EPJ Web of Conferences **343**, 04005 (2025) https://doi.org/10.1051/epjconf/202534304005
AIMACE-2025

Experimental Study of a Mixed-Mode Solar Dryer with Internal Reflectors for Tomatoes Preservation

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Abstract. A mixed-mode solar dryer with forced circulation and internal reflectors has been developed and evaluated for its performance for drying of tomato slices. Two solar PV module powered, 3 W DC fans, are installed for ventilation. The cabinet of the dryer is 70 cm in length and 70 pm wide and loading capacity of 2 kg of tomatoes, respectively. Tomatoes were cut into slices and loaded in perforated trays within the cabinet. The drying characteristics were studied and compared with natural convection based indirect solar dryer. To investigate its performance, three experimental runs with 1 kg of tomatoes were carried out in the dryer during the month of October 2024. The experiments showed that drying rate initially increased and then started decreasing gradually as the drying progressed. It was also observed that the forced convention drying produced better quality, color and texture of the dried product compared to natural convection based dryer. The drying temperature also improves with internal reflectors in dryer. At the start, the moisture content of tomatoes was 91-95 %. The time taken to dry 1 kg tomatoes up to 5-10% moisture content without auxiliary heating in 11-20 hours, while the drying efficiency was varying from 12 to 20%.

1 Introduction

Tomato is widely consumed in culinary due to its versatility and nutritious nature, particularly as lycopene source, which has been linked to reduced risks of coronary heart disease and certain cancers [1] (Brooks et al., 2008). Tomato cultivation is prevalent across many regions, producing high yields within short harvest periods. In developed countries, excess tomatoes are typically processed into products like paste, sauce, and ketchup or canned whole, sliced, or diced. However, these preservation methods rely on high-energy thermal processing, often unaffordable in developing nations, especially in rural areas, with limited electricity accessibility [2] (Heredia et al., 2007).
According to Paul et al. [3] (2020), tomatoes are a valuable cash crop for small-scale farmers and a dietary staple in many cuisines. However, tomatoes are highly perishable, resulting in

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substantial post-harvest losses during peak seasons, as surplus produce may be consumed fresh, sold at low prices, or allowed to spoil. The solar drying is being used since long however, with time the process is getting more sophisticated in terms of color, texture of dried product, cost effectiveness and nutrient retention which is critical to address micronutrient deficiency [4] (James & Zikankuba, 2017). The studies have shown that solar drying can assist in food preservation over extended durations [5] (Wulyapash, Phongphiphat, & Towprayoon, 2022).

This study focusses on devising energy efficient, low cost solar drying method for preserving tomatoes to avoid post-harvest spoilage and improve nutrient retention at the same time. The developed cabinet solar dryer with internal reflectors and PV operated fan based air circulation was implemented, tested and analyzed for tomato drying. The internal reflectors helped in proper light distribution within the cabinet and elevated the drying temperature and resulted in better and firm texture of the dried product which was visually vibrant and appealing.

