

## **PERFORMANCE ASSESSMENT OF INDIRECT TYPE SOLAR DRYER FOR *DAUCUS CAROTA* (CARROTS)**

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### **ABSTRACT**

Indirect-type dryers present an optimal solution by addressing crop preservation challenges while maintaining their nutritional quality, resulting in increased profitability for farmers. These dryers utilize both sensible and latent heat storage materials for energy retention. Comprising a solar flat plate air collector with a clear glass cover, an insulated drying chamber, and an exhaust chimney, the dryer boasts a cabinet surface area of 0.273 square meters and collector dimensions of 1.62 meters in length, 0.60 meters in width, and 0.36 meters in height. In practice, carrot slices experienced moisture reduction from 90% to 4.6% within 16 hours of drying at temperatures ranging from 41 to 47 degrees Celsius, outperforming sun drying, which achieved a moisture content reduction from 90% to 5.4% over 20 hours at temperatures ranging from 37 to 41 degrees Celsius. Efficiency testing yielded 31.5% with load tests and 65% without load tests for the collector.

**Keywords:** Collector efficiency, Chimney, Drying rate, Latent heat, Solar dryer.

### **INTRODUCTION**

Renewable energy sources have gained widespread recognition and adoption across a multitude of sectors, with solar energy emerging as the foremost contender among alternatives like biomass and wind energy (Lingayat et al., 2020). Its unparalleled accessibility sets solar energy apart, making it a cornerstone in sustainable energy practices. Solar energy is harnessed through various systems, ranging from solar stills and photovoltaic power plants to solar water heaters (Lingayat et al., 2020). These systems serve diverse purposes, but perhaps one of the most impactful applications

of solar energy lies in the realm of food preservation, especially within the food processing industry.

Solar dryers stand out as a pivotal technology in this domain, offering a sustainable solution to reduce moisture content and inhibit microbial growth in agricultural produce. Unlike traditional methods such as open sun drying, which leave crops vulnerable to uneven drying, over-drying, and contamination by insects and environmental debris, solar dryers provide a controlled environment for drying, safeguarding the quality and integrity of the produce throughout the process (Goud et al., 2019).

The versatility of solar dryers is reflected in their design variations, which can be categorized as direct, indirect, or combined types, each offering distinct advantages depending on the specific application. Direct solar drying involves exposing food to sunlight through a transparent cover, harnessing the heat directly, while indirect solar drying incorporates additional heat-absorbing materials into the process, enhancing efficiency and precision (Aghilinategh et al., 2015; Sharma, Atheaya, & Kumar, 2021).

Furthermore, the classification of solar dryers as passive or active is based on how airflow is managed within the system. Passive dryers rely on natural convection and airflow, whereas active dryers utilize fans or blowers to enhance circulation and optimize drying conditions (Chowdhury et al., 2020).

Several factors influence the performance of solar dryers, including airflow rate, supply air temperature, and environmental parameters such as relative humidity and wind speed. Understanding and optimizing these variables is crucial for achieving optimal drying outcomes and maximizing efficiency.

This study endeavors to evaluate the efficacy of an indirect type solar dryer in the agricultural landscape of southern India, where farming activities are central to livelihoods. The significance of this research lies in its potential to empower farmers and agricultural practitioners with effective drying techniques, thereby enabling value addition to their produce. By focusing on the drying of sliced carrots as a case study, this project aims to quantify the enhanced effectiveness of the solar dryer and establish its viability as a sustainable solution for food preservation and value chain enhancement in agricultural communities.

