Development of a Hybrid Solar Dryer for Tomato Preservation in Ikole-Ekiti, Nigeria.

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ORIGINAL RESEARCH

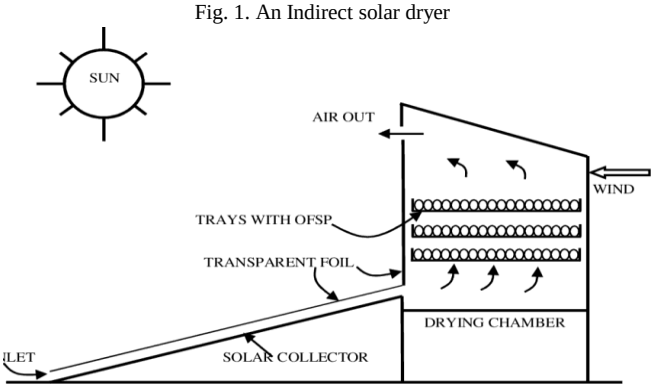
Abstract— Solar dryer technology is considered a viable alternative method to the traditional means of drying. It helps maintain a clean and hygienic means of food drying, while achieving sustainability. This paper emphasizes the effectiveness of a hybrid solar dryer in food preservation. Most parts of Ekiti State, especially Ikole-Ekiti adopt the traditional means of drying food materials, which poses a risk of food contamination, poisoning and post-harvest losses. These numerous challenges demand a strategic approach towards quality food preservation through sustainable drying technologies. Hence, the hybrid solar dryer was developed to improve on existing types of indirect solar dryer; by combining an auxiliary heater to speed up the drying process; during low solar radiation intensity. The drying process is achieved through convection mode of heat transfer, using a solar collector and a drying chamber with a centrifugal fan, to remove moisture from the food material loaded. This research elaborates on the design of a location-specific dryer system valuable for food processing within the community, and it's environs, while incorporating the use of stored energy from a solar panel and a battery pack to facilitate the drying process during nighttime and humid weather condition. Analysis performed shows that an average of 3 kg of tomato slices could be dried from approximately 94% (wb) down to an average of 11% (wb) within 30 hours. It was found that the ambient air recorded an average value of 38.5ºC, while the average temperature of the solar collector is 48.1ºC, with a dryer efficiency of 20.9%. Therefore, the auxiliary heater was found to effectively improve the performance of the solar dryer by supplying heated air above ambient air temperature, during periods of limited solar radiation.

Keywords— Hybrid Solar-Dryer, Heat Transfer, Renewable Energy.

1 INTRODUCTION

Drying is one of the most ancient methods of food preservation using solar energy, where agricultural and marine products such as vegetables, fruits, fish, and meat are dried through direct exposure to heated air (El-Sebaii & Shalaby, 2011, There & Sharma, 2024). It involves the removal of moisture from food products to achieve required storage and quality standards (El-Mesery et al., 2022). Open-sun drying remains economically attractive for large-scale applications due to its low operating costs compared to mechanical drying systems. However, this method poses several disadvantages, including contamination from rain, wind, dust, insects, animals, and microbial infestation, leading to quality deterioration and post-harvest losses (Saini et al., 2023, Kong et al., 2024). The challenges outlined above is the exact for Ikole-Ekiti, where the solar dryer was constructed and tested. To address these limitations, a solar dryer technology was considered a viable alternative capable of providing a more hygienic drying environment. Solar dryers enhance energy efficiency, reduce labour requirements, increases the shelf life of products, shorten drying time, and require less surface area for product spreading, thereby improving process efficiency and environmental sustainability (Mugi et al., 2022, Hadibi et al., 2021). Solar dryers are generally classified into three main categories: direct, indirect, and mixed-mode systems, depending on whether the product mixed-mode systems, depending on whether the product is exposed directly to solar radiation or heated air from a collector (Khanlari et al., 2022). An indirect solar dryer typically consists of a drying chamber and a solar collector as shown in Figure 1 of this study. Solar energy is harvested by a separate unit called a solar collector, which is covered with a transparent layer made of glass or durable plastic. The collector heats the air that is then circulated into the drying chamber, where the product are arranged (Kalita & Singh, 2026). The drying process occurs primarily through convective heat transfer between the heated air and the moisture in the product (Fernandes & Tavares, 2024). The product is not exposed directly to solar radiation, which helps minimize surface *discoloration, cracking, and overall quality deterioration (S. Singh et al., 2021, Suresh et al., 2023).*

Fig. 1. An Indirect solar dryer



The novelty of this research is that it combines both the Indirect and active solar dryers, and an auxiliary heating system to support continuous drying during night-time, humid conditions and rainy season, hereby providing a location-specific hybrid solar drying solution tailored to the climatic conditions of Ikole-Ekiti, where limited drying performance data currently exists.