2 Literature Review

Sintie and Aduye [6](2020) carried out the feasibility and assessment of tomato and other vegetable drying for Ethiopian conditions to reduce the losses, post-harvest. Their study found high efficiency and exergy ratios, supporting solar drying as a suitable solution for improving food preservation in areas with high post harvest waste. The study outlines economic and social advantages of sun drying in resource constrained agricultural set-up. Al Maiman et al. [7] (2021) studied the impact of solar drying of tomatoes to enhance its storability and physicochemical changes post drying. The findings showed that drying enhanced its antioxidant properties. It also postulated that drying enhances the shelf life of tomatoes and reduces the spoilage thus making it cost effective. Mencarelli et al. [8] (2023) discussed two-stage drying for tomatoes in order to optimize the drying parameters efficiently. The two-stage drying helped in reducing the drying time by up to 25% without compromising with the quality of the dried product thus, making it energy efficient. Bayana and İçier [9] (2024) examined the drying of tomato pomace using a photovoltaic-assisted dryer, analyzing the impact of different lighting conditions and heating sources. Their findings indicated that combining UV and infrared light with hot air drying enhanced the preservation of lycopene and β-carotene, two critical antioxidants in tomatoes. The study supports the integration of advanced lighting in solar dryers for nutritionally sensitive crops. Hybrid solar-biomass drying systems have gained attention as efficient solutions for preserving perishable products such as fish. Rizal et al. [10] (2018) developed and tested a hybrid solar-biomass dryer designed to operate with solar energy during the day and biomass heating at night. The system maintained a drying chamber temperature of 40–50°C, effectively drying 25 kg of fish to 12.5 kg within 22–23 hours. The dryer, fabricated at a cost of $1870 for 100 kg production capacity, demonstrated significant potential for improving drying efficiency and product quality. Economic analysis revealed its feasibility, with a break-even period of 2.6 years, making it a viable option for small-scale fish preservation operations in resource-limited areas. This study highlights the advantages of integrating renewable energy sources to optimize drying performance and reduce operational costs.

There has been advancements in drying technology over time, still there are gaps in terms of optimized drying efficiency, drying rate, dried product quality for tomatoes. The existing studies often do not take into consideration the impact of using internal reflectors during drying for effective and uniform heat and light distribution. This can have significant impact in terms of drying time reduction. Coupled with effective air flow can result in effective drying with firm dried product and better nutrient retention however, limited research has been carried out to understand the combined impact under controlled conditions. The same

still needs to be investigated in combination with the internal mirrors i.e. incorporating reflective surfaces in solar dryers synchronized with air control mechanisms, specifically for tomatoes, to enhance drying consistency and minimize spoilage. A modified solar drying system with these characteristics can be designed and developed to test its efficiency, nutrient-preservation, and economic viability of such hybrid system.
This study aims at investigating the drying characteristics of tomatoes in a solar cabinet dryer equipped with internal reflectors, with controlled air temperature and velocity, to enhance drying efficiency and preserve product quality. This setup aims to optimize solar energy utilization, reduce drying time, and improve nutrient retention.

3 Materials and Methods

This study encompasses the designing and developing an energy-efficient drying system with internal reflectors and solar PV fans for forced convection within the drying chamber/cabinet which results in improved quality of the dried product. The solar rays enters through the glass lid, made of 4mm thick toughened glass, facing south, at 23° tilt (latitude of the location) to maximize incident solar radiation. The other sides of the cabinet are made of PVC foam board. The sliced tomatoes are placed of the perforated tray placed within the cabinet. The inner surface of back vertical wall of cabinet is provided with reflective mirror sheet. The cabinet dryer is simple in construction. The ambient air enters from one hole (on the side), is heated due to the incoming radiation through the glass cover creating a green-house effect within. The PV fans helps in regulating the air speed inside the dryer. The air is sucked into the chamber by one and discharged using the other, provided on the second hole as shown Figure 1. Thus, assisting moisture removal at faster rate, due to forced convection that is achieved using these two fans.
Fresh good quality tomatoes from same group of plants were procured from the local market. Selection was based on visual evaluation of uniform color and geometry. During each test, one kg tomatoes are washed, steamed and sliced. Proper hygiene was maintained while slicing, weighing and placing the samples inside the drying cabinet. The weight was measured every hour using digital electronic balance, accuracy 0.01 g, to calculate the loss in weight. The tomato samples were dried from 9:00 am to 5:00 pm. The dryer was shut down during off-sunshine hours and drying was continued on the following day until equilibrium moisture content was reached (no change was observed in mass). The temperatures (of ambient air and cabinet), relative humidity and solar radiation intensity were measured. PT-100 RTD sensors and SE20-D1 pyranometer, accuracy of 0.01°C and 1% respectively, were used for temperature and solar radiation intensity. There are two temperature sensors and two humidity sensors were incorporated, one each within the cabinet and one each outside, to measure air temperature and humidity. Furthermore, Solar PV fans were incorporated to the system to set the forced convection of hot air in the cabinet.
The solar dryer was constructed using locally available materials with the assistance of a local carpenter, which ensured affordability and ease of replication in rural or resource-constrained settings. Table 1 shown the cost analysis of fabricating and operating a cabinet dryer with forced convection and internal reflectors.