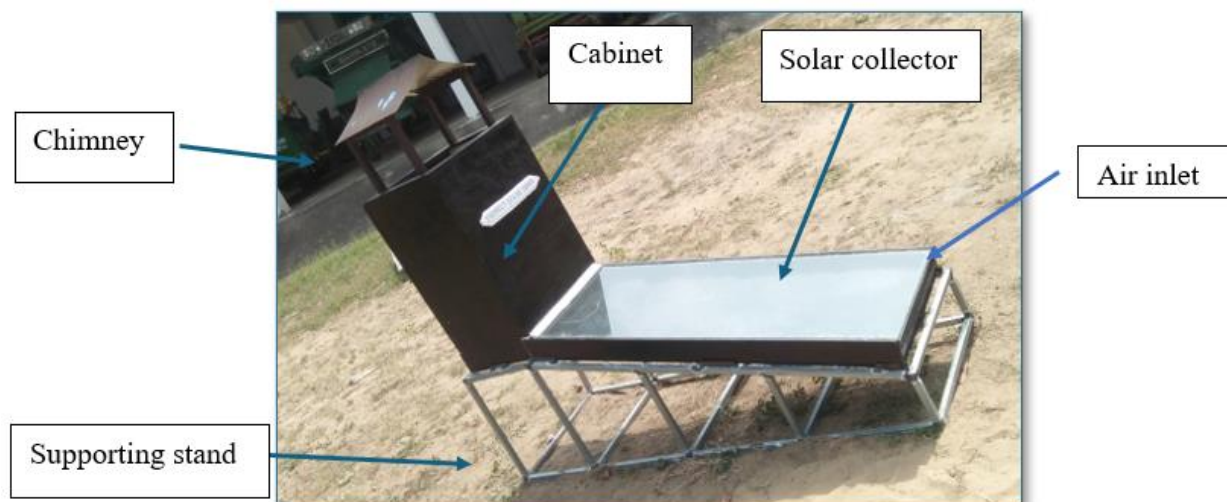
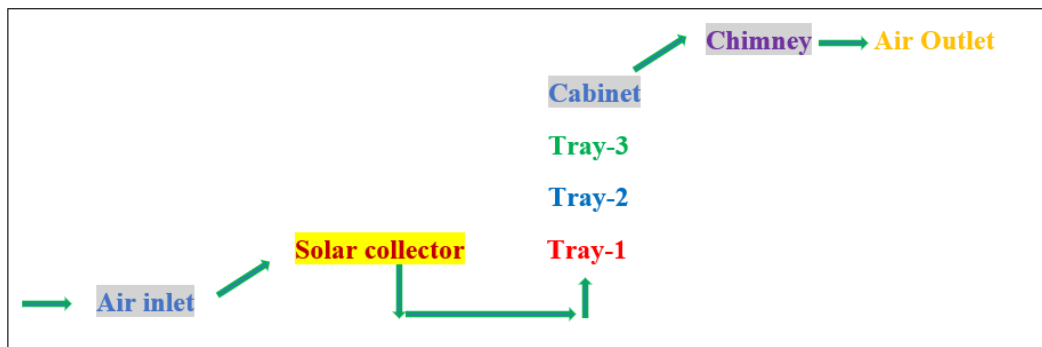
## **MATERIALS AND METHODS**

### **Experimental Setup**

Four essential parts make up an indirect solar dryer: a collector, a drying chamber, a chimney, and a frame (**Fig. 1**). The flat form of the collector has a transparent glass cover that prevents heat

loss and aids in raising the temperature. The glass walls, glass ceiling, and trays make up the drying room. An average flat plate collector's efficiency is reportedly between 25 and 45% (Klevinskis and Bučinskis, 2011). The collector area required 35% efficiency, which was 0.6 m<sup>2</sup>. The length-to-width ratio of a solar collector should be one to two, according to Forson et al. When the ratio was adjusted to 2, the collector's length and width were 1.1 m and 0.6 m, respectively. The air velocity can range from 0.51 to 5.08 m. s<sup>-1</sup> and the air collector channel depth was adjusted at 0.058. 6.38 cm was discovered to be the optimal air gap between the collection and absorber and the mass flow rate ranged between 0.02 and 0.9 kg.s<sup>-1</sup> (Irtwange and Adebayo, 2009). The specification of the design is shown below in Table.1.

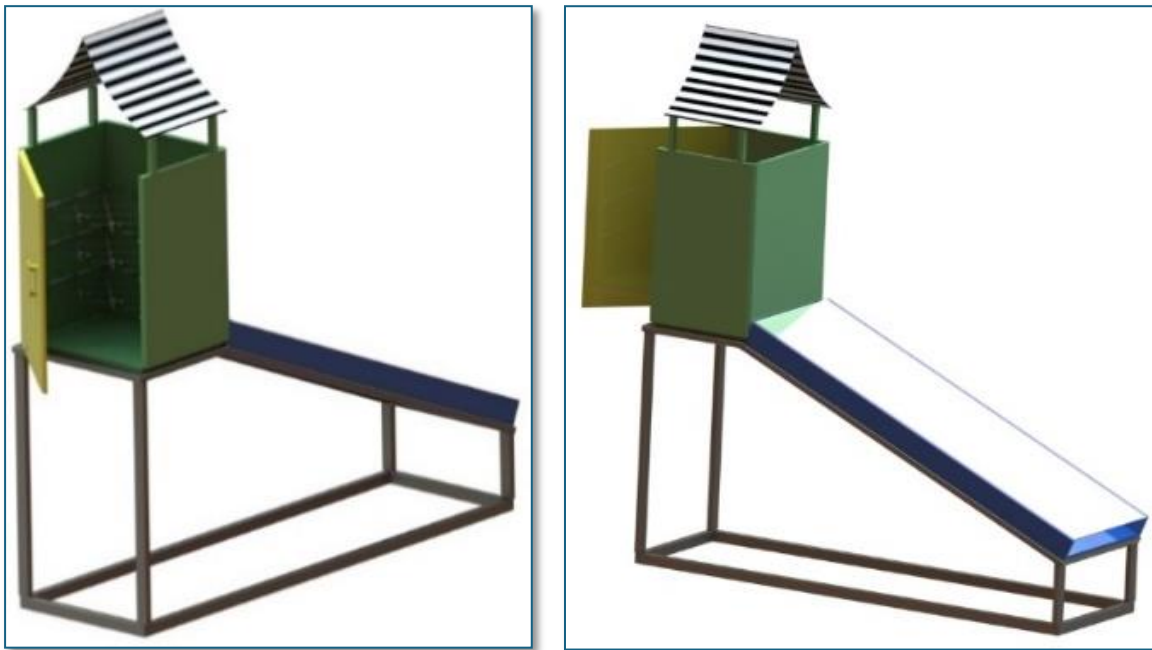
**Flow Chart** of indirect type solar dryer



