Experimental Investigations of a Simple and Cheap Passive Solar Dryer for Preserving Agricultural Products

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Abstract- In this study, a simple passive solar dryer was designed and built with low-cost materials, then tested to determine its drying performance. Developing a sustainable solar dryer using low-cost materials sourced locally to outperform open sun and direct solar drying techniques readily used for preserving agricultural products is novel in this work. The passive solar dryer features a single-pass solar collector, a drying chamber with multiple trays for drying food, and a chimney. The drying performance of potatoes was compared to that of open sun drying (OSD) and direct solar drying methods based on the solar collector's thermal efficiency and air outlet temperature. The drying tests revealed that collector efficiency varied with time, peaking at 1:00 pm with a maximum outlet temperature of ~54.2 °C. In addition, the efficiency of the solar collector is found to increase as the airflow rate increases. Potatoes were dried from an initial moisture content (MC) of 82% to below 10% using the passive solar dryer. Compared to direct solar and open sun drying methods, the studied passive dryer was more efficient, resulting in 11.1% and 20% less drying time, respectively. The drying rate was seen to be higher at the start of the drying process and decreased at the end. The average drying efficiency was found to be 4.3, 14.4, and 18% using samples of 100, 300, and 500 g, respectively. Sensory tests revealed that potatoes dried using the passive solar dryer were more appealing in colour, taste, and flavour.

Keywords Solar energy, passive solar dryer, collector efficiency, moisture content, solar air collector.

1. Introduction

Seasonally grown agricultural products appear for a short period in developing countries before disappearing for the rest of the year. Farmers suffer financial losses as a result of crop failure. Drying agricultural products is a popular way to preserve crops and ensure higher prices when sold out of season. Many agricultural products are used in their natural dried state, which means they have been dried using open sun drying (OSD) or a traditional drying method that uses heat generated by the combustion of fossil fuels before storage. Open sun drying is a popular method for preserving foods or grains in developing countries [1]. Despite its low cost, the main disadvantages of OSD are the possibility of contamination by specks of dust, insects, birds, or pests, as well as the degradation of nutritional values of food due to prolonged direct sunlight exposure. About 40% of agricultural products are lost during post-harvest handling and storage in developing nations [2]. The use of traditional drying methods to preserve those harvests is one of the major causes.

As a result of widespread environmental concern, many countries are shifting toward methods or systems that use renewable energy, particularly solar energy, to reduce greenhouse gas emissions [3-7]. Replacing fossil fuels with solar energy in crop drying systems will be critical to our long-term sustainability. In Bangladesh, due to high solar insolation throughout the year [8], a simple solar dryer utilizing a clean energy source can be one of the most economical and cost-effective ways to preserve grains, fruits, and vegetables. Solar dryers with the necessary features are popular for drying fruits and vegetables because the final products are contamination-free and hygienic [9]. In addition, the significant benefit of solar dryers is that they protect the environment by not emitting carbon monoxide, carbon dioxide, or any other greenhouse gases. Recently, Ahmadi et al. [1] thoroughly reviewed different solar drying methods, including direct, indirect, mixed, and hybrid modes. Over the last few decades, a large variety of solar dryers have been developed and investigated, with a few widely used types being direct solar dryers [10-13], indirect [14, 15], mixed-mode [16, 17], and hybrid solar dryers [18, 19].

One of the most well-known dryers used to dry food is the indirect type solar dryer (ITSD). A simple ITSD with natural air draft comprises two major parts: a drying cabinet with trays for drying food products and a solar air collector made primarily of a transparent glass sheet and an absorber plate. Among the various solar dryers, an ITSD has superior dried product quality than OSD and direct-type solar dryers because it can provide the required temperature, better drying control, and product with the original colour and taste. The two most common types of ITSD are (a) natural circulation and (b) forced circulation [20, 21]. Lingayat et al. [21] critically reviewed the most recent ITSD research, including natural and forced air circulation types. However, the natural circulation type ITSD is more sustainable and economical than the other types due to the inherent external energy requirement for the latter. However, recently, many research works [14, 15, 22-31] have been carried out to preserve agricultural products using different designs of ITSD.

As seen in the above literature, solar dryers can effectively dry and preserve agricultural products compared to other solar-based techniques and help farmers earn more. Moreover, since solar dryers inherently need no external energy, they are considered the more economical and environment-friendly way of preserving fruits and vegetables. Besides, most indirect-type solar dryers studied were constructed with either complicated structures or thermal storage materials/phase change materials containing carbon nanotubes, nanomaterials, nanocomposites, etc. Although it was found that the performance of the studied solar dyers improved, the initial cost of the dryers' also increased. Furthermore, in a developing economy, the initial price and ease of availability, and cost of resources for the product's maintenance, if needed, are vital concerns for farmers with low income and little or no formal education.

