

Research Article

Fabrication and Performance Evaluation of Solar Tunnel Dryer for Ginger Drying

Assefa Tesfaye ¹ and Nigus Gabbiye Habtu ²

¹Department of Mechanical Engineering, College of Engineering and Technology, Mettu University, 318 Mettu, Ethiopia

²Faculty of Chemical and Food Engineering, Bahir Dar Institute of Technology, Bahir Dar University, 26 Bahir Dar, Ethiopia

Correspondence should be addressed to Assefa Tesfaye; asefaseng2003@gmail.com

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A series of tests were conducted to investigate the performance of a solar tunnel dryer for drying ginger. To supply hot air to the dryer, two axial flow fans with a power rating of 28 W, a supply voltage of 220 V, and a 50 W photovoltaics (PV) module were employed. By dividing the 8.5-meter-long solar tunnel dryer into four equal portions every thirty minutes, solar radiation, dry air temperature, ambient temperature, relative humidity, and air velocity were measured at five solar tunnel dryer stations. The hot air temperature at the collector output grew from 34°C to 65.5°C for an 8-hour operation in the no-load condition when the solar radiation was changed between 540 and 820 W/m². At 9:00 a.m., the average maximum temperature was 30°C. During the loading operation, the temperature was 77°C at 1:00 p.m. The moisture content of sliced ginger was reduced from 90.4 to 11.8% on a wet basis using the solar tunnel dryer. With a solar collector area of 6 m², open sun drying takes 40 hours to achieve the same wet basis condition. A total of eight experiments were carried out, both with and without loads. The dry air temperature at the collector outlet ranged from 34.0 to 65.5 °C. As the drying efficiency, collector area, and time savings improve, the drying time decreases. The ginger is kept in a controlled area, resulting in high-quality dried ginger. The solar tunnel dryer showed a net saving in drying time of 40% over open sun drying.

1. Introduction

The agricultural business is the primary user of solar dryers. Solar drying is a highly important solar energy application. The goal of drying an agricultural product is to reduce the amount of moisture in the product. For Ethiopia as a whole, the average daily solar radiation reaching the ground is 5.5 to 6.5 kWh/m²/day of solar insolation [1].

Direct, indirect, natural, or forced convection dryers, as well as mixed-mode dryers, are among the designs of solar dryers. The majority of these collectors are angled southwards, with an inclination of 0° to 60° to the horizontal [2–5].

The use of solar energy in Ethiopia will become increasingly essential in the future. Understanding many physical and biological processes requires detailed information on the availability of solar radiation on the earth's surface [6–8]. In Ethiopia, solar energy is used for domestic and commercial water heating in major cities, as well as solar electricity for tele-

communication stations, lighting systems for households, cooking, drying grains (traditionally), and water supply in rural areas, and even refrigerating medicine in health centers [9–15]. In most areas, the farmers or institutions grow fruit and vegetables that have to be sold in the market immediately after harvesting. When production is high, the farmers have to sell their products at very low prices, incurring a great loss. Estimations of these losses are generally cited to be 40%–80%. A significant percentage of these losses are related to improper or untimely drying. Because there is a large amount of ginger production during the harvest season, farmers can process, dry, and store the products to avoid losses [16, 17].

With some dryers that can be equipped with a supplementary heating source or a store of energy, the design has concentrated on the exploitation of accessible local resources. Solar drying research in African countries is often low, and it requires expenditure to boast about it. In the experimental study, it was observed that high temperatures

and lower relative humidity could enable inactivation of weevils of maize from field infestation due to accumulation of heat from solar irradiation and moisture migration from the insect pests at lower relative humidity [9, 18].

During the storage term of the dried grain, the effects of several types of solar drying methods and the amount of sample load in the dryer on insect populations, percentage of grain damage and weight loss, bulk density, and thousand-grain weight were studied. The amount of sample loaded in the dryer influences all metrics. A thin layer of dried maize grain showed less weight loss than a thick layer of dried maize grain [18, 19]. The lowest losses were found in the open sun and solar bubble dried (SBD) items at each storage time. SBD dries grain faster and is more effective than cabinet dryers. A semicylindrical forced convection type solar tunnel dryer was designed for drying processed tobacco. Essentially, it is based on the mixed-mode with the direct and indirect types of heating mechanism [17, 19–21]. A batch of processed tobacco weighing 500 kg with an initial moisture content of 138% db. was successfully dried in full load condition to have a final moisture content of about 8.7% db. in 8 h [17]. Critical design specifications and field performance of a walk-in type hemicircular solar tunnel dryer for drying 1500 kg of industrial products were reported by Seveda, Damena et al., and Qin et al. [9, 22, 23].

Traditional drying, which is often done on the ground in the open air, is the most widely utilized method in developing nations since it is the simplest and cheapest form of food preservation [10–13, 20, 24, 25]. Plants, seeds, vegetables, fruits, meat, fish, and other agricultural commodities have been preserved using traditional open-air solar drying methods for generations [26]. Because of the need for a vast area, the risk of quality degradation, air pollution, and bird and insect infestation, and intrinsic problems in managing the drying process, open-air drying has been increasingly limited during the last few decades [25, 27]. Solar thermal technology is quickly gaining traction as an energy-saving strategy in agricultural applications where sunlight is abundant. Solar energy is favored above other alternative energy sources like the wind because it is abundant, inexhaustible, and nonpolluting [25].

Such data is also required for the most efficient design and study of solar energy conversion devices [10]. Alternative energy sources must be used to replace nonrenewable and polluting fossil fuels to meet the present rising energy demand and growing environmental concerns. Alternative energy sources include solar energy. Because of its geographical location, Ethiopia has a large amount of solar energy potential that can be used for a variety of purposes.

According to a cautious first estimate [28–30], solar energy's commercial potential is estimated to be 100 MW for water heating and 100 MW for solar electricity. Domestic and commercial water heating in major cities and solar electricity for telecom stations, lighting, and water delivery in rural areas are all examples of solar energy usage in Ethiopia. The overall installed solar energy capacity for water heating and electrical use is expected to be around 1 MW [26, 27, 31, 32]. The country's total solar energy potential is projected to be 7,466,232 kWh/m² [28, 33, 34].

Around 13,500 individuals are intended to be reached by solar thermal systems (cookers, heaters, and dryers). The market for off-grid and alternative systems will be strengthened by public education, coordination for higher efficiency, and increased access to financing for both providers and users, all of which will increase access to these systems [8, 29, 30, 35, 36].