**Fig. 1: Indirect-type solar dryer**

The glass collection is positioned on top of the waterproof plywood drying chamber at an angle of 13 degrees to the location's latitude. The drying room has space for three trays. The tray is made of stainless-steel mesh with a wooden frame. Air enters the collector from the bottom and travels

through the drying chamber after being heated. The drying chamber was also connected to a flattened chimney, which enhances natural circulation. Fruits and vegetables are dried more quickly and effectively thanks to natural circulation. **Fig. 2** shows a CAD representation of an indirect-type solar dryer.



**Fig. 2: Isometric view of indirect type solar dryer**

### **Experimental protocol for performance evaluation of dryer**

Experiments were conducted from 09:30 to 16:30 hours at no load and full load conditions in an indirect-type solar dryer at Bapatla (latitude 16.3613° N, longitude 80.4337° E). The following parameters viz., solar insolation, ambient temperature, and weight of carrot slices were recorded at one-hour intervals during experimentation. The drying rate, moisture content, and collector efficiency were computed to study the performance of the dryer. The amount of moisture content was determined using the Weiss and Buchinger method (Weiss and Buchinger, 2005). The drying rate is defined as the ratio of moisture removed per kg of the dry weight of material in unit time. The drying rate also commuted with the moisture content values concerning experiment time. Solar radiation helps to predict the quantify the heat available to remove water from produce. The total heat required for removing moisture from carrot slices (6,311.9 kJ) was calculated using Mercer's method.

### **Instruments Used for Data Collection**

The parameters measured during the evaluation of the indirect type solar dryer included the weight of the material to be dried, temperature, relative humidity, wind speed, and solar radiation. The air velocity was measured by using a waning type of anemometer. Solar radiation is measured by using an Ethernet radiation sensor (pyranometer). The weight of products (carrots) is measured by using a digital weighing pan.

The temperature and humidity inside the dryer and collector as well as the ambient temperature were measured by using a portable type Thermo-hygrometer. The M288CTHW thermo-hygrometer was set to record data every hour. It mainly consists of a sensor that is connected to the display through a wire. To measure the temperature and relative humidity of a particular area simply place the sensor on the surface and the readings are automatically displayed as shown in **Fig. 3**. The temperature and relative humidity were measured in each tray and collector at various places (entry, middle, and exit). Anemometer is used to measure the speed of the wind at any place. For this study, a wane-type anemometer (AM-4201) was used as shown in **Fig. 4**. It consists of a wane probe attached to a digital meter through a wire. The wane probe continuously rotates whenever air threw. To measure the wind speed, turn on the power button, and then automatically air velocity is displayed in terms of  $m.s^{-1}$ .



**Fig. 3:** Thermo-hygrometer



**Fig. 4:** Anemometer

### **Solar radiation measurement**

Ethernet solar radiation sensor device is designed to sense the radiation signal received from the pyranometer and transmit through Ethernet the total short-wave radiation measured by an external radiation sensor as shown in. RS485 interface is provided for future use. Technical features are about Power supply was 12V, Sensor input was from 0-200 mV

The temperature range varies from 30 °C to +85 °C. Make sure to follow connections. Power up the Ethernet radiation sensor with 12V 2 amp. Once the device is powered up run the finder.exe application to find out the IP address of the Ethernet Radiation Sensor as shown in Fig. 5. below.



**Fig. 5: Ethernet solar radiation sensor device and IP allocation**

Copy the obtained IP to the browser. The Ethernet solar radiation sensor home page will be displayed. Total shortwave radiation will be displayed on the home page. Every 5-8 seconds radiation data will be updated automatically.