Hence, this study tries to develop a natural convection-based solar dryer that is simple in construction and can be fabricated with locally available materials at a reduced cost. To show the designed solar dryer's potential over the other two drying methods commonly used by the farmers, the indirect type solar dryer developed was tested in outdoor conditions and compared to direct solar and open sun drying methods.

2. Materials and Methods

2.1. Design and Fabrication of the Passive Solar Dryer

The solar dryer was built with two modules: a solar air collector (SAC), and a drying chamber, due to the inherent benefits of a modular design such as ease of production, maintenance, portability, and easy installation in any geographical location. The drying chamber has an approximate dimension of (width × depth × height) of 27 inch × 16 inch × 29.5 inch, while the solar air collector is 27 inch × 60 inch × 5 inch. The solar air collector, as shown in Fig. 1, was constructed of a wooden absorber frame lined with Styrofoam insulators. For maximum light transmissibility, an aluminium sheet with high thermal conductivity was chosen as the solar absorber, and 4 mm thick glass was chosen as the highly transparent glazing. Table 1 shows different physical, mechanical, and thermal properties of aluminium and glass. To absorb the most heat from the incident solar insolation, the aluminium absorber plate was painted black. The drying chamber is constructed with 1-inch-thick wood frames and a wooden back door sealed with rubber gaskets. The back door as shown in Fig. 1(b) serves to load and unload the food while also maintaining an airtight seal in the chamber. The air velocity was controlled by a sliding door made of particle board in the exhaust area, and the air velocity was measured by an anemometer installed in this area. A food tray arrangement consists of ten food trays made of aluminium wire mesh and wooden frames. The wire mesh allows more air to circulate around the food grains. The solar air collector (SAC) and the drying cabinet were both supported by four wooden pillars.

Table 1. Different properties of aluminium and glass [32].

Properties	Aluminium	Soda lime glass
Density ($kg.m^{-3}$)	2698	2530
Melting point (°C)	660.3	726
Young's Modulus (GPa)	70	72
Thermal conductivity ($W.m^{-1}.K^{-1}$)	237	0.937
Specific heat capacity ($J.kg^{-1}.K^{-1}$)	903	700-800

2.2. Sample preparation

Fresh and high-quality potatoes of comparable size were sliced in thicknesses of about 4mm using a hand-operated slicer. Prior to slicing, the vegetables were cleaned in tap water and blanched in water with a small amount of salt to stop enzyme action. The potatoes were blanched for 30-40 minutes. For drying measurements, a number of batches containing sliced foods weighing 100–500 gm were used. Solar drying has been reported to use sliced potatoes with similar thicknesses as considered in the present work by Vigneshkumar et.al [15].

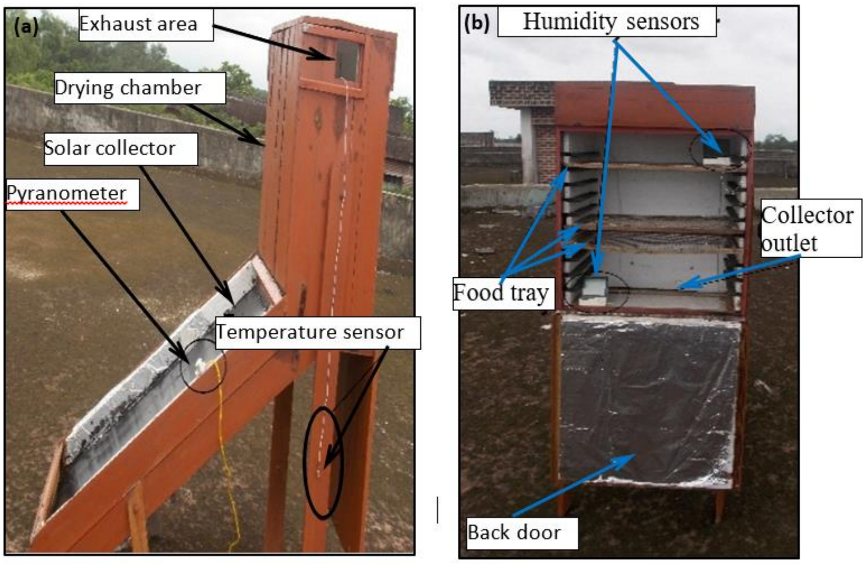

Fig. 1. Experimental setup for the indirect type solar dryer: (a) side view and (c) rear view.