Therefore, the present study tries to fill the gap between the farmer/institutions and the importance of proper drying technology with reverse engineering to adapt the solar tunnel dryer technology by solving the drawbacks of the open sun drying system and minimizing the postharvest losses of ginger. Ginger (*Zingiber officinale*) is a major agricultural commodity in Ethiopia, where it is utilized both fresh and dried in small quantities. The dried rhizome of ginger is utilized for commercial applications. It is used as a local medication and as a flavoring spice in most families. It is quite important in the country's traditional eating patterns [26, 37]. Gingers are dried by putting them out in the open during the day [24, 31, 38]. The components of the solar tunnel dryer are the flat plate solar collector, fans, the drying chamber, and the PV module [39, 40]. Therefore, the postharvest losses of ginger products can be reduced by using a well-performed solar drying system [28, 41]. A preprint has previously been published online [42]. The objective of this research is to reconstruct the solar tunnel dryer and evaluate its performance by using ginger.

2. Methods and Materials

2.1. Materials. In this research, chipboard, clear polyethylene sheet, clear glass sheet, metal elements such as angle iron, L-metal, and T-metal, and insulating materials were employed in this research. Materials were chosen depending on availability and pricing in the local area.

2.2. The Design of a Solar Tunnel Dryer

2.2.1. Moisture Content Determination. The moisture content on a wet basis (μ_m) is expressed as kg of moisture per kg of wet product to be dried.

$$\mu_m = \frac{Mw - Md}{Mw}. \quad (1)$$

The moisture content on a dry basis (μ_d) is expressed as kg of moisture per kg of dried product.

$$\mu_d = \frac{Mw - Md}{Md}, \quad (2)$$

where μ_m is the moisture content at wet basis (kg/kg) of wet product, Mw is the weight of the wet product (kg), Md is the weight of the dry product (kg), and μ_d is the moisture content on a dry basis (kg/kg) of the dry product.

The following assumptions and conditions were used to carry out the design calculation and size of the solar tunnel dryer, as shown in Table 1.

TABLE 1: Design conditions and assumptions for the design of the dryer.

Items	Conditions and assumptions
Location	11°33'36"N, 37°22'12"E, and 1770 m height
Orientation	Southwards direction (0° to 60°)
Product	Ginger (<i>Zingiber officinale</i>)
Loading capacity	8 kg per time
Initial moisture content (%)	90.4
Final moisture content (%)	11.8
Latent heat of vaporization	2369.49 kJ/kg at 55.5°C
Total solar hours	8 hours
Drying period required	16-24 hours
Dryer efficiency (%)	31.6
Length of solar tunnel dryer	8.5 m
Width of solar tunnel dryer	2.0 m
Height of solar tunnel dryer	47 cm
Area of solar collector	6 m ²
Area of the drying chamber	11 m ²
The total area of the dryer	17 m ²

2.3. *Description of the Solar Tunnel Dryer.* Solar tunnel dryers have been used successfully in fields to dry fruits, harvests, vegetables, coffee beans, chili peppers, ginger, and coconuts, and they may be made with locally available materials. The tunnel's cross-section might be triangular, semicircular, or flat with a flat cover. The solar tunnel dryer is 8.5 m long and 2 m wide, with a collector area of 6 m² and a drying area of 11 m². It was reconstructed to make it more affordable for drying small quantities of agricultural products, taking into account the land-holding capacities of marginalized rural farmers in the Ethiopian region. The constructed solar tunnel dryer comprises a solar collector (air heater), a drying chamber, and two tiny axial flow fans with solar PV modules to produce the required airflow over the dried items. Through the limitation of the stagnant air layer between the absorber plate and the glass cover, the clear cover was employed to reduce convection losses from the absorber plate. Because the glass is transparent to the sun's shortwave light, it minimizes radiation losses from the collection as well. A glass cover is attached to the solar collector glass frame and protects the solar collector. A UV-stabilized polyethylene sheet is used to cover the drying chamber as well. This sheet is attached to the tunnel frame on one side and a metal tube on the other, allowing it to be rolled up and down to load and unload the dryer. In the event of rain, the covering glass and plastic sheets are inclined like a roof to prevent water from entering or draining.

Chipboard with an 8 mm thickness was employed as an insulation material on the bottom side of the collector and drying chamber to minimize heat losses, according to the dryer's optimal design. Inside the drying tunnel, the items were laid out in a single layer on a wire mesh. Using two fans (14 W and 220 volts each) connected to the solar collector's intake, air entering the solar collector was heated and pressed against the products put in the drying chamber. These fans were used to blow a specified mass flow rate of air into the drying chamber, which improved the convection heat transfer coefficient between the air and the dried product. Each of these fans can handle between 130 and 650 m³/h of air. The fans were powered by either a grid-connected electric motor or solar photovoltaic module-generated electricity. Solar radiation heats the absorber as it travels through the collector's transparent cover. The collector has been compelled to gather ambient air. The heat was transferred from the absorber to the air in the collector, and heated air from the collector passed over the products, absorbing moisture. Solar radiation travels through the dryer's transparent lid and heats the items inside. Figure 1 shows the overall dimensions and a clear picture of the solar tunnel dryer.

2.4. *Solar Tunnel Dryer Experimental Set-Up.* The solar tunnel dryer's performance was assessed by running experiments with sliced ginger at full load and no load under various conditions.

The incident solar radiation on the collector/dryer was measured using a standard solar intensity meter called a pyrometer with a resolution of 0.1 W/m² and an accuracy of ± 10 W/m². The solar radiation measuring instrument is manufactured by Testo Instruments in Germany (Volt Craft PL-110SM Model) and provides instantaneous solar radiation in W/m².

An infrared thermometer was used to measure the ambient temperature. This equipment is manufactured by Testo Instruments, which is based in Germany. With an accuracy of 0.5°C, a laboratory-type mercury bulb thermometer (made in Germany by Testo Instruments) was used to measure the dry air temperature at five points on the solar tunnel dryer (inlet, middle of collector, outlet of collector, inlet of drying chamber, middle of drying chamber, and outlet of drying chamber). Laboratory-style mercury bulb thermometers were put into the hole at five different points in the solar tunnel dryer to measure the temperature of the air inside. The equilibrium readings were recorded. Cole-Parmer scientific specialists designed these laboratory thermometers, which were manufactured in Germany. They feature a temperature range of 100°C and a precision of 0.5°C. An anemometer (TA 6000, a product of Testo Instruments, made in Germany) was used to measure air velocity at the solar tunnel dryer's entrance, middle, and output positions. The relative humidity (RH), dry bulb temperature, and wet bulb temperature of the air within the solar tunnel dryer were measured with an accuracy of 1% using a hygrometer (made in Germany and a product of the Testo Instruments firm). From 9:00 a.m. to 6:00 p.m., all measurable data (dry air temperature, relative humidity, air velocity, ambient temperature, and solar radiation) were manually recorded at 30-