### Drying rate

The drying rate is defined as the ratio of moisture removed per kg of the dry weight of material in unit time. The amount of moisture removed on each experiment is initially determined and then the drying rate is calculated. It is calculated for different temperatures of drying throughout the study for each day using the following formula:

$$R = \frac{dm}{d\theta} = \frac{\text{amount of moisture removed}}{\text{time taken (h)} \times \text{Bone dry weight of the sample}} \quad (1)$$

The moisture content of the carrot slices is the relationship between the moisture content present in the crop at any time ‘t’ and the initial moisture content of the food crop (Sharma et al., 2018) while drying on a tray dryer is measured. as per ASTM, 2014 standards. The sample of 20 gm is taken in the moisture box and is kept in the hot air oven at 105 °C for 24 hours and the weights are measured by using a digital weighing balance having an accuracy of 0.01 gm. From the initial and final moisture weights, the moisture content of the sample is determined and expressed in percentage (%) by using the following formula (Lingayat et al., 2021):

$$\text{Moisture content (w.b.)} = \frac{(W_1 - W_2)}{(W_1)} \times 10 \quad (2)$$

$W_1$  = Initial Weight of the sample, gm

$W_2$  = Dried Weight of the sample, gm

### Heat Energy Required to Remove Water

The amount of heat required to remove water from a product is quantified. It views drying as a two-stage process, with the first step being to raise the temperature of the wet material to the desired level, allowing the moisture to evaporate. This information is provided by:

$$Q_1 = W_w \times C_p \times T \quad (3)$$

where:  $C_p$  is the specific heat capacity of the produce (in  $\text{kJ.kg}^{-1} \text{ } ^\circ\text{C}^{-1}$ ) and

$T = T_d - T_a$ , is temperature change (in  $^\circ\text{C}$ ).

$T_d$  – drying temperature,  $^\circ\text{C}$

$T_a$  – ambient temperature,  $^\circ\text{C}$

The second stage is evaporating the moisture from the produce. As the water starts to evaporate after the product is warmed up to the drying temperature, the heat required to evaporate it is given by:

$$Q_2 = M_w \times L \quad (4)$$

where  $L = h_g - h_f$ , is the latent heat of vaporization. The values for  $h_g$  (enthalpy of water as a vapor) and  $h_f$  (enthalpy of water as a liquid) at the drying temperature are obtained from steam tables.

$$h_g = 2583 \text{ kJ. kg}^{-1}$$

$$h_f = 188 \text{ kJ. kg}^{-1}$$

Therefore, the total heat requirement is 6,311.9 kJ.

The collector efficiency was determined using solar radiation and temperature values at no load and load conditions. The collector efficiency is a dimensionless parameter that measures the ratio of heat output from the inlet to the heat input from the solar collector surface at any given time. It is a time-varying parameter and depends on insolation, collector area, and the quantity of heat extracted from the heated air per unit of time.

$$\eta_c = \frac{\vartheta \rho \nabla T C_p}{I_c A_c} \times 100 \quad (5)$$

$\vartheta$  is the Volumetric flow rate of air,  $\text{m}^3.\text{s}^{-1}$ ;

$\rho$  is the air density,  $\text{kg.m}^3$ ,

$T$  is the Air temperature elevation,  $^\circ\text{C}$ ,

$C_p$  is the air-specific capacity,  $\text{J.kg}^{-1}\text{ } ^\circ\text{C}^{-1}$ ;

$I_c$ – Insolation on collector surface,  $W.m^{-2}$ ;

$A_c$ – Collector area,  $m^2$ .

Statistical analysis was also performed based on ANOVA to validate the drying results of carrot slices.

### **Sensory analysis of dried carrot slices**

The quality of dried carrot slices obtained from drying under the open sun and indirect type solar dryer was analysed using sensory evaluation such as appearance, colour, taste, flavour, mouth feel, and overall acceptability (Palipane, 2012; Noutfia *et al.*, 2021). 30 untrained panel members were selected from academic staff, students, and technicians from the university. The dried samples were coded and placed randomly and were evaluated by the panelists for sensory analysis viz. colour, taste, mouth feel, flavour, and overall acceptance of dried carrot slices using a five-point hedonic scale where 2 is disliked and 3 is extremely like. The panel members were instructed to clean the mouth palate with water after assessing each sample before accessing the next sample.

## **RESULTS AND DISCUSSION**

The dryer tested for no-load and load conditions the results obtained are summarized. The average sun irradiation was  $340.8 W.m^{-2}$ , according to observations taken by the Meteorological Services Department. The test location's ambient temperature,  $T_a$ , was found to be  $25\text{ }^{\circ}C$  with a relative humidity of 70 %. The drying temperatures of fruit and vegetables should vary between  $37.7$  to  $54.4\text{ }^{\circ}C$  (Afolabi, 2014). Higher temperature drying causes sugar caramelization or browning of sugar in the products. Hence an average drying temperature of  $45\text{ }^{\circ}C$  was considered for drying carrots in this dryer.

### **No load tests**

In this test solar radiation, air flow rate, and temperature increased because of a free circulation of air through all the trays. The maximum average temperature inside the dryer during no load test was found to be  $62^{\circ}C$  corresponding to the drying time of 12:30 pm, and corresponding solar radiation was found to be  $756 W. m^{-2}$  from this it can be concluded that the temperature inside the dryer was suitable for drying of carrot as shown in Fig.6.