Table 1. Cost analysis of fabricating a solar cabinet dryer with forced convection and internal reflectors.

Component	Quantity	Cost per Unit (₹)	Total Cost (₹)
PVC Foam Board (Cabinet Walls)	1 panel	500	500
4mm Toughened Glass (Top Cover)	1 piece	500	500

Reflective Mirror Sheet	1 piece	400	400
Solar PV Panels (6W)	1 units	800	800
DC Fans (3W)	2 units	100	200
Perforated Trays (for Tomatoes)	2 units	100	200
Sensors (Temperature, Humidity)	4 units	200	800
Miscellaneous (wires, fasteners)	-	100	100
Labor for Assembly	-	1000	1000
Total Material Cost	-	-	4,500

4 Materials and Methods

The drying phenomenon is basically removal of water from the solid through evaporation. The majority of energy is consumed in water evaporation. The moisture content in the product can be on dry or wet basis. Equation 1 and 2 gives the level of moisture on wet and dry basis.

$$M_{wb} = \frac{m_w}{m_w + m_d} \tag{1}$$

$$M_{db} = \frac{m_w}{m_d} \tag{2}$$

The mass of water extracted is defined as follows:

$$m_w = m_p \left(\frac{M_{wb,i} - M_{wb,f}}{100 - M_{wb,f}} \right) \tag{3}$$

Solar dryer efficiency is the ratio of the energy consumed to evaporate the water to the energy given. It also provides the productiveness of the drying set-up. The heat supplied is the incident solar radiation which is calculated using equation 4.

$$\eta_d = \frac{m_w h_{fg}}{A_c I_{GT}} \tag{4}$$

The rate of drying is a principal parameter to representing the water removal from the tomato slices. This is determined using the equation give below:

$$DR = \frac{M_{db,t+dt} - M_{db,t}}{dt} \tag{5}$$

Where $\boldsymbol{M_{db,t+dt}}$ is the moisture content (kg water per kg dry matter) while $\boldsymbol{t + dt}$, and $\boldsymbol{t}$ is the drying time in minutes.