2.3. Drying Experiments

The drying tests were conducted in Sylhet, Bangladesh, at latitude 24.89 N and longitude 91.88 E during the winter (November to January). At 25° inclined planes, the average solar insolation was reported to be around 5.2 W/m^2 [8]. The experiments, however, were conducted on mostly sunny days with wind speeds of up to 2.5 m^2/s. The drying methods tested in this investigation were open sun drying, direct solar drying, and indirect type solar drying with the fabricated passive solar dryer. Prior to the drying tests, the initial moisture contents of potato slices were determined by averaging three consecutive tests. In this work, the initial moisture content of the studied agricultural products was determined using the vacuum oven method at 70 °C for 24h [33].

The moisture content (MC) of the potato samples ranged from 67 to 82%wb (wet basis). Several drying tests to dry samples of potato slices were performed on sunny days between 10:00 am and 4:00 pm. During the drying period, the moisture loss of the vegetables was determined by weighing the sample with a digital electronic balance (resolution ±0.01g) at every 1hr time interval. After 4 pm, if the foods were not dry enough (less than 10% moisture content), the potato slices in the drying cabinet were collected and stored in sealed plastic boxes to induce moisture diffusion within the drying samples. The partially dried sample was placed in the dryer again the next morning, and the drying process was repeated until the moisture content of the potato was less than 10%. The dried products were then packed in low-density polyethylene bags until the sensory tests began one week later. To compare the performance of the studied passive solar dryer, several control samples of potatoes were placed on a tray inside the solar air collector for direct solar drying and outside the solar dryer for open sun drying under the same weather conditions.

During the drying tests, three humidity sensors with uncertainty ±1% were used to measure relative humidity and air temperatures (ambient and at various locations inside the dryer). The instantaneous solar radiation was measured using a solar intensity meter, Pyranometer (SP Lite2, Netherlands) with a resolution of ±1%. A van type thermo-anemometer (Equinox, Germany) with a ±0.5% uncertainty was utilized to determine the air velocity at the collector inlet and dryer exhaust vents.

2.4. Analysis of Drying Parameters

The performance of the developed passive solar dryer was assessed based on the air temperature of the solar air collector and dryer, collector efficiency, flow rate, moisture ratio, drying rate, dryer efficiency, drying time, and sensory characteristics of the dried foods. The percent moisture content of the food products was measured using Equation 1 and 2 as given below [21]:

$$\%\ MC\ (wet\ basis) = \frac{m_i - m_d}{m_i} \times 100 \quad (1)$$

$$\%\ MC\ (dry\ basis) = \frac{m_i - m_d}{m_d} \times 100 \quad (2)$$

where, m_i is the initial mass of the food product, m_d is the mass of the partially or fully dried product. The drying rate (DR) is determined by calculating the rate at which the moisture content changes between time t and t+Δt, as shown in Equation 3 [34]. Equation 4 can be used to calculate the percentage savings in drying time when using direct solar drying and passive solar drying methods versus open sun drying.

$$DR = \frac{MC_{t+\Delta t} - MC_t}{\Delta t} \times 100 \quad (3)$$

$$Drying\ time\ savings(\%) = \frac{DT_{open\ sun\ drying} - DT_{other\ methods}}{DT_{open\ sun\ drying}} \times 100 \quad (4)$$

During the drying tests, the moisture ratio (MR) was calculated using Equation 5 [34].

$$MR = \frac{MC_t}{MC_i} \times 100 \quad (5)$$

where MR is the moisture ratio, MC_t is the product moisture content at time, t on wet basis (kg water/kg wet matter) and MC_i is the initial product moisture (kg water/kg wet matter). The drying efficiency is defined as the ratio of energy consumed for moisture evaporation to energy supplied to the drying cabinet. This study takes into account the overall drying efficiency. As a result, the drying efficiency has been calculated using solar energy input to the collector or absorber (Equation 6).

$$Drying\ efficiency\ (\eta_d) = \frac{m_w L_w}{I A_c} \times 100 \quad (6)$$

where, m_w is the mass of moisture of water evaporated (kg), L_w is the latent heat of vaporization for water (kJ/kg), I is the solar radiation (W/m^2) *and* A_c is the area of aperture for the collector (m^2).

The solar collector efficiency is defined as the ratio of usable energy gain to incident solar energy over a given time period. As a result, the efficiency of a solar collector is expressed as follows (Equation 7):

$$Collector\ efficiency\ (\eta_c) = \frac{m_a C_{ap}(T_c - T_a)}{I A_c} \times 100 \quad (7)$$

where C_{ap} is the specific heat of air at constant pressure, m_a is mass flow rate of air, T_c is the temperature of air leaving the collector and T_a is the ambient temperature.