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2 Materials and Methodology

This study was conducted at Ikole-Ekiti, Federal University Oye-ekiti, Nigeria. An indirect hybrid solar dryer in active mode was designed and constructed. The dryer consists of four components; a flat plate collector, an air duct, a food drying chamber and an auxiliary heater. The dryer uses the sun as a source of energy. However, an auxiliary heating system which consists of a 180Watt mono-crystalline solar panel, 12V DC battery and a filament bulb, integrated to enable the drying process continue during nighttime as well as periods of low solar radiation.

2.1 Materials

2.1.1 Solar Collector

The size of the collector was 112 × 51 cm. It consists of three components: a transparent cover, two absorber plates and insulation. The transparent cover is made from a single layer glass of 4 mm thickness. Aluminum sheet of 0.15 mm thickness, painted black, was used as absorber. The collector casing was made of plywood.

2.1.2 Drying Chamber

The drying chamber is made of plywood and lined with aluminum foil on the inside to reduce accumulation of moisture on the surface of the drying chamber which can result in moisture absorption by content meant to be dried. It consists of racks for five trays, each with size of 42 × 24 cm, for the product to be dried. The trays were made of aluminum wire mesh supported with wood on the edges. The drying chamber is covered with aluminum sheet on the exterior to resist water penetration and prevent direct heat concentration on the plywood.

2.1.3 Air Duct

The air duct connects the flat plate collector to the drying chamber, and its main purpose is to facilitate the transfer of the heated air from the solar collector to the drying chamber. The air duct is made up of stainless-steel pipe, elbow-joints and a blower fan which forces the heated air through the air duct into the drying chamber under a high velocity. The blower fan is a 12V DC fan; it is made of polypropylene material which makes it safer for such a range of temperature. The air duct is lagged on its exterior with insulation material and aluminum foil on the external surface to prevent leakages, heat loss and direct contact with moisture.

2.1.4 Chimney (Exhaust)

The exhaust is located on the left side of the drying chamber, two lateral holes of 8 cm and 5 cm respectively. Zinc metal sheet was fabricated into a panel with arrays of air gaps on its surface. The exhaust is situated on the opposite side of the air inlet which enhances moisture removal from the drying chamber.

2.1.5 Auxiliary Heater

The auxiliary heater is powered by a "180 Watt" mono-crystalline solar panel, harvesting solar energy from the sun during period of high solar radiation intensity and stored in a 12V DC battery. The battery is used to power the filament bulb located in the collector during night-time.

2.2 Design Procedures

The design of the solar dryer took into consideration different parameters and design criteria as shown in Table 1. Some of these parameters were determined using a series of mathematical calculations. The drying is done at a controlled temperature due to the quality of products required from the process. Therefore, the materials used are based on specifications and availability.