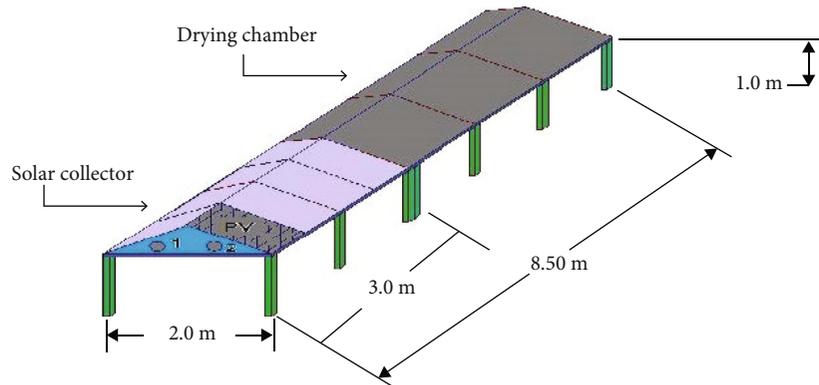


FIGURE 1: Solar tunnel dryer.

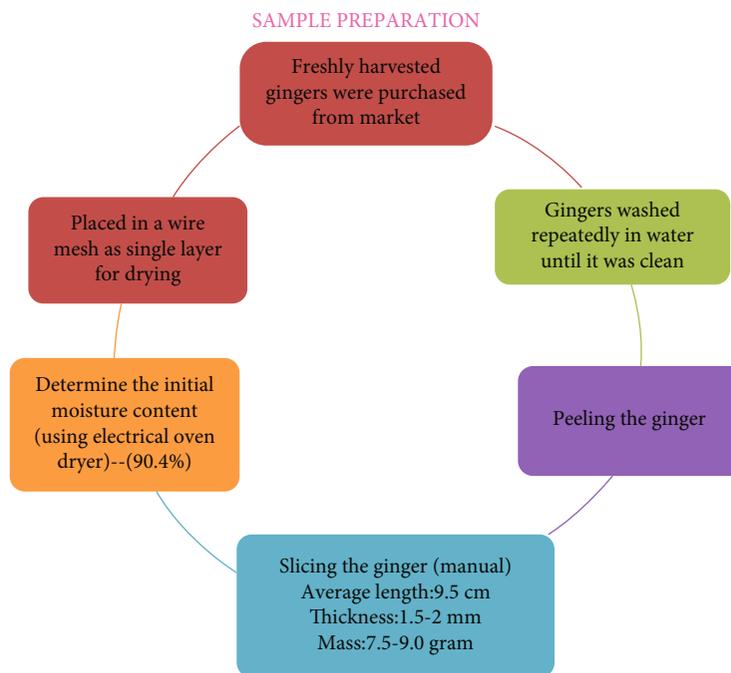


FIGURE 2: Sample preparation of the experiment.

minute intervals. During the experiment, the weight of the material to be dried was measured using a digital precision balance (WA-2Y Model) made in China by Wan Jun Co., Ltd., with an accuracy of 0.01 grams and a maximum measurement capacity of 100 kg. The solar tunnel dryer has been used to conduct the experiment as shown in Figure 1.

2.5. Preparation of the Sample and Determination of Moisture Content. As it can be seen in Figure 2, the freshly harvested gingers were purchased from a small market in Bahir Dar city to prepare the sample and determine the moisture content. Then, the ginger was cleaned by hand in water until it was clean, before being sliced with a manual slicing machine to speed up the drying process. The ginger was sliced into 7.5–9.0-gram pieces (average length = 9.5 cm and thickness = 1.5–2.0 mm). To see the drying properties, the sliced ginger must be of the same product kind. The rate of drying increases as the particle size decreases. The sliced gin-

ger (samples) were then put out in the drying chamber in wire mesh trays to cover an area of 11 m^2 . An electrical oven dryer made in India is used to evaluate the initial moisture content of ginger (DHG-9140 Model). 10 g of sample ginger was dried for 24 hours at 105°C in two different sample holders in an oven dryer. The dried sample was maintained in a desiccator for at least 10 minutes after 24 hours before being weighed. After 24 hours, the weight of the sample ginger was measured with a computerized precision balance. Using a conventional formula, the initial moisture content was estimated as the difference between the beginning and end weights [24, 25, 27, 31, 38, 43]. The sample ginger's original moisture content was determined to be 90.4% (wet basis).

2.6. Experiment Loading and Unloading Procedure. Before the test was conducted, the dryer was calibrated with no-load conditions. The dryer is preheated for several minutes at a set temperature and velocity. The outlet and inlet flow

areas were reduced by closing the airflow channels at the expense of the airflow rate until a drying air temperature above 380°C was achieved, which is required for the drying of fruits and vegetables.

The sliced ginger was weighed first before being dried in the solar tunnel dryer. The sliced ginger is then evenly distributed in a thin layer across the wire mesh pan. The temperature and velocity of the hot air are measured just before the sample is spread over the wire mesh tray. The control sample was left in the open sun and dried under natural conditions in the sun. The mass of the sliced ginger was recorded before and after drying each day, and the moisture content of the samples at different drying periods was calculated using a standard equation [27]. Finally, the reduction in moisture content of the ginger in the solar tunnel dryer was as compared to a control sample that dried under natural conditions in the open sun. The second phase involved manually recording data from the collector and dryer, including air temperature at five points of the solar tunnel dryer, RH at the intake and outflow of the drying chamber, solar radiation, and ambient temperature at 30-minute intervals. The solar tunnel dryer has a total length of 8.50 m and a width of 2 m (making the area 17 m^2). The tunnel dryer's height is 74 cm and is consistent throughout. In Figure 3, the location of the thermocouple is divided into four equal portions across the length of the dryer. Figure 3 depicts the positions of the measured parameters during the experiment.

To prevent the ginger from regaining moisture, the dryer's inlet and outlet were closed at night, and the control sample was placed in the room. The drying procedure was deemed complete when the moisture content of the slices had been reduced to 11-12% on a wet basis. Color, taste, and fragrance parameters are used to assure the dried product's quality.

3. Results and Discussion

3.1. Solar Drying of Ginger. The suitability of the solar tunnel dryer for drying ginger under Bahir Dar circumstances was tested using a reconstructed solar tunnel dryer at the Bahir Dar University. Solar radiation, ambient air temperature, relative humidity, air velocity, and temperatures were measured at five points along the dryer's length. Apart from elements like collector performance and drying temperature, the performance of a dryer, or drying efficiency, is determined by the drying time and the quality of the end product.