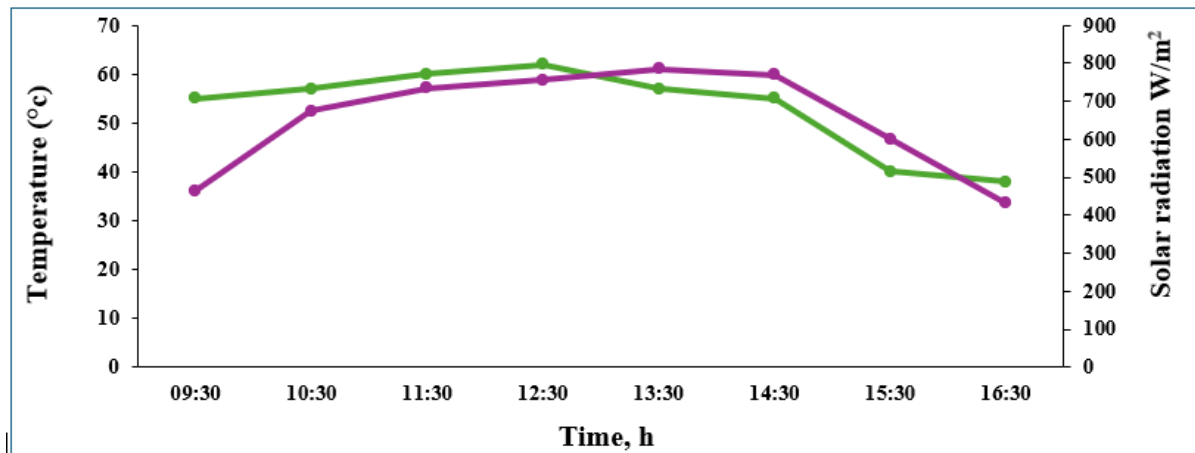


Fig. 6: Solar radiation and temperature against time at no-load condition

### Full load test

The maximum temperature inside the dryer during the load test was 47°C in tray-1 to at 12:15 pm, corresponding solar radiation was found to be 550 W m<sup>-2</sup>, during day 1. The maximum temperature inside the dryer during the day<sup>-2</sup> load test was 47°C in tray-1 to at 12:15 pm, and corresponding solar radiation was found to be 574 W. m<sup>-2</sup> as shown in Fig.7. The effectivity of the drying rate was increased in the afternoon section when compared with the morning and evening times on both days. Tray-1 has got more temperature as well as solar radiation because the airflow was started from tray-1, the remaining trays got less radiation and temperature. The weight increased in trays then the capacity of drying was reduced the temperature, and solar radiation was reduced even though the air flow rate was more (Lee, 2013; Wu, Zhang and Li, 2019).

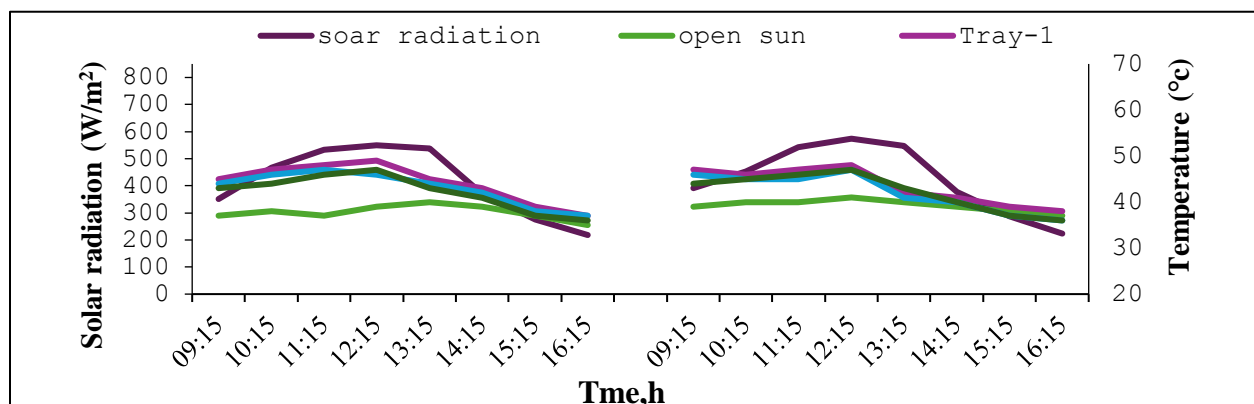
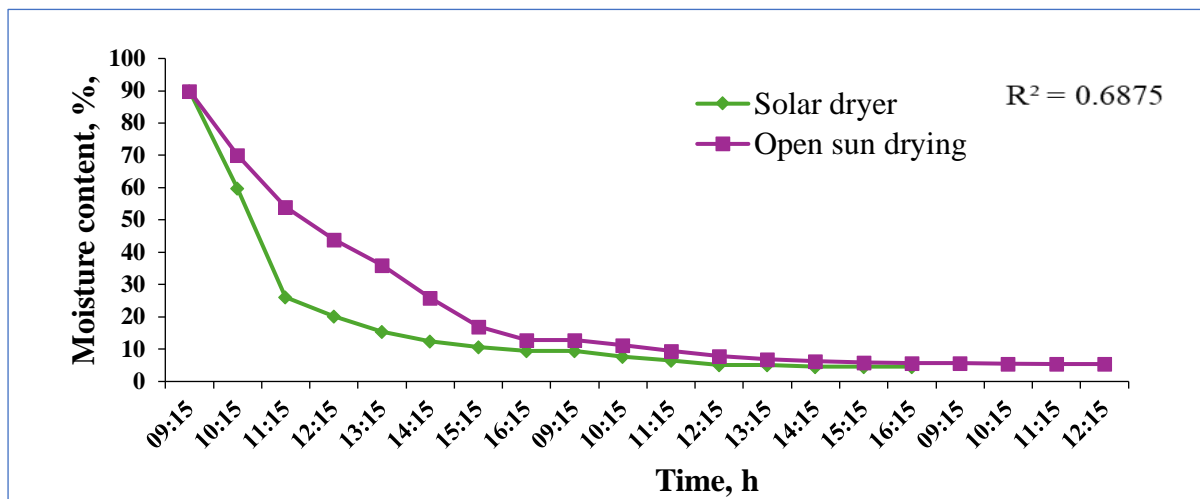