Table 1: Design Parameters and Criteria for the Dryer

Parameter	Symbol	Unit	Design Criteria	Purpose
Initial Mass of Tomato	W_i	kg	3 kg	Quantity of fresh product
Final Mass of Tomato	W_f	kg	0.21 kg	Desired dried product mass
Initial Moisture Content	M_i	% wb	95 % wb	Moisture level before drying
Final Moisture Content	M_f	% wb	15 % wb	Safe storage moisture content
Drying Temperature	T_d	°C	45°C	Prevent nutrient degradation
Ambient Temperature	T_a	°C	25°C	Environmental operating condition
Solar Radiation Intensity	I	W/m^2	400 -900 W/m^2	Available solar energy
Collector Area	A_c	m^2	0.64 m^2	Solar heat absorption surface
Air Velocity	V_a	m^3	0.51 m/s	Moisture removal enhancement
Drying Time	t	m/s	30 - 40 hr	Time required for drying
Collector Efficiency	η_c	%	35%	Thermal performance of collector
Dryer Efficiency	η_d	%	20 - 30 %	Overall drying effectiveness
Auxiliary Heater Power	P_h	W	200 W	Backup heat supply
Number of filament Bulbs	N_b	-	1 - 2 bulbs	Supplemental heating
Fan Voltage	V_f	V	12 V DC	Forced convection airflow
Fan Power	P_f	W	10 - 20 W	Air circulation
Tray Material	-	-	Aluminium mesh	Hygenic food support
Glazing Material	-	-	Glass	Solar radiation transmission
Tilt angle of collector	θ	Degree	30°	Maximum solar absorption
Heat Source	-	-	Solar + electric hybrid	Continuous operation
Airflow Mechanism	-	-	Forced convection	Improved drying uniformity

2.2.1 Drying Temperature

Rizalman et al., (2023) recommended drying temperatures for fruits and vegetables in solar dryers to be maintained within the range (38–55°C), depending on the type of product, to avoid nutrient loss, sugar caramelization (browning of sugar), or warping and discoloration of fruit products when dried. Hence, for this dryer, an average drying temperature, Td, of 45 °C was considered.

2.2.2 Quantity of Moisture to be Removed

The amount of moisture to be removed from a product according to Mujumdar, (2014) and Kumar and Prakash (2017), can be calculated as:

$$M_w = \frac{w_w(M_i - M_f)}{1 - M_f} \quad (1)$$

Where: M_w is amount of moisture removed;
W_w is initial weight;
M_i is initial moisture content on wet basis;
M_f is final moisture content on wet basis;

The quantity of material to be dried is dependent on the drying capacity of the dryer. In this study, the dryer has five trays and is intended for experimental purposes, an initial batch of 3kg was considered for design calculations. Fresh tomato was selected as the test product, with an initial moisture content of approximately 94% wet basis and a final moisture content of 15% wet basis, consistent with recommended ranges for quality preservation (Oladipo et al., 2025). Using Equation (1),

$$M_W = \frac{3\ kg \times (0.94 - 0.15)}{1 - 0.15} = 2.79kg$$

2.2.3 Heat Required for Moisture Evaporation

The drying process involves two major stages: heating the wet product to drying temperature and evaporating

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the moisture. The heat required to raise the temperature of the product can be calculated as:

$$Q_1 = W_w \times C_p \times \Delta T \quad (2)$$

Where: Cp is the specific heat capacity of the produce (in KJ/ kg°C) and
$\Delta T = T_d - T_a$, is temperature change (in °C).
Specific heat capacity of a food material can be determined using the following equation:

$$C_p = 1.424\, m_c + 1.549\, m_p + 1.675 m_f + 0.837\, m_a + 4.187\, m_w + 2.0505\, m_i \quad (3)$$

where: m_c is mass fraction of carbohydrate,
m_p is mass fraction of protein
m_f is mass fraction of fat
m_a is mass fraction of ash
m_w is mass fraction of water
m_i is mass fraction of ice

Using these values in equation (3) gives Cp = 3.81 kJ/kg°C. Hence,

$$Q_1 = 3\ kg * 3.81 \frac{kJ}{kg^oC} \times (45 - 25)^oC = 228.6\ kJ$$

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

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

$L = h_g - h_f$, is latent heat of vaporization. The value for h_g (enthalpy of water as a vapour) and h_f (enthalpy of water as a liquid) at the drying temperature are obtained from steam tables (Cengel & Boles, 2015).

h_g = 2583 kJ/kg
h_f = 188 kJ/kg
Q_2 = 2.79 kg × (2583 – 188) kJ/kg = 6682.1 kJ

Therefore, the total heat requirement = $Q_1 + Q_2$ = 228.6 kJ + 6682.1 kJ = 6910.7kJ. This value obtained is the theoretical value. It does not take into account the heat lost through the walls of the dryer or the heat leaving the dryer through the exhaust. Though, the components are adequately insulated to prevent heat loss.