3.2. Dryer Performance in No-Load Conditions. The fans were tested in no-load mode using DC/photovoltaic power. No-load data includes solar insolation, relative humidity, air velocity, ambient temperature, and dry and wet bulb temperatures. Solar radiation ranged from 543 to 820 W/m^2 during the no-load test. The maximum solar insolation of 820 W/m^2 was observed at 1:00 p.m. RH varied from 26.2% to 36.3%. The ambient temperature varied from 21.5 to 35.6°C . The temperature of the drying air at the collector outlet of the solar tunnel dryer varied depending on the weather and time of day. With variations in solar radiation

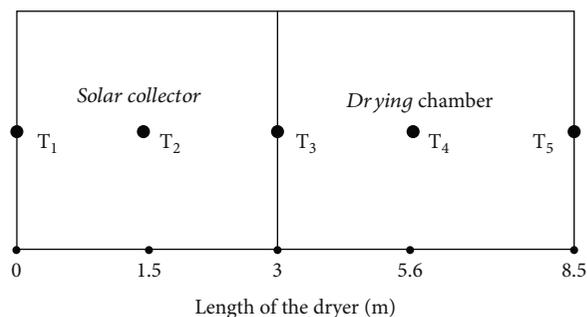


FIGURE 3: Positions where the temperature is taken (side view).

levels, the temperature also varies. At low levels of solar radiation, the flow rate is automatically reduced due to the reduced electrical power output of the solar panels and vice versa. The lower the flow rate, the higher the outlet temperature, and hence, the air temperature inside the dryer is maintained almost steady. Figure 4 shows the performance of the dryer at no-load conditions.

Airflow rate is an important factor influencing the performance of solar tunnel dryers. Figure 5 shows the variations of the temperature at the collector outlet and the air velocity with the time of day of a typical experimental run. The drying air temperature at the collector's outlet is 50.2°C at 9:00 a.m., 70°C at 12:00 p.m., and 74°C at 4:00 p.m. The air flow rate at the outlet of the collector at 9:00 a.m. is 3.6 m/s; at 12:00 o'clock, it is 4.0 m/s; and at 16:00 o'clock, it is 4.2 m/s.

This shows that there is an increment in drying temperature and airflow at the outlet of the collector throughout the day. The variation in the airflow rate helped to regulate the drying air temperature. During the low solar insolation period, less energy was received by the collector and the airflow rate was low. This resulted in the minimum variation of the drying air temperature throughout the drying period. The temperature profile along the length of the collector/dryer for unloading conditions has been shown in Figure 6 with PV-operated fans. To show the variation of temperature, three specific hours in a day have been chosen. As seen in Figure 6, the drying air temperature at 12:00 p.m. increases steadily, and the maximum temperature is achieved at this time. The temperature at 4:00 p.m. increases from the inlet to the outlet of the solar tunnel dryer. It is interesting to note that the temperature profile over the length of the drying chamber is not significantly influenced by the moisture content of the product. At unloading conditions, the drying air temperature increases steadily from the inlet of the collector up to the outlet of the drying chamber throughout the day.

3.3. Solar Tunnel Drying of Ginger at Loading Conditions. The experiment on drying ginger was conducted in the solar tunnel dryer constructed at the Bahir Dar University to evaluate the performance of the dryer under loading conditions. The dryer was loaded at 9:00 a.m. with 8 kg of ginger by spreading the ginger in a wire mesh tray in a thin layer. At the end of each day, the sample ginger was collected and stored in a plastic bag. The drying process was extended

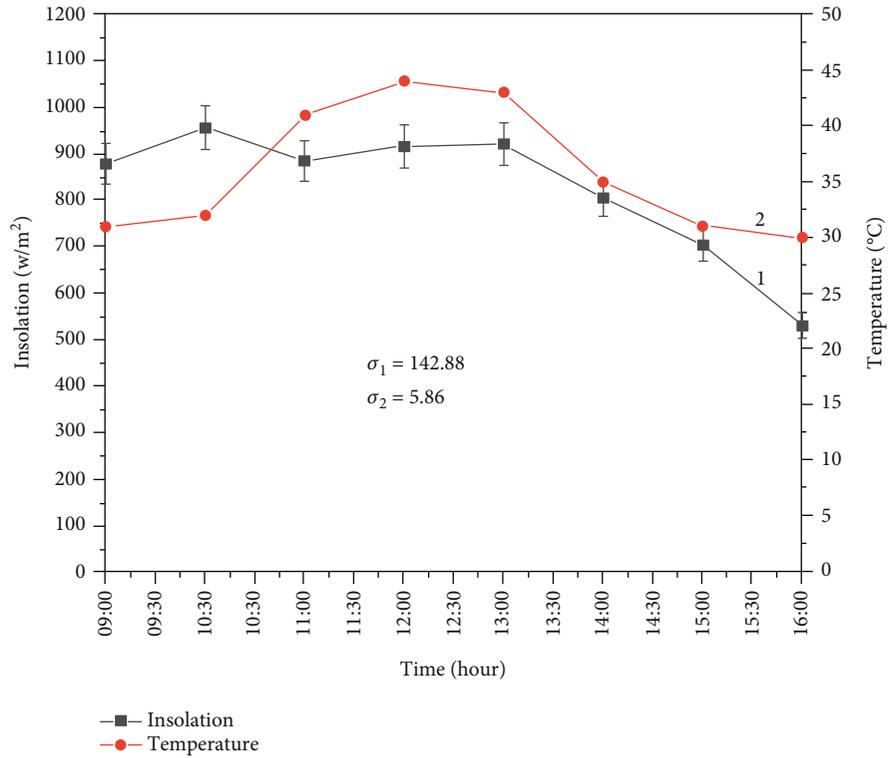


FIGURE 4: The effect of solar radiation on outlet air temperature.