Fig. 7: solar radiation and temperature against time at load condition

**Variation of drying rate and moisture content with time**

From Fig. 8. open sun-drying took 18 hours to dry the given carrot sample during the full load test, whereas solar dryer took 14 hours to dry the given sample as shown in the above graph. The maximum moisture content in the sample was 90% on a weight basis it was reduced to 5 % as it is safe for storage of carrots. The temperature has a reminiscent effect on drying time (Abideen *et al.*, 2019). The regression between moisture and time was 0.6875 so, nearly got results as earlier mentioned. Moisture content was reduced when the effectiveness of solar energy absorption is more.



**Fig. 8: the moisture content of solar dryer and sun drying against time**

The amount of moisture vaporized over a specific period is known as the drying rate. The expression for drying rate (Sharma, Atheaya and Kumar, 2021). The maximum drying rate inside the solar dryer was 168 gm per hour whereas in the open sun drying it was 100 gm per hour from this; we can say that more drying rate inside the dryer leads to faster and more efficient drying. The regression value was 0.48 because of the slight variation between open and indirect type solar dryer. The relation between solar drying and open sun drying varies due to the environmental factors in open sun-drying that can affect the carrots because sometimes the drying rate increases and sometimes decreased due to uncontrollable solar energy, and the appearance, taste, and quality were very low when compared with the solar dryer which has designed and fabricated depends on all the effects of sun drying as shown in Fig. 9. The drying rate based on varied air flow rate and carrot thickness is tabulated in Table 2.