2.5. Sensory Tests

Sensory tests were performed to evaluate the quality of the dried food samples. Colour, taste, flavour, and appearance were all taken into account, and samples were collected using three different drying methods and labelled A, B, and C for solar passive, direct solar, and open sun drying, respectively. Students in their fourth year of Food Engineering and Tea Technology at Shahjalal University of Science and Technology in Sylhet tested the dried samples. For all attributes, the samples were graded on a scale of 1 to 5, with 1 denoting very good and 5 denoting very bad.

3. Results and Discussion

The area of the exhaust window of the drying cabinet was found to have a strong influence on the drying characteristics, so the optimum area was determined to maximize its drying performance. Fig. 2 depicts the variations in air temperature and relative humidity observed in the drying chamber as a result of a change in exhaust area. On shiny days between 12:30 pm and 1:00 pm, four tests with four different exhaust areas were carried out. For an exhaust area of 1.19×10^{-3} m^2, the highest air temperature and relative humidity in the drying chamber were observed as 47.8 °C and 13%, respectively. Therefore, this exhaust area was maintained for all subsequent tests.

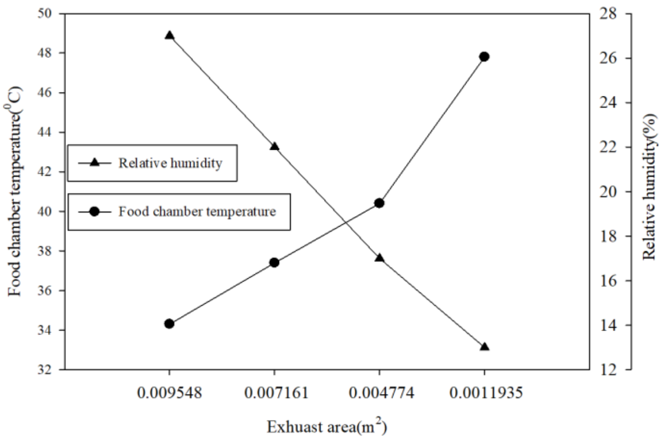

Fig. 2. Variation of air temperature and relative humidity in the drying chamber with exhaust area.

3.1 Drying Characteristics

Solar irradiance was measured under various sky conditions from 9:00 am to 5:00 pm as shown in Fig. 3. The figure depicts the expected fluctuations in solar irradiance due to the presence of cloud and the change in time of day. The sky was mostly clear during the drying tests, with a peak solar radiation of more than 950 W/m^2 at noon. During the tests, the average solar irradiance was found to be greater than 700 W/m^2.

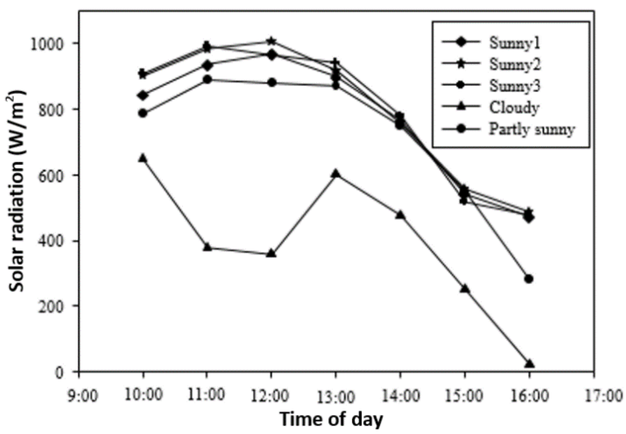

Fig. 3. Solar radiation variation over time on sunny, partly sunny, and cloudy days.

The fluctuations in air temperature and relative humidity at the entry and exit of the dryer as well as their atmospheric values are shown in Fig. 4. At 1:00 pm, the maximum temperatures at the entry and exit of the drying chamber were 54.2 °C and 51.1 °C, respectively, while the maximum ambient temperature was 26.5 °C. As shown in Fig. 3, solar radiation was at its peak at 12:00 pm, but air temperature was at its peak at 1:00 pm. This result is explained by the fact that the collector continues to absorb heat energy from its hot surroundings even after 12:00 pm. Fig. 4b depicts the variation in relative humidity at ambient and at the entry and exit of the drying chamber under no load conditions. As expected, the relative humidity of the air inside the drying chamber was lowest at 1:00 pm. According to the graph, the minimum relative humidity of the air at the inlet and outlet of the chamber was about 10% and 15%, respectively, while it was about 37% in the ambient air. Because of the high temperature and low relative humidity, the passive solar dryer had a higher drying potential than the open sun drying technique. These results are consistent with those of Çiftçi et al. [19].