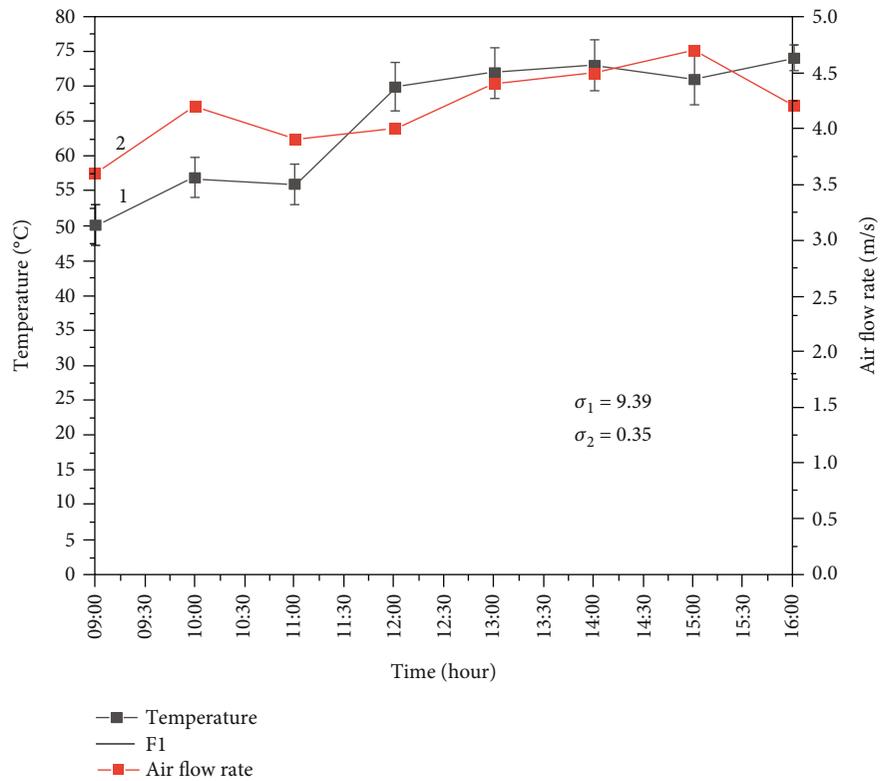


FIGURE 5: Drying temperature and airflow rate as a function of time.

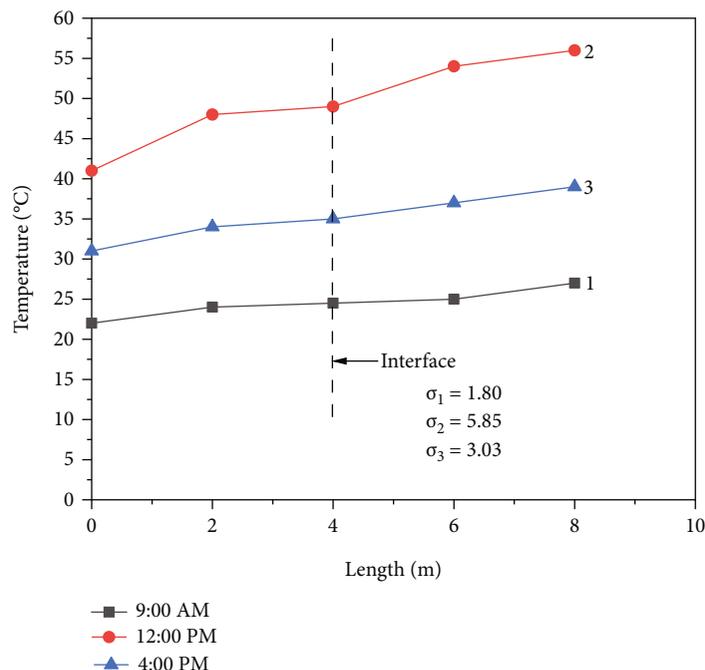


FIGURE 6: The temperature profile along the length of the collector/dryer during unloading conditions.

the next day by spreading the ginger in a wire mesh tray in the solar tunnel dryer. The process was continued until the required moisture content was achieved. Control samples were dried simultaneously, in the open sun, under the same weather conditions, for comparison.

Eight experimental tests were conducted between September 15 and November 30, 2014. Solar insolation, relative humidity, air velocity, ambient temperature, and dry and wet bulb temperatures are recorded manually every 30 minutes. In this research work, one of the test data was used to evaluate the collector efficiency, drying curves, RH, and temperature measurements in the collector and dryer. During the test period, heated air was used to dry the sample ginger.

It was observed that the maximum temperature inside the solar tunnel dryer at the outlet of the solar collector was found to be 77.9°C with a relative humidity of 33%. It was found that the average temperature and relative humidity inside the solar tunnel dryer were 59.45 and 45.2%, respectively. The solar radiation during the loading test varied from 445 to 858 W/m². The maximum solar insolation of 858 W/m² was observed at 12:30 p.m. RH varied from 26.2% to 36.3%. The ambient temperature varied from a minimum of 21.5°C to a maximum of 35.6°C. At the collector outlet of the solar tunnel dryer, the drying air temperature ranged from 33.0°C to 77.9°C. It depends on weather conditions and the time of the day. With variations in solar radiation levels, the temperature also varies. The variation of drying air temperature and solar radiation intensity with time at the outlet of the solar collector is shown in Figure 7.

3.4. Temperature Profiles in the Collector and Dryer Units.

Figure 8 shows the temperature profiles along the length of the solar tunnel dryer. At loading conditions, the drying air

temperature increases steadily throughout the collector at 9:00 a.m., 12:00 p.m., and 4:00 p.m. But, the drying air temperature decreases across the drying chamber at the same drying time. This is due to the sample ginger having a 90.4% moisture content and having evaporated. The temperature profile over the length of the drying chamber was influenced by the moisture content of ginger. The temperature profile along the length of the collector/dryer has been shown in Figure 8, for dryer operation with PV-operated fans.

3.5. Relative Humidity and Air Capacity. The humidity of the drying air is a critical factor in controlling the drying rate of the product. The lower the relative humidity, the greater the absorbing capacity of dry air. An ideal drying process would ensure 100% RH in the air leaving the dryer, but considerably less relative humidity at the inlet of the drying chamber.

The relative humidity of air at the outlet of the dryer shows that the air still has considerable drying potential, implying that the rated capacity of the dryer has not been fully utilized [38].

Figure 9 indicates that the average RH of the ambient air was 41.4% compared to the relative humidity of the air at the collector exit, which has an average of 38.1% in the morning, 33.5%–42.6% between 11 and 15 hours, with a minimum of 30.2% at 13:30 hours and an average of 35.4% in the late afternoon.