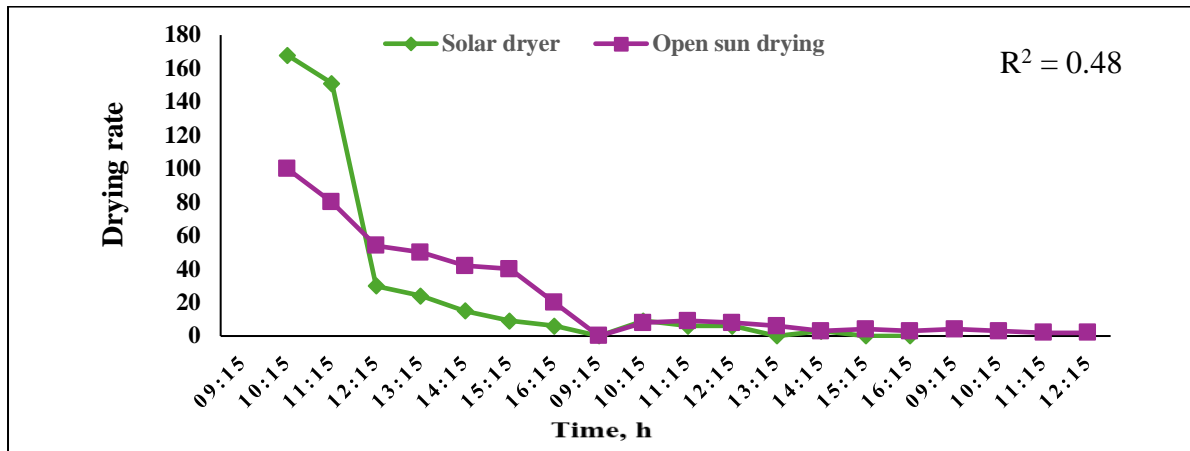


Fig. 9: drying rate and time

Table 1: Drying rate on different air flow rates and carrot thickness

Air flow rate, (m. s <sup>-1</sup> )	Carrot thickness, (2 mm)	Carrot thickness, (2.5 mm)	Carrot thickness, (3 mm)
2.4	70	60	54
	67	61	56
	68	63	57
	78	74	70
3.7	75	71	73
	80	75	71
	88	83	80
4.1	90	80	81
	86	82	83

From the experimentations at the varied air flow rates, it is inferred that the drying rate varies from 54 to 90 kg. h<sup>-1</sup>. The minimum and maximum drying rates were found at 2.4 m. s<sup>-1</sup> airflow rate for 3 mm thick carrot slice and 4.1 m. s<sup>-1</sup> airflow rate for 2 mm thick carrot slice. Thickness increased then airflow increased which led to a decreased drying rate. The thickness is reduced, the airflow rate is increased then the drying rate also increased (Aghilinategh *et al.*, 2015; Raj and Jayaraj, 2021).

### Efficiency of Dryer

The overall drying efficiency of the indirect type solar drying (ITSD) system is the fraction of thermal energy utilized to vaporize moisture from the crop by the system to that of thermal energy accumulated by the solar collector (Irtwange and Adebayo, 2009) The efficiency of the collector

was calculated using the no-load test and was found to be 31.7 %. The collector efficiency under load conditions was found to be 65.81%. Typical flat-plate collector efficiency should be between 25 and 65% (Beikircher *et al.*, 2014). After 1 hour, the minimum temperature for three trays was found to be 37°C, and the minimum temperature obtained for open sun drying was 35.5°C (Vigneshkumar *et al.*, 2021). At 10 h, the maximum temperature received by three trays was 48 °C. However, open sun drying receives lower temperatures than solar drying after 12h was found to be 40.6 °C. Open sun drying will receive low temperature after drying for a long period in the sun (Seshachalam, Thottipalayam Velliangiri and Selvaraj, 2017). The collector efficiency based on different air flow rates and carrot thicknesses is tabulated in Table 2.

**Table 2: Collector efficiency on different air flow rates and carrot thickness**

Air flow rate, (m. s <sup>-1</sup> )	Carrot thickness (2 mm)	Carrot thickness (2.5 mm)	Carrot thickness (3 mm)
2.4	45	40	36
	42	44	38
	40	43	39
3.7	58	54	47
	55	51	43
	50	50	45
4.1	68	63	60
	65	60	58
	63	66	62

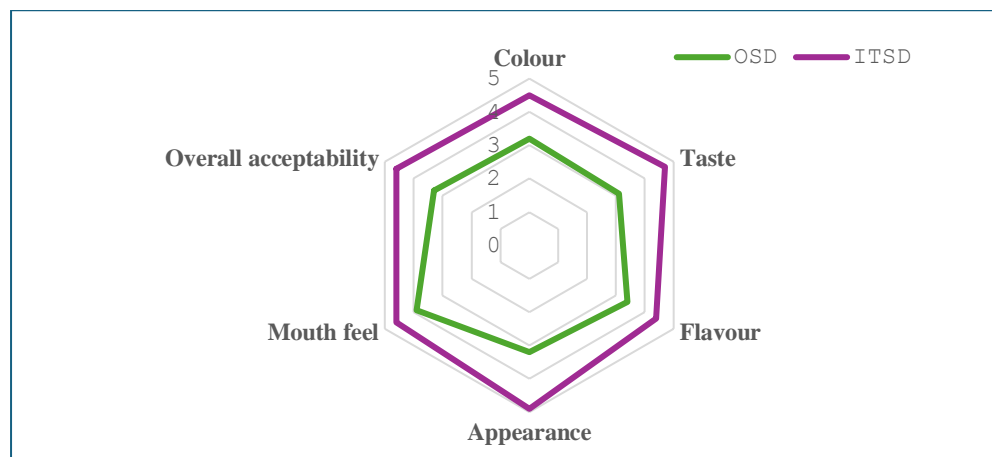
From the results at different airflow rates, the collector efficiency of the indirect-type solar dryer ranged from 36 % to 68 %, with the highest efficiency observed at 4.1 m s<sup>-1</sup> for 2 mm thick carrot slices and the lowest at 2.4 m s<sup>-1</sup> for 3 mm slices. These values are higher than those reported for many conventional indirect flat-plate solar dryers, which typically achieve efficiencies between 30 % and 45 % for drying vegetables and fruits (Irtwange and Adebayo, 2009; Lingayat *et al.*, 2020). Mixed-mode solar dryers, which utilize both direct solar radiation and preheated air, have been reported to reach overall efficiencies of 50 %–60 %, offering faster drying rates but requiring more complex designs (Goud *et al.*, 2019). In contrast, simple direct-cabinet or tunnel-type dryers generally exhibit lower thermal efficiencies, often below 35 %, due to exposure to uncontrolled environmental conditions and less effective heat transfer (Vijayan, Arjunan and Kumar, 2020). The comparatively higher efficiency in the present study can be attributed to optimized airflow, proper tray loading, and effective insulation, which enhance heat transfer from the collector to the drying chamber.