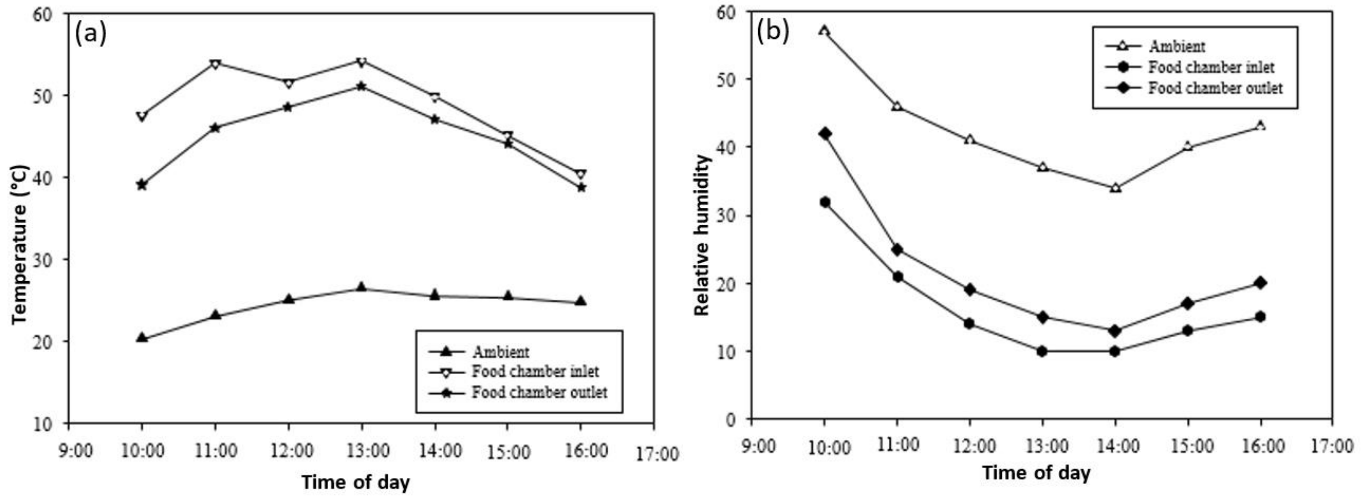

Fig. 4. Variation in (a) air temperatures and (b) relative humidity over time on a typical sunny day under no load conditions.

The variations in collector efficiency with time and air flow velocity are shown in Fig. 5. For the selected exhaust area, the figure shows that collector efficiency varies positively with air flow rate. The collector efficiency varied in a pattern similar to that of solar irradiance for the same air flow rate of about 0.4m/s (Fig. 3). As a result, it can be seen to vary proportionally with both solar irradiance and drying air temperature. The collector efficiency peaked at 1:00 pm due to the maximum air temperature (~54.2 °C in Fig. 4a) and air flow rate (~0.4m/s). Due to the maximum air temperature attained, the collector efficiency peaked at around 1:00 p.m. with a value of about 24%. This value is in line with the results of a previous study [29] that used nanofluids in a similar kind of flat plate solar collector.

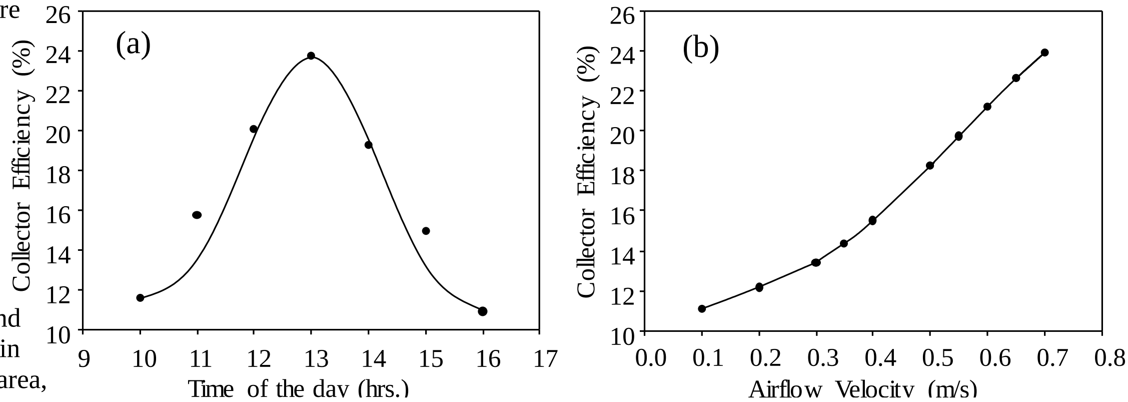

Fig. 5. Variation in collector efficiency with (a) time and (b) air flow velocity.