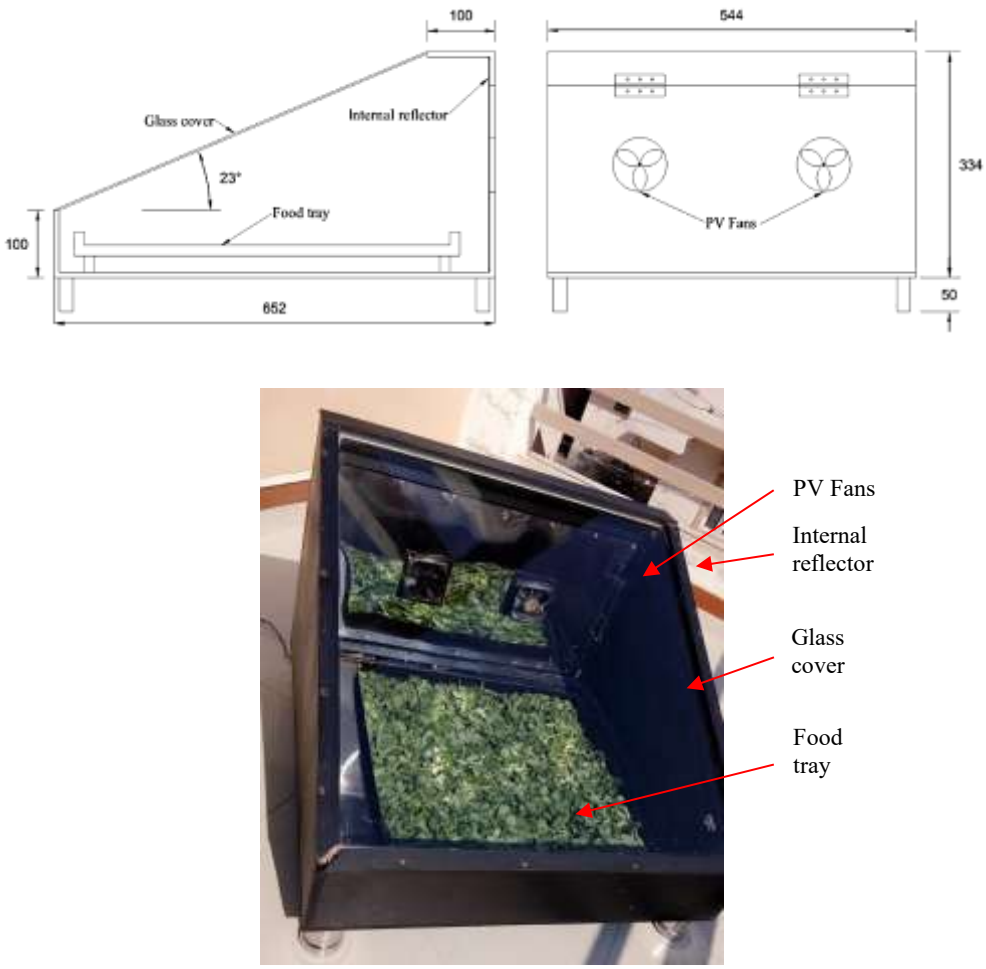

Fig. 1. Schematic and pictorial view of solar cabinet dryer with internal reflectors and solar PV fans

5 Results and Discussion

The experiments were conducted considering three cases:
Case 1: Cabinet dryer with natural convection.
Air movement in the cabinet arises from solar-induced density gradients.
Case 2: Cabinet dryer with forced convection
Two Solar PV fans in the solar dryer ensure proper airflow, maintaining optimal drying temperature for tomatoes through suction and discharge.
Case 3: Cabinet dryer with forced convection and internal reflectors
Solar PV fans and internal reflectors enhance cabinet dryer efficiency.
When sample weight was found according to final moisture content in wet basis in range of 5 to10 percentages, this was regarded as final drying weight. The initial content of moisture on wet basis was in the range of 90 to 94 percentages. The test was conducted in the month of October, 2024 at Gandhinagar (23.22° N, 72.68° E). The average solar radiation is 5.12 kWh/m^2/day. This study tries to understand the impact of the modified design of solar cabinet dryer with internal reflectors and PV fans for forced drying. Table 2 illustrates the time, moisture content as well as temperature, for different cases. It shows that the drying time for

the this modified dryer (Case 3) is less than the other cases also the final moisture content was lower compared to Case 1 and 2.

Table 2. Moisture Content of different experimental cases.

Type of experiment	Drying temperature	Drying time	Moisture content, wet basis	
			Initial	Final
Case 1	70-75 °C	18-20 hr	90.7%	9.39%
Case 2	60-65 °C	11-13 hr	92.7%	6.76%
Case 3	65-75 °C	10-12 hr	94.1%	5.76%

The results shown in Figure 2 and 3 shows the moisture content with respect to time on wet and dry basis for the three cases. For Case 3 (modified set-up) showed that tomato drying was completed in 11 hours which is 39% of time saving with respect to Case 1 which took 18 hours with higher final moisture content. According to Figure 2 and 3, the tomato dried fast in earlier hours due to free moisture in the product. Then the drying behavior was dropped down gradually. Figure 4 clearly shows that forced convection has much lower drying times compared to natural convection.