2.2.4 Solar Collector Design

The daily average insulation of Ikole-Ekiti is taken to be 4500 Wh/m² to 5300 Wh/m² and is rarely below 30°C during day-time and 21°C during night-time. Menya et al., (2025) reported that the efficiency of a flat-plate collector ranges between 30% and 50% under ambient temperature condition of 25°C and solar radiation intensity, I = 400 W/m². The collector efficiency is mainly influenced by factors such as air flow rate, temperature, thickness of insulation, types of transparent material, quality of absorber plate and insulator used (Özden & Kaya, 2025). To achieve an optimal design, an average value of 35% was considered as design parameter for collector efficiency. As a result,

Daily expected energy production by the collector = 15.48 MJ/m²/day × 0.35
= 5.42 MJ/m²/day
For a drying period of 2 days, the energy production would be
= 2 × 5.42 = 10.84 MJ/m²
Since the total heat energy required for drying is 6.91 MJ,

$$\text{Collector Area} = \frac{6.91\ MJ}{10.84 \frac{MJ}{m^2}} = 0.64\ m^2 \quad (5)$$

Hence, the parameter for the collector area was approximated to 0.6 m². Al-Juamily et al., (2007) suggested the length-to-width ratio of a solar collector to be 1 – 2. Considering the ratio to be 2 for this design, the length and width of the collector was 1.1 m and 0.5 m, respectively. However, the calculations done are approximated to fractions that are suitable during construction.

2.2.5 Solar Collector Orientation and Tilt Angle

For this design, since the test location is Ikole-ekiti (Latitude 7°47'53.76"N and longitude 5°30'52.17"E), a collector tilt angle of 30° was used and due to the position of the flat plate collector with respect to the drying chamber, the flat plate collector was made to rise above the top of the drying chamber in order to allow an appreciable amount of airflow get into the air gap. This also help to avoid the accumulation of rain water on the collector during rainy periods.

2.2.6 Air Flow Requirement for Drying

Mkhize, (2025) recommends the range for air velocity to be between 0.15 m/s to 5.0 m/s. In addition, the depth of the air channel should be 1/15 to 1/20 of the length of collector. Taking the average factor of the depth of the air channel (0.058) and multiplying by the height of the collector gives the air channel depth (Sun et al., 2010).

Depth of air channel = 0.058 × 1.1 m= 0.0638 m = 6.38 cm

Also, Embarek, (2025) applied a new approach by optimizing the maximum air gap between the absorber and the transparent cover with gap variation between 3 cm and 12 cm. The calculated air gap of 6.38 cm falls within this range, but 8 cm air gap was used for this design in order to accommodate two layers of the absorber plate stacked on top of each other.
Hence,
Vent Area = width of collector × air gap
= 51 cm × 8 cm = 408 cm² = 0.0408 m²

For an air velocity of 0.51 m/s,
Volume flow rate = Vent Area × Air Velocity (6)
= 0.0408 m² × 0.51 m/s = 0.0208 m³/s
Mass flow rate was determined by multiplying the volume flow rate by the density of air, 1.2 kg/m³, yielding 0.025 kg/s. The solar dryer was designed to perform efficiently at a faster drying rate. Figure 2 represents the hybrid solar dryer developed for tomato preservation.

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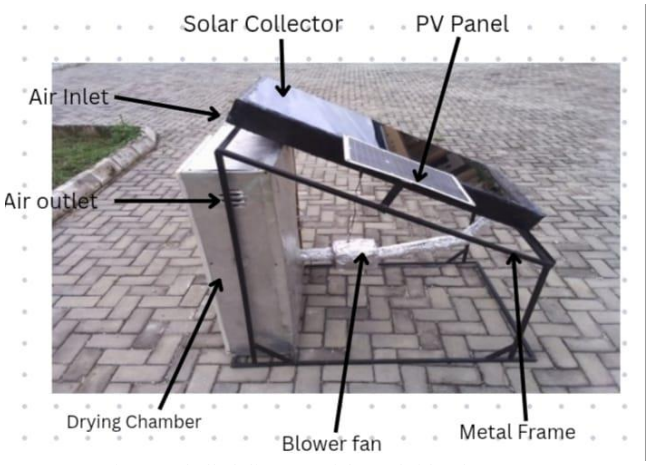

Fig. 2. Labelled diagram of the Hybrid Solar Dryer.