3.2 Comparison of the Studied Drying Methods

On mostly sunny days, the open sun, direct solar, and passive solar drying methods are tested for 200 gm of blanched potato samples. The average values of ambient air temperature, relative humidity, and solar radiation varied from 20 to 27 °C, 34 to 57 percent, and 470 to 1008 W/m^2, respectively, during the experiments, and their variations were also observed as previously discussed. Fig. 6 shows how the moisture content and moisture ratio of potato samples vary. Using all drying methods, the original moisture content of potato samples was reduced from roughly 82% to 8%. As seen in the figure, the moisture content drops somewhat sharply for first few hours till about 1:00 pm and then it decreases slowly due to the slow drying kinetics. The drying time for the developed passive solar dryer was found to be shorter than those of other drying methods. Similar findings have been reported for tomato slices by Olimat [14]. Fig. 6b shows that the solar passive dryer has the lowest moisture ratio at any time of day when compared to the other drying methods. Because of the higher water content of the sample, the moisture ratio was higher at the start of drying. However, it gradually decreased to a minimum value at 2:00 pm and then increased dramatically. During the final stage of drying, moisture content in potatoes is thought to be extracted from their inner core, slowing the rate of water evaporation. Therefore, that increase in moisture ratio can be attributed to the slower drying rate (Fig. 7a) and lower water content of the samples.

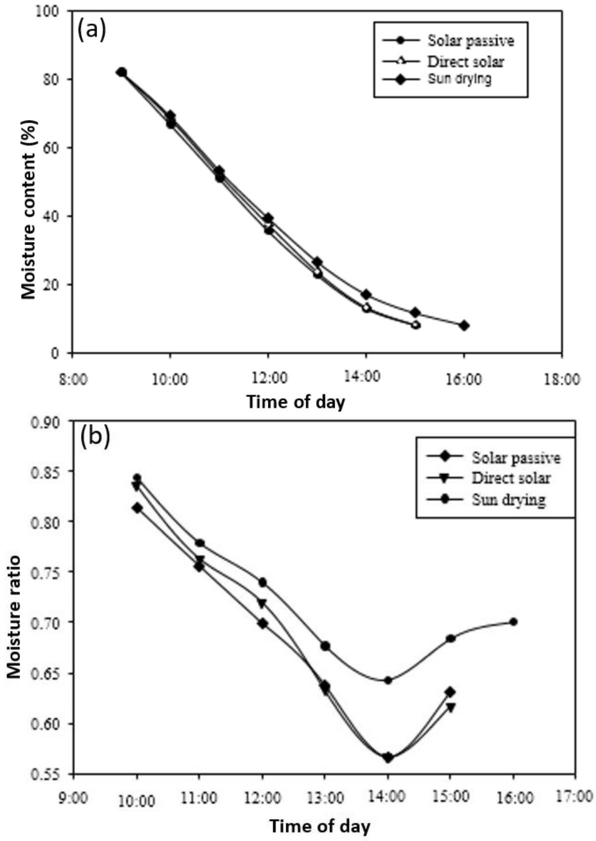

Fig. 6. (a) Moisture content and (b) moisture ratio of potato samples using solar passive, direct solar and sun drying methods.

Fig. 7 depicts the trends in drying rates as a function of time and moisture content of potato samples dried using the studied drying methods. The drying rate decreases near the end of the drying process because the samples contained less water to evaporate. The samples dried in the solar passive dryer shows a faster drying rate compared to the other methods with the lowest rate in the OSD method. Noteworthy, the solar passive drying rate fell below that of the direct solar drying method at 1:00 pm, because the sample of solar passive dryer had less water to evaporate. As shown in Fig. 7b, the drying rate increased for higher moisture content and then decreased rapidly at a lower moisture content. The trends of drying rate for potato samples observed in this study is in close agreement with Vigneshkumar et al. [15] and Çiftçi et al. [19].