**Statistical analysis**

The performance of indirect dryer to dry carrot slice is analysed statistically based on drying rate and collector efficiency concerning air flow rate and carrot slice thickness (Supplementary Tables 1 and 2). The degrees of freedom for drying rate and collector efficiency were 2 to 26. The interaction of air flow rate and carrot slice thickness shows significant results in enhancing the drying rate and collector efficiency. Numerous researchers used the evaluation criteria of the solar dryer based on efficiency and drying rate (Izli, Izli and Taskin, 2018). This experimentation showed that air flow rate and carrot slice influence the performance of the dryer. Solar radiation can heat the air effectively at higher airflow with a low thickness of commodity. This indirect dryer is a more efficient and feasible technology to dry the food commodity to meet the energy demand and supply gap.

### Sensory Analysis

Sensory evaluation was carried out between open suns drying and indirect type solar dryers between colour, taste, flavor, appearance, mouth feel, and overall acceptability. All the sensory analysis parameters were better in indirect-type solar dryers than in open-sun dryers. The overall acceptability was higher in the indirect solar dryer than in the open sun drying (Barrientos *et al.*, 2019; Mohammed, Edna and Siraj, 2020). Overall protection from the environmental factors to carrot slices is very good in indirect type solar dryers than in open sun dryers. It is shown in Fig. 10.



**Fig. 10: sensory analysis chart**

**Economic feasibility Analysis**

<b>Component/Parameter</b>	<b>Estimated Cost (Rs.)</b>	<b>Remarks</b>
Flat plate collector	25,000	Includes glass, absorber plate, insulation
Drying chamber (wood + insulation)	15,000	Plywood and thermal insulation
Trays and accessories	5,000	Stainless steel mesh trays (3 units)
Miscellaneous (frame, chimney, sensors)	5,000	Airflow management, mounting
<b>Total Initial Investment</b>	<b>50,000</b>	
Operational cost per cycle	500	Cleaning and maintenance only
Productivity improvement	20–25% faster	Reduced drying time increases throughput
Postharvest loss reduction	10–15%	Better quality and less wastage
Estimated payback period	1–2 cropping cycles	Depending on crop scale and market price

The analysis indicates that the indirect solar dryer is economically feasible, with a payback period achievable within 1–2 cropping cycles. By lowering postharvest losses and enhancing product quality, the system improves profitability while promoting energy-efficient and sustainable agricultural practices. Adoption of this technology can provide tangible benefits to small- and medium-scale farmers by enabling value addition and better market competitiveness.

**CONCLUSIONS**

The study demonstrates that the indirect-type solar dryer designed—with a cabinet area of 0.273 m<sup>2</sup> and a flat plate collector of 1.62 m × 0.60 m × 0.36 m—can effectively reduce the moisture content of carrot slices from 90% to 4.6% within 16 hours. This represents a substantial improvement over conventional open sun drying, which required 20 hours under slightly lower temperature conditions (37–41 °C) to achieve the same moisture reduction. The dryer maintained optimal drying conditions, with chamber temperatures reaching up to 47 °C and relative humidity dropping to 20%, are indicating that the system creates an environment conducive to rapid moisture removal while preserving product quality.

The measured average collector efficiency of 73.14% and drying rate of 51.30% highlight the system's capability for energy-efficient drying. The variation in collector efficiency under load (31.5%) versus without load (65.81%) suggests that further optimization of air flow, insulation, or collector design could improve performance consistency during active drying.

The indirect solar dryer has several advantages: it reduces drying time and dependency on weather conditions, minimizes postharvest losses and ensures better product quality compared to open sun drying. This makes it suitable for small- and medium-scale agricultural applications, especially for farmers and processors looking to extend shelf life and marketability of perishable vegetables like carrots.

Potential improvements include enlarging the collector surface area or enhancing its thermal properties to increase heat capture, implementing automated airflow control to maintain uniform drying and exploring hybrid designs integrating solar with low-grade auxiliary heating to ensure consistent performance during cloudy days or peak demand. Adoption of such improvements could further increase energy efficiency, reduce drying times and expand the applicability of the system for other fruits and vegetables.

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