2.3 Experimental Methodology

The following experiments were conducted using the hybrid solar dryer to determine its drying characteristics, collector performance and moisture removal capability. The experiments were performed under the climatic conditions of Ikole-Ekiti using tomato slices. The major experiments conducted included drying performance test, drying air temperature measurement, collector efficiency evaluation and moisture content determination.

1) Drying Performance Test: Digital thermometers and data loggers were used to monitor temperature variation during the drying period. Fresh tomato samples was purchased from a local market in Ikole-Ekiti, they were washed, sliced and arranged on the trays in the drying chamber. Readings were recorded at one-hour intervals, and measured temperatures were used to evaluate the thermal performance of the dryer.
2) Drying Air Temperature: Temperature measurements including ambient air (T_a), collector temperature (T_c) and drying chamber temperature (T_d).
3) Collector Efficiency: Experimental readings were obtained at regular intervals during peak sunshine hours. Apparatus such as Solar collector and Digital Anemometer were used.
4) Moisture Content Determination: A digital weighing balance and drying trays were used to weigh the tomatoes before and after drying, for the 30-hour drying period.

3 Result and Discussion

The temperature recorded in the drying chamber and the solar collector were much higher than the ambient temperature during most hours of the day. The temperature inside the drying chamber was found to be highest (48.1 °C) at 1pm, while for the auxiliary heater (54°C). The rate of drying is evaluated to be higher in the hybrid mode compared to direct solar drying. The higher temperature and lower humidity favours better drying without much change in colour of the tomato samples.

3.1 Tomato Drying Performance Test

During this test, the dryer was mounted. The digital weighing balance was used to periodically measure the weight of the tomatoes, all stacked in a pile. Initial total weight (W_w) was marked at 3kg, while the final total weight (W_f) of 0.21kg was obtained. The moisture loss percentage is 93%, and the time range is 30 Hours. Higher moisture reduction rates were observed during periods of peak solar radiation intensity between 11:00 AM and 2:00 PM. The reading was plotted at intervals of 1 hour. The result is represented in Figure 3 and 4:

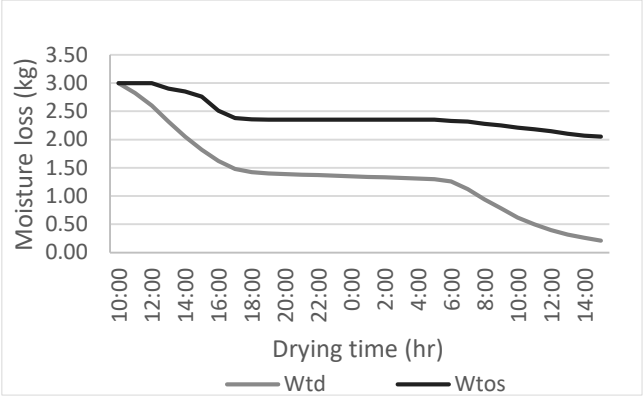

Fig. 3. Graph to determine moisture loss of tomato in the drying chamber (W_{td}) and under open-sun drying (W_{tos}) for a 30-hour period.

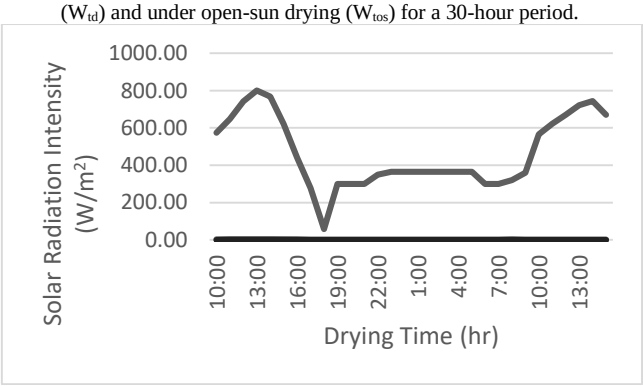

Fig. 4. Graph to determine the solar radiation intensity over 30 hour period.