3.3 Drying Performance of the Solar Passive Dryer

The variations in dryer efficiency with time and mass of the samples at 11:00 am using the passive solar drying method are shown in Fig. 8. The drying efficiency was found to increase until 11:00 am, after which it decreased for all three sample masses. The higher drying efficiency during the initial drying period is thought to be due to their higher drying rate and higher moisture content at that time. These findings are consistent with those found in a previous work by Vigneshkumar et al. [15]. Fig. 8b shows that as the loading increased, so did the dryer efficiency. The average efficiency was found to be 4.3, 14.4, and 18% using samples of 100, 300, and 500 g, respectively. This was primarily due to the fact that as loading increased, a greater amount of water was evaporated at the start, and as moisture content decreased, drying efficiency decreased due to less evaporation of water. Fig. 8b depicts the increase in maximum dryer efficiency as the number of samples loaded into the drying chamber increases. Because the trays were brought out for inspection every hour, the drying efficiency curve was not as smooth as it should have been due to a smaller number of experimental data. It is worth noting that the passive solar drying technique has the highest dryer efficiency of about 21% at 11:00 am using a sample mass of 500 g. The drying time for potato samples was calculated as the time required to achieve a moisture content of about 15%. The drying time for 500g samples was found to be 320, 360, and 400 minutes using the solar passive, direct solar, and sun drying methods, respectively. The studied passive dryer was found to be more efficient than direct solar and open sun drying methods, resulting in 11.1% and 20% less drying time, respectively. Because direct solar drying occurs inside the collector under refracted sunlight through a glass cover, the samples are not exposed to direct solar irradiation and ambient wind flow, so drying the potato samples takes longer than open sun drying.

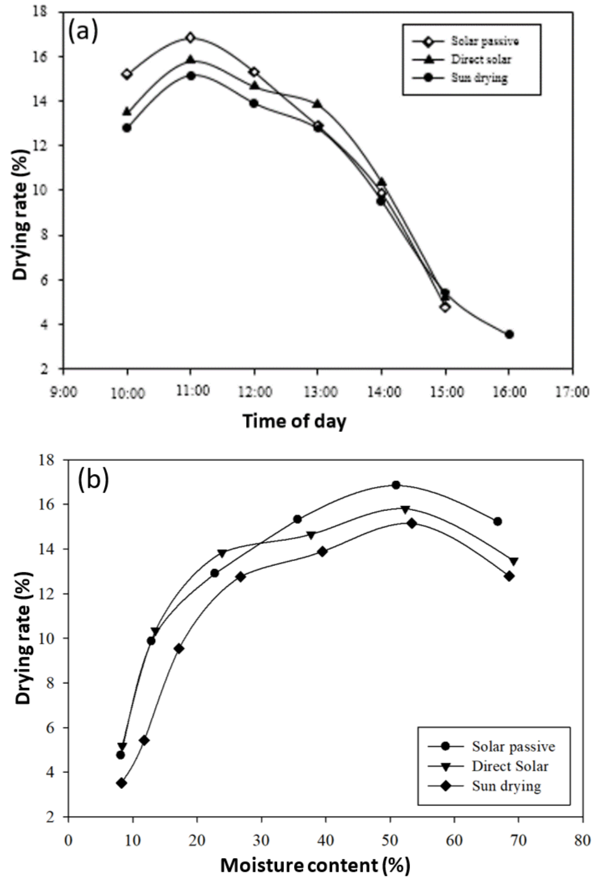

Fig. 7. Variation of drying rate with (a) time and (b) moisture content.

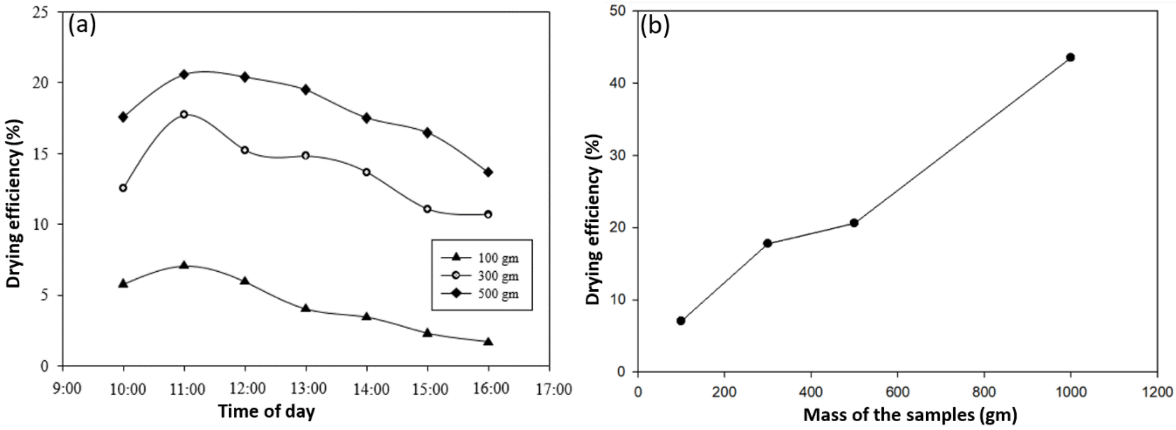

Fig. 8. Variation in dryer efficiency with (a) time and (b) mass of the samples dried at 11:00 am under sunny conditions.

