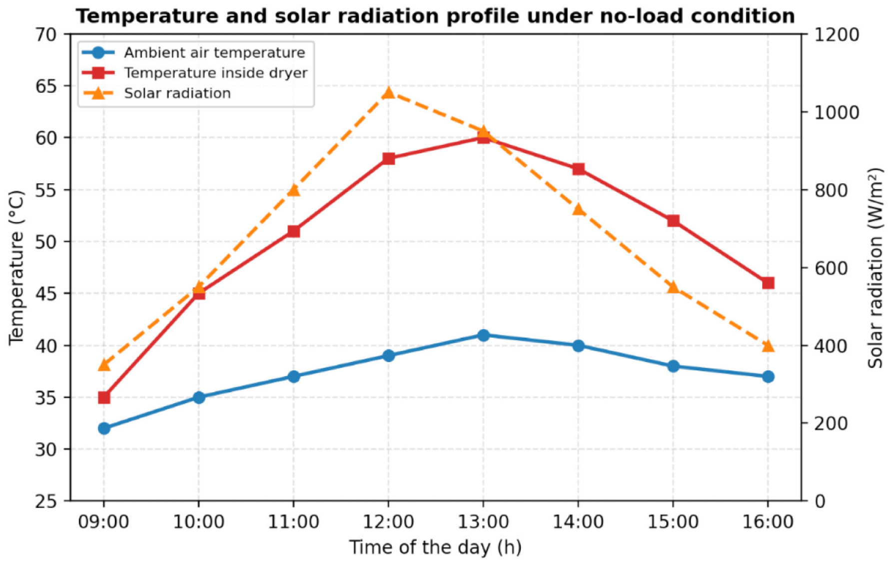

Fig. 2. Temperature and solar radiation profile under no-load condition

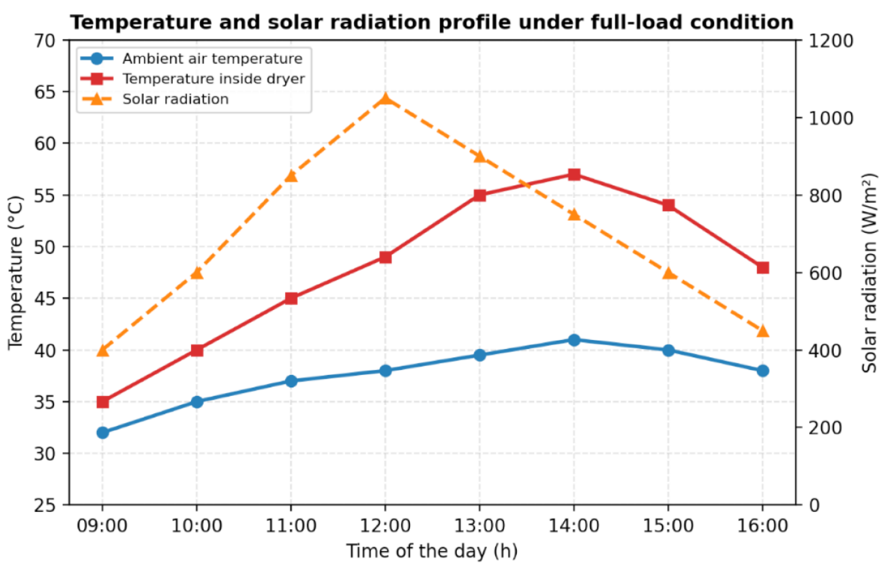

Fig. 3. Temperature and solar radiation profile under full-load condition

As presented in Table 3 and Fig. 3, the temperature inside the loaded dryer followed a trend similar to the no-load test, but with comparatively lower peak values, owing to the latent heat absorbed during evaporation of moisture from the product. The maximum temperature recorded inside the dryer was 57 °C at 2:00 PM, while the minimum was 35 °C at 9:00 AM. The ambient temperature during this period varied between a minimum of 32 °C (at 9:00 AM) and a maximum of 41 °C (at 2:00 PM).

Under full-load conditions, the temperature inside the drying chamber was found to be about 16

Table 3. Variation of ambient temperature, temperature inside dryer and solar radiation under full-load conditions

Time (h)	Ambient temperature (°C)	Temperature inside dryer (°C)	Solar radiation (W/m²)
09:00	32	35	400
10:00	35	40	600
11:00	37	45	850
12:00	38	49	1050
13:00	39.5	55	900
14:00	41	57	750
15:00	40	54	600
16:00	38	48	450

Fig. 4. A view of before and after drying of tomato slices

°C higher than the ambient temperature at its peak, which is slightly lower than the 19 °C rise observed under no-load conditions. This reduction can be attributed to the cooling effect of moisture evaporation from the tomato slices, which consumes a part of the collected solar heat as the latent heat of vaporisation, thereby moderating the rise in air temperature inside the chamber. The solar radiation during the full-load trial varied from about 400 W/m² at 9:00 AM to a maximum of about 1050 W/m² around solar noon, following a diurnal pattern similar to that observed during the no-load test. The Figure 4 shows the view of tomato slices before and after drying.

Thermal Efficiency

The collector area of the developed small-scale solar tunnel dryer was found to be 0.56 m², designed to handle a batch capacity of 2 kg of tomato slices per drying cycle. Considering an average solar radiation of about 600 W/m² during the full-load drying period and a drying time of 8 hours, the total heat required for reducing the moisture content of the product from 95% to 15% (wb) was estimated as 5242.1 kJ. Based on these values and calculations done using Eq. 1 & 2, the thermal efficiency was found to be 42%, as summarised in Table 4.

It can be observed that the collector consistently maintained the air temperature inside the drying chamber within the range of 35–60 °C, which is adequate for safe drying of tomato slices without causing case-hardening or loss of nutritional and sensory quality. The marginally lower temperature rise observed under full-load conditions compared to the no-load condition confirms that a significant portion of the absorbed solar energy was effectively utilised for moisture removal from the product rather than being lost as sensible heat. Overall, the results indicate that the polythene-covered tunnel structure, combined with chimney-induced natural convection, was capable of generating and sustaining a useful temperature differential of 16–19 °C above ambient conditions, which is sufficient to accelerate the drying process considerably compared to open sun drying.

Table 4. Summary efficiency parameters

Parameter	Value
Collector area (A)	0.56 m²
Average solar radiation (I)	600 W/m²
Drying time (t)	8 h (28,800 s)
Total heat required for drying (Q)	5242.1 kJ
Collector thermal efficiency (η)	42%

CONCLUSIONS

The developed small-scale solar tunnel dryer demonstrated satisfactory thermal and drying performance under both no-load and full-load conditions. During operation, the dryer maintained temperatures significantly higher than the ambient environment, reaching a maximum of 60 °C under no-load conditions and 57 °C during tomato drying. The system effectively reduced the moisture content of tomato slices from 95% to 15% (wet basis) within 8 hours, indicating rapid moisture removal and improved drying conditions. The overall drying efficiency of 42% confirms the suitability of the developed dryer for small-scale agricultural drying applications, offering a cost-effective and energy-efficient solution for preserving perishable produce.

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