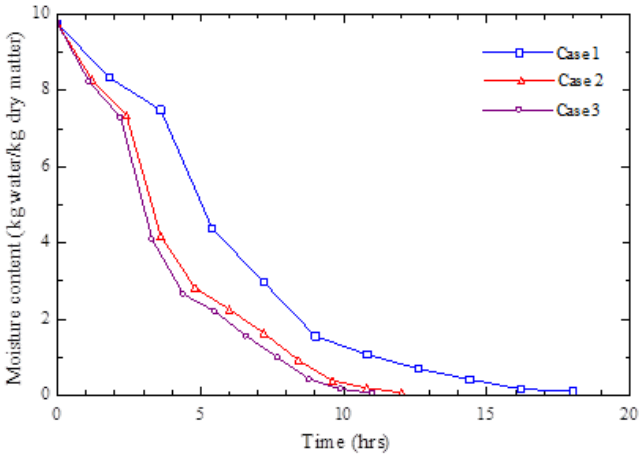

Fig. 2. Moisture content (dry basis) variation with drying time

The drying rates (DR) obtained for the different cases are given in Figure 4. DR increases with increase in air temperature as well as air circulation due to provision of solar PV fans and internal reflectors. From the curves, it is clearly indicated that the drying temperature had considerable effect on the DR. It is observed that solar drying revealed highest moisture diffusivity followed by solar cabinet drying with Solar PV fans and internal reflectors. Drying rates values were calculated from Equation (5). The drying rate and moisture content comparison is represented in Figure 5. It is observed from this figure that, drying rate decreases as the moisture content of the tomato decreased. This drying operation plays a

significant role in maintaining the quality products as well as texture, color, and essence of tomato samples. Figure 6 represents the comparison of color of tomatoes after drying in all the three cases.

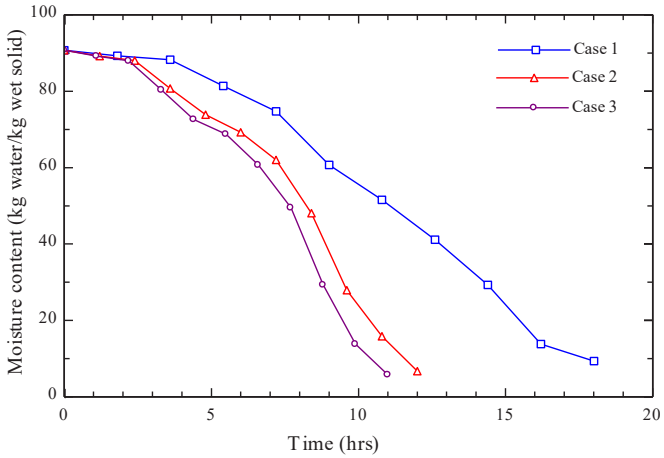

Fig. 3. Moisture content variation (wet basis) with drying time

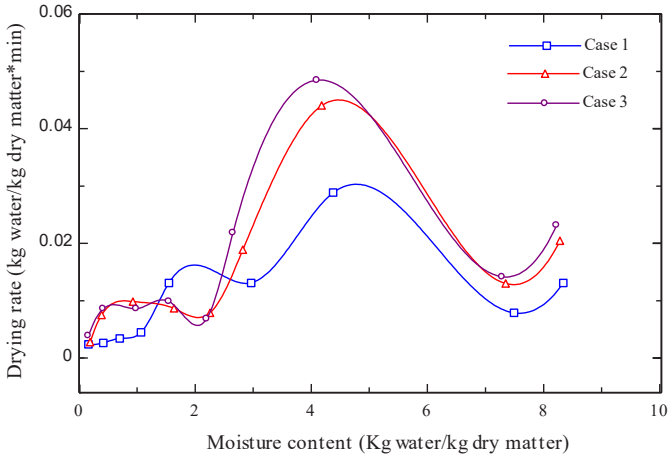

Fig. 4. Impact of drying method on drying rate and moisture content for tomato

The experimental investigations revealed that solar dryer dries 1 kg tomatoes without any auxiliary heating method to the final moisture content of 5-10 % within 11-20 hrs. Considering latent heat of vaporization for water as 2407 kJ/kg and average sun radiation as 422 W/m2 to Equation (4) obtained drying efficiency of 12.9% for conventional solar cabinet dryer, 18.9% for same dryer with forced convection and 20.4% for dryer with forced convection and internal reflector.