However, the low RH of the exhaust air shows that the potential of the drying air to remove moisture was not fully utilized, which can be seen from the results in the afternoon. This can be improved through proper utilization of the drying potential of the air by recirculating the dried air. RH is affected by the air temperature. Heating the air decreases RH and, therefore, increases the capacity of the air to carry away moisture during a drying process. The extent to which this is achieved depends

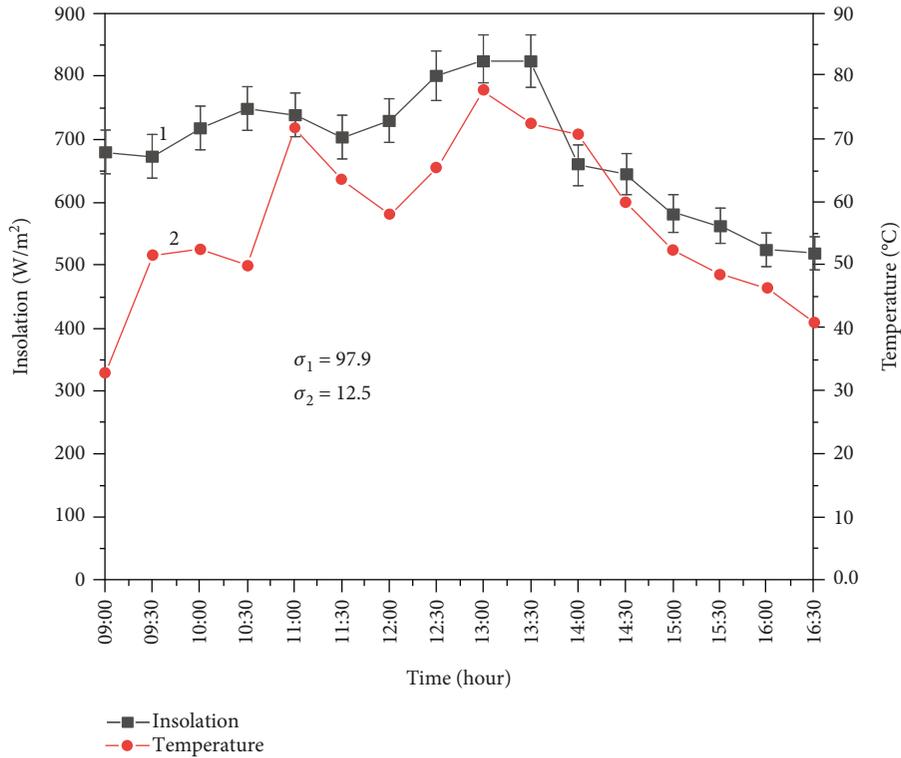


FIGURE 7: Variations of insolation and temperature at the outlet of the collector.

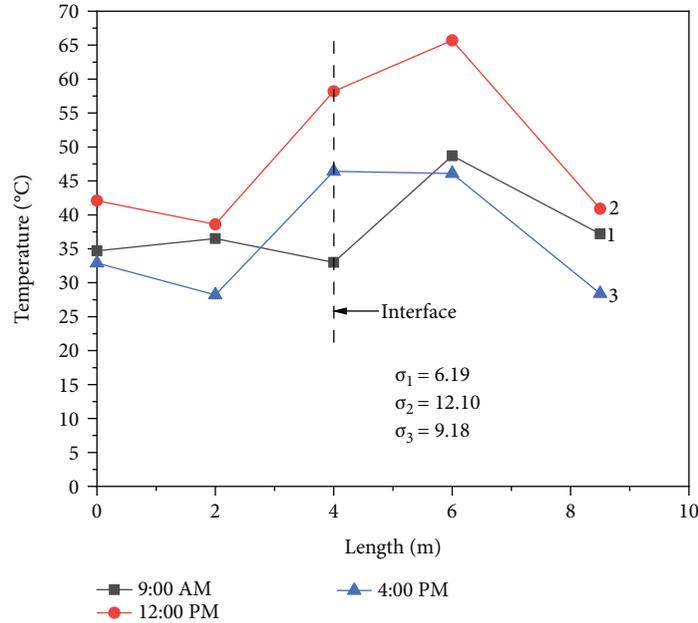


FIGURE 8: Temperature distribution along the length of the collector/dryer during a loading test.

on the weather conditions, namely, the absolute humidity and the temperature of the ambient air. In Figure 9, the RH and temperature of the ambient air are compared.

3.6. Variation of Moisture Content and Drying Efficiency. The moisture content of ginger before and after drying for

each day was determined by taking a sample for analysis. The drying curve in Figure 10 shows the comparison of the variations of the moisture content with time during solar drying of ginger with those of open sun drying for a typical experimental run with a drying area of 11 m² and a loading rate of 8 kg. The moisture contents of the samples at

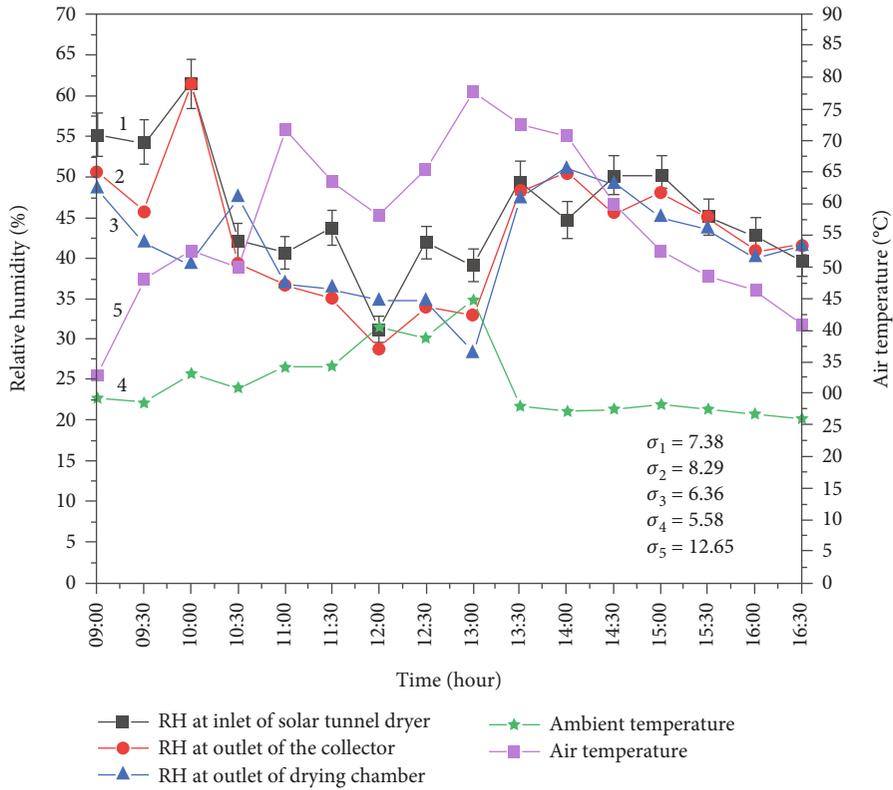


FIGURE 9: Time variation of relative humidity in the dryer.