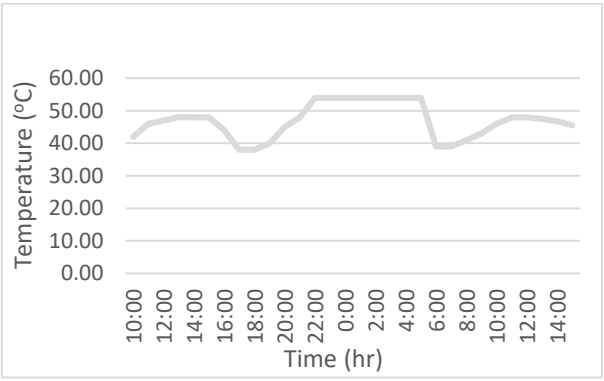

Fig. 5. Graph to determine the drying air temperature Change of the drying chamber

3.2 Drying Air Temperature

The drying air temperature was obtained from the average measurement taken during the performance testing of the solar dryer using a thermometer. The average drying air temperature was obtained from the drying chamber temperature, which is 46.9°C.

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3.3 Collector Efficiency

The collector efficiency calculated under load condition was found to be 48.7%. This value is for the average solar insulation on the surface of the collector and is slightly above the value given by S. Singh et al., (2021), which gives a typical flat-plate collector efficiency to be 46.1%, while the initial design was focused on an average value of 35% collector efficiency. The collector was insulated at the bottom with a thick insulation to avoid heat loss. Additionally, two layers of Aluminium sheets were used as absorber, arrayed in the collector to help store heat generated for a longer period. Hence, the collector efficiency for this dryer was improved by adequately sealing the glass cover over the edges. This totally reduced the possibility of heat loss from the collector.

3.4 Drying Efficiency

The drying efficiency of the solar dryer was found to be 20.9%. This value is higher than typical ranges reported for natural convection solar dryers, which are generally between 10–15% under similar conditions (Singh et al., 2021). Recent experiments on hybrid solar dryers for mango and other fruits report efficiencies around 11–13% in natural convection mode (Schiavone et al., 2013, Tesema et al., 2025), confirming the performance improvements achieved with hybrid designs, especially with the use of the auxiliary heating system.

4 Conclusion and Recommendation

4.1 Conclusion

The rate at which moisture and mass of water was removed in the drying chamber was faster compared to open sun drying. An additional heating system facilitated the continuous of the drying process through the night. Under performance test condition, the average collector temperature reached 48.1^{o}C and that of the dryer reached 46.9^{o}C while the average ambient temperature was 38.5 ^{o}C. When only the auxiliary heater was used, the average collector temperature reached 61.5^{o}C and that of the dryer reached 50.3^{o}C. The auxiliary heating system is effective for drying due to its possibility of accomodating varieties of food materials under controlled temperature. Conservative analytical procedure was followed in the design and development of this indirect hybrid solar dryer. From this mathematical procedure, a 106 cm high drying chamber was designed to accommodate food materials. Evaluation of the dryer showed that under performance test condition, an average temperatures of 48.1°C was attained for trials, while during periods of low solar radiation intensity, 54°C was obtained when the auxiliary heater was activated. Analysis performed shows that an average of 3kg of tomato slices could be dried from approximately 94% (wb) down to an average of 11% (wb) within 30 hours. From these experiments and mathematical calculations, the collector and drying efficiency were determined to be 48.7% and 20.9% respectively. Furthermore, the auxiliary heater effectively stored and dissipated heat energy during periods of limited solar radiation. Using the water activity meter, solar dried tomato was found to have an average water activity of 0.56, which indicates an effective level of preservation as compared to commercially available dried tomatoes. Furthermore, colour and texture were also preserved in these solar dried tomato slices. Thus, this dryer was found to be effective and technically feasible for producing dried tomato and fruits with the utilization of the available natural energy.

4.2 Recommendations

1) An additional suction fan, preferably a radial or centrifugal fan can be installed on the exhaust of the drying chamber, in order to enhance evaporation of moist air from the drying space. This enables the dryer to perform at a higher efficiency.
2) The number of collectors can be increased based on the amount of drying air temperature required to achieve drying specifications.
3) A suitable alloy material that is readily available and also cost effective can be considered for the design of the drying chamber.
4) Tilting of the trays in the drying chamber to degrees of about 5^{o} to 10^{o} could further improve the efficiency of the dryer.
5) A digital thermostat can be incorporated in the solar dryer system for effective control of the drying temperature, this can also help select exact temperature for certain crops.

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