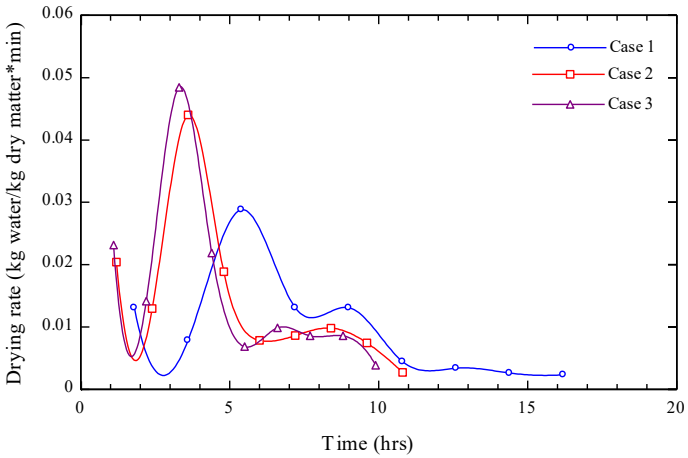

Fig. 5. The change of drying rate in the experiments

(a) natural convection (b) forced convection (c) forced convection with internal reflector

Fig. 6. Dried samples of Tomatoes

The performance parameters of solar drying configurations for tomato preservation are compared as shown in Table 3.

Table 3. Comparison of Solar Drying Configurations for Tomato Preservation.

Configuration in the present study	Drying temperature (°C)	Drying time (Hrs)	Drying efficiency (%)	Optimized Drying Quality
Cabinet dryer with natural convection (Case – 1)	73	18	12.9	Uneven coloration and a coarse texture
Cabinet dryer with forced convection (Case – 2)	63	12	18.9	Uniformity in color and texture
Cabinet dryer with forced convection and internal reflectors (Case – 3)	70	11	20.4	Natural colour with smooth and firm texture

The working of solar dryers is inherently affected by variations in solar radiation and ambient conditions, such as atmospheric temperature and humidity, which can affect drying efficiency and product quality. Higher solar radiation typically enhances drying rates by increasing chamber temperature, while lower radiation levels may extend drying times. Additionally, ambient humidity plays a critical role in moisture removal, with lower humidity facilitating

faster drying. Future studies could focus on a detailed analysis of these factors under varying environmental conditions to optimize system performance across diverse climatic regions.

6 Conclusion

Experiments were conducted in a the designed setup in order to study the drying characteristics of tomato in comparison with natural circulation solar cabinet dryer during the month of October 2024. A user friendly and economical setup was developed using materials available locally. The dryer showed effective ability in to dry tomatoes at significantly faster time in safe moisture content at a considerable rapid time while also ensured a superior texture, color, smell and test after drying. At the start, the moisture in tomato was 91-95 %. The experimental results revealed that solar dryer dries 1 kg tomatoes without auxiliary heating to the moisture content of 5-10% within 11-20 hours while the drying efficiency was varying from 12 to 20%. The developed setup with forced convection and an internal reflectors obtained the final moisture content for tomatoes in 11 hours, compared to 18 hours taken by the conventional cabinet solar dryer, resulting in a 39% reduction in solar drying time. However, the results are solely dependent on weather conditions. The dryer is easy to fabricate by any semi-skilled labor with limited manufacturing facilities. Integration of solar thermal storage would be a promising area of improvement in the dryer to store heat for use when solar insolation is insufficient due to cloudy weather conditions and during the off sunshine hours.

The first author contributed to the experimental design, and initial data collection for the study. The second author conceptualized, supervised research, offered overall guidance, and reviewed the paper for final approval. The third author focused on data analysis, interpretation of results, and manuscript drafting. The fourth author provided critical technical expertise, ensuring the accuracy of methodologies and contributing to revisions.

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