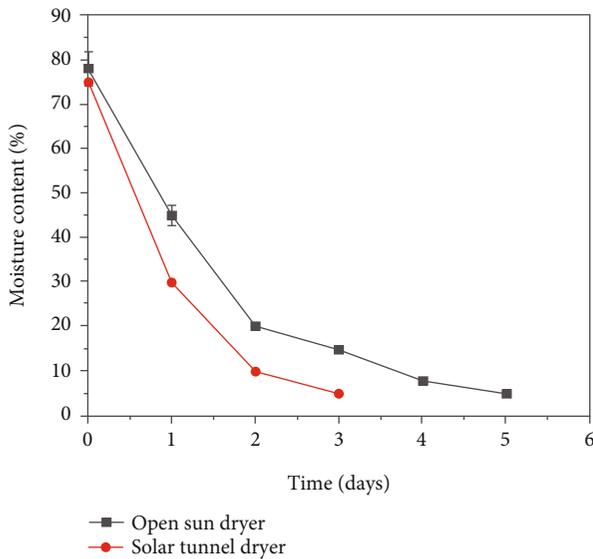


FIGURE 10: The drying curves for open sun drying and solar tunnel drying at a 11 m² drying area.

different drying periods were calculated using a standard equation. A total drying time of 24 hours was required for the solar tunnel dryer for ginger drying at a total loading rate of 8 kg per batch to reduce the moisture content from 90.4% (w.b) to 11.9% (w.b), while the corresponding drying time for open sun drying was 40 hours (five sunny days) to bring down the moisture content from 90.4% (w.b) to 11.74% (w.b). There is a considerable reduction in the drying time

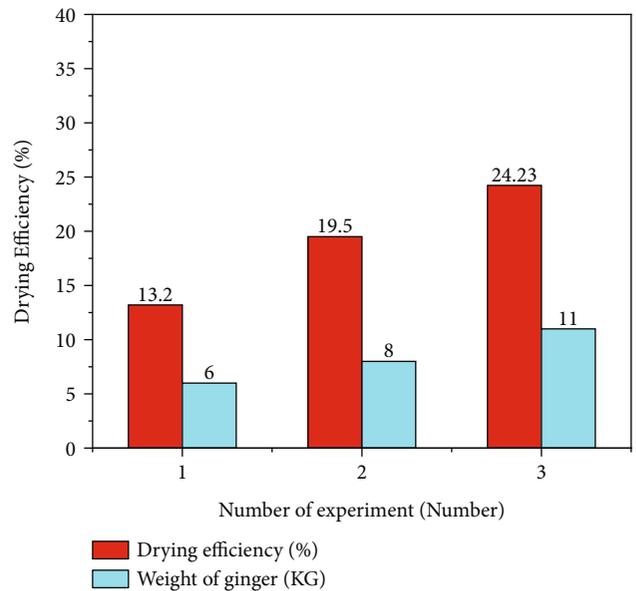


FIGURE 11: Drying efficiency (per mass) of ginger.

of ginger in a solar tunnel dryer as compared to open sun drying of ginger. The drying efficiency of a solar tunnel dryer with a 11 m² area is 31.6%. When we dry the ginger using an open sun dryer (OSD), it suffers undesirable effects of dirt and dust. It will be exposed to insects and rodent attacks. It has difficulties controlling the drying process. Overall, the OSD caused quality degradation.

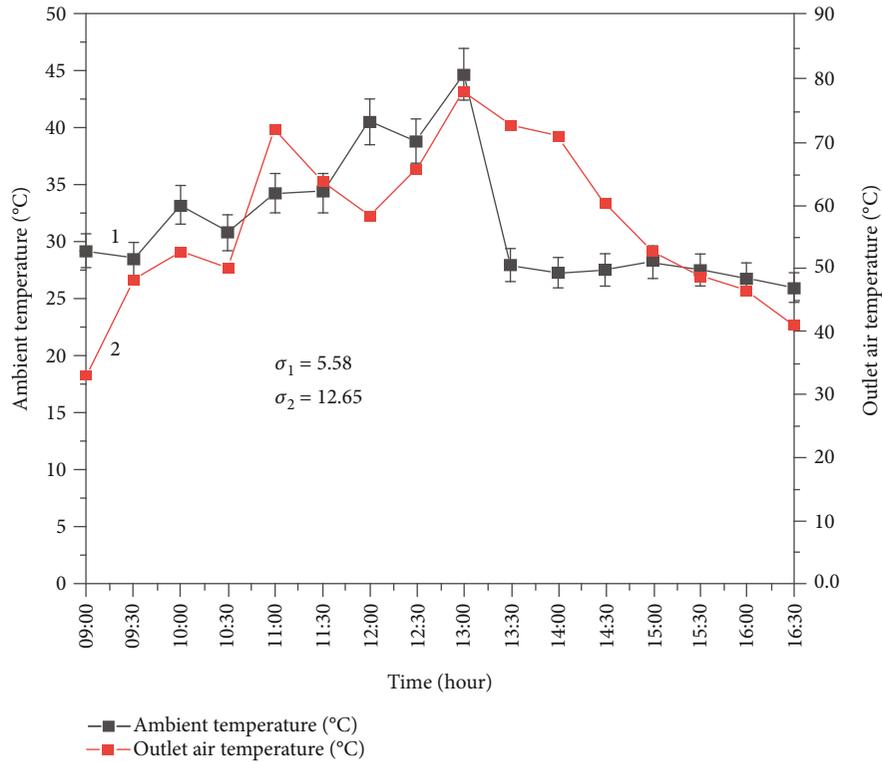


FIGURE 12: The ambient and outlet air temperatures for the collector.

Since the solar tunnel dryer (STD) is a closed system, it keeps the food from birds, insects, and unexpected rain-fall. In addition, the dried product was also protected from dirt, pests, and other rodent attacks. We can conclude that the gingers being dried in the solar tunnel drier were completely protected from rain, insects, and dust, and

high-quality dried gingers were obtained. We can manage the drying process. For ginger drying, the savings in drying time of solar tunnel drying are compared with open sun drying. The saving in drying time for solar dryers over open sun drying was calculated using the following formula.

$$\text{Saving in drying time (\%)} = \frac{\text{Time taken for drying in OSD} - \text{Time in for drying in STD}}{\text{Time taken for drying in OSD}} * 100. \quad (3)$$

It showed that a net saving in drying time of 40% was achieved through a solar tunnel dryer over open sun drying without affecting any considerable change in the quality of the dried product. The solar-dried products were also protected from dirt, pests, and other attacks. Dried ginger is a quality dried product.

3.7. Solar Tunnel Dryer Drying Efficiency

3.7.1. Drying Efficiency with Variations of Area. The drying efficiency of the solar tunnel dryer has been estimated by taking solar energy input to the collector and dryer parts into account. The drying efficiency of ginger was estimated by considering the total radiation incident and the initial and final weight of the product, thus the amount of water evaporated. The system drying efficiency is defined as the

energy used to evaporate the moisture in the product divided by the energy input to the dryer.

Drying efficiency for solar tunnel dryers is given by

$$\eta_d = \frac{W * L}{I * A}, \quad (4)$$

where η_d is the drying efficiency (%), W is the weight of water evaporated from the product (kg), L is the latent heat of evaporation of water (kJ/kg), I is the hourly average solar radiation on the aperture area (kWh), and A is the drying area of the solar tunnel dryer (m^2).

The drying efficiency depends on the amount of water evaporated (kg) from the product and the drying area. As the drying area decreases (increasing the collector area),

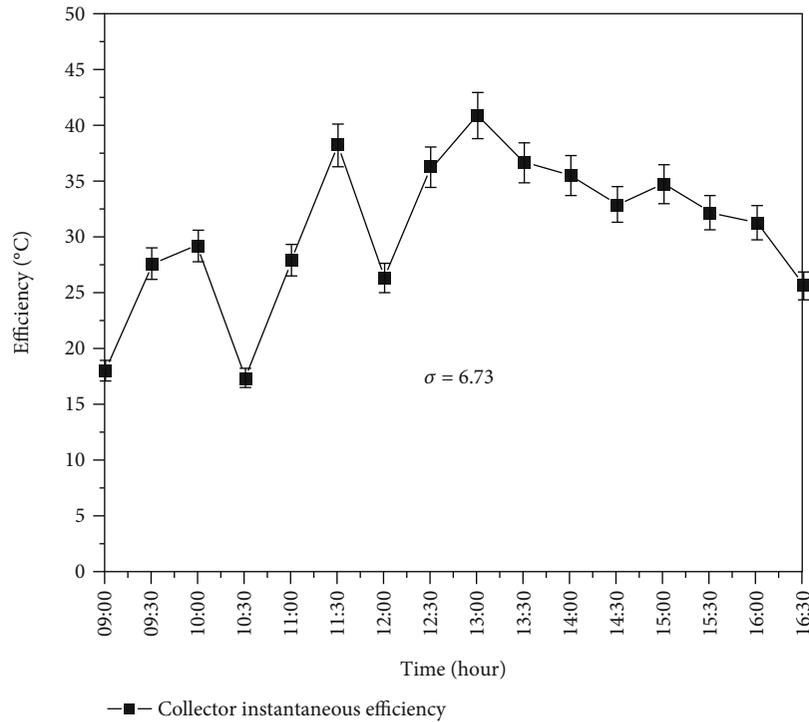


FIGURE 13: Variation of instantaneous efficiency of the flat plate collector.

the drying efficiency (%) of the solar tunnel dryer increases. The savings in drying time also increase.

3.7.2. Drying Efficiency (per Mass) of Ginger. The drying efficiency is calculated by using Equation (2), using the results from the experiment. The drying area is fixed and only the weight of the product to be dried is varied. Three experiments are done by fixing the drying area and varying the weight of the product to be dried: 6 kg, 8 kg, and 11 kg. The result is presented in Figure 11. As it can be seen in Figure 11, significant variation is observed by varying the weight of the sample ginger. As we have varied the weight of the product, the drying efficiency also varies. As the weight of the product to be dried increases, the drying efficiency also increases.

3.8. Collector Performance. The efficiency of a solar collector is defined as the ratio of the useful energy gain to the incident solar energy.

$$\eta_c = \frac{Q_u}{H_t A_c}, \quad (5)$$

where η_c is the collector efficiency (%), Q_u is the useful energy collected by the solar collector (KJ), A_c is the area of solar collector (m^2), and $\overline{H_t}$ is the average daily total radiation on a tilted surface ($w/m^2/day$).

The efficiency of the collector could be seen from the difference in temperature between the outlet and the inlet of the air to the solar collector. The solar collectors have to be cleaned from time to time to eliminate the dust deposits. This improves the performance of the solar tunnel dryer. In this

dryer, by fully opening the inlet and the outlet of the dryer, a temperature within $10\text{--}40^\circ\text{C}$ higher than the ambient air temperature was recorded. However, for drying ginger, the temperature was increased by decreasing the inlet of the collector and outlet of the dryer areas, and a temperature within $14.0\text{--}33.2^\circ\text{C}$ higher than the ambient air temperature was obtained, and this variation is shown in Figure 12.

As it can be seen in Figure 13, the instantaneous efficiency of the solar collector started to rise in the morning period and dropped at 10:30 a.m. It started to rise again at 11:30 a.m. to 38.3%. The collector efficiency reaches a maximum at 1:00 p.m. It was relatively constant at 34.79% from 1:30 p.m. to 3:00 p.m. and dropped off in the late afternoon. The variation obtained is typical for a flat plate collector and indicates a strong dependence of efficiency on the metrological data. The daily efficiency averaged over 8 hours (9:00 a.m. to 4:30 p.m.) is 30.7%.

4. Conclusions

In both no-load and full-load situations, eight trials were performed. A maximum solar insolation of 820 W/m^2 was reported at 1:00 p.m. under no-load conditions. At the collector output, the temperature of the drying air ranged from 34.0 to 65.5°C . At 12:30 p.m., during the full-load test, the highest solar insolation was 858 W/m^2 . At 1:00 p.m., the highest temperature recorded was 77.9°C . The moisture content of ginger influences the temperature profile at loading circumstances across the length of the drying chamber. The drying efficiency of sample ginger improves as its weight increases for a fixed solar collector area. In addition, as the

drying area decreases, the drying efficiency increases. The solar collector's instantaneous efficiency rises steadily from morning to evening, depending on metrological conditions. A temperature of 10–40°C greater than the ambient air temperature was measured at the collector output. The average daily efficiency over eight hours was calculated to be 30.7%.

The solar tunnel dryer requires a total drying period of 24 hours to reduce the moisture content of ginger from 90.4% to 11.8% (wet basis) using an 8 kg loading rate. In comparison, open sun drying takes 40 hours to achieve the same amount of moisture content. The products dried in the solar tunnel dryer are sheltered from the elements, including rain and insects. The solar tunnel dryer showed a net saving in drying time of 40% over open sun drying.

Data Availability

The authors confirm that the data supporting of this study are available within the article and the data that support the findings of this study are available from the corresponding author, upon a reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

The authors contributed equally. They did “conceptualization, methodology, formal analysis, investigation, funding acquisition, resources, writing—original draft preparation, prototype development, visualization, experimentation, supervision, project administration, and writing—review and editing.” The authors have read and approved the published version of the manuscript.

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