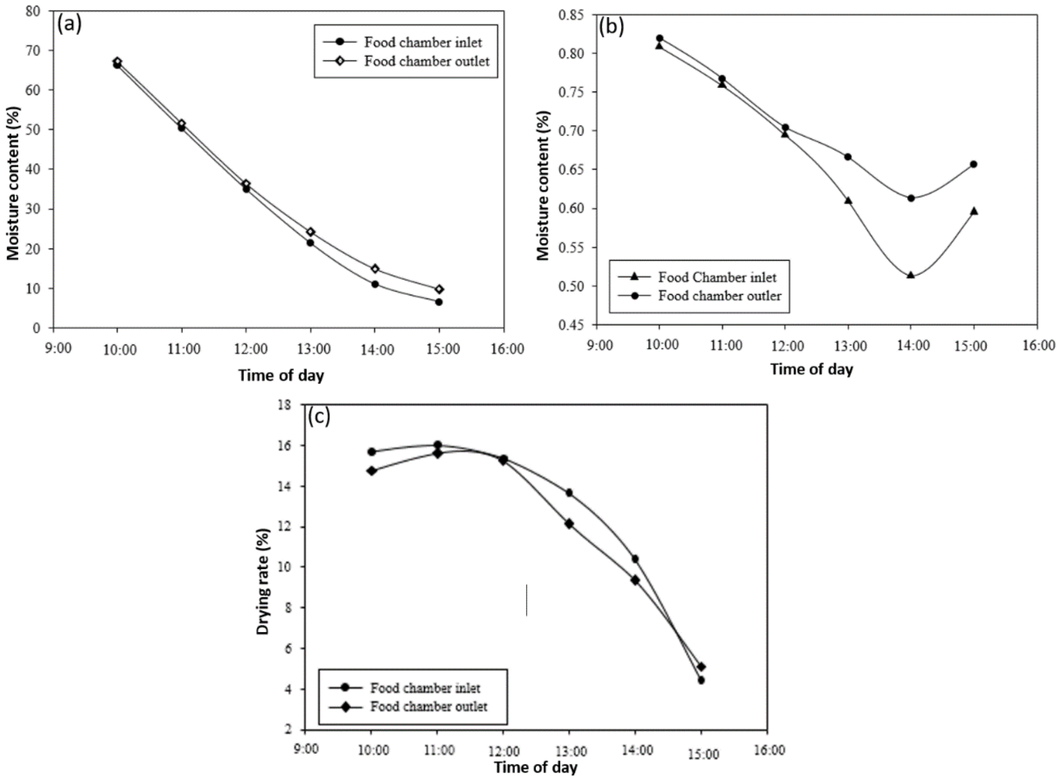

Fig. 9. Variation in (a) moisture content, (b) moisture ratio and (c) drying rate with time at the dry chamber inlet and outlet.

Variations in air temperature and relative humidity at the dryer inlet and outlet (Fig. 4) are expected to result in variations in drying characteristics. Therefore, the samples near the entry and exit of the drying cabinet were separately investigated for moisture content, ratio, and drying rate to see the variation of drying parameters inside the dryer chamber, as shown in Fig. 9. The moisture content (MC) of the potatoes (82%) was reduced to 6.5% after 320min and 9.8% after 350min for the samples at the inlet and outlet, respectively. Because of the higher temperature at the inlet, the moisture content and moisture ratio of the samples were found to be higher at the inlet than at the outlet, as shown in the figure. The drying rate of the potato samples at the inlet was also slightly higher than that of the samples at the outlet.

3.4 Food Quality Attributes

Table 2 displays various quality attributes on a scale of 1 to 5, with 1 being the highest quality and 5 being the lowest quality. In this study, potatoes dried by the open sun and direct solar drying methods were of acceptable quality but slightly inconsistent in colour. The colour of the samples dried in the solar passive dryer was pleasing and even (Fig. 10). The mean value in the table for sample A is lower than the mean value in the other two samples, indicating that sample A has better attributes than the other two samples. The mean value of sample A for colour and appearance, as shown in Figure 10, was found to be around 1, indicating that the colour and appearance were quite attractive and good, whereas samples B and C had medium colour and appearance. In terms of taste and flavour, sample A had a mean value near 2, indicating good taste and flavour, whereas samples B and C had a medium value. It is worth noting that the cost of fabricating the solar passive dryer were calculated to be around BDT 28000 or USD280, thereby, a cheap and effective solar dryer have been successfully built.

Table 2. Quality attributes of the potato samples dried using various drying methods.

	Sample A (Solar passive drying)	Sample B (Direct solar drying)	Sample C (Open sun drying)
Sample size/Expert interviewee (N)	7	7	7
Colour	1	2.6	3
Taste	1.9	2.6	2.9
Flavour	1.7	2.7	2.9
Appearance	1	2.7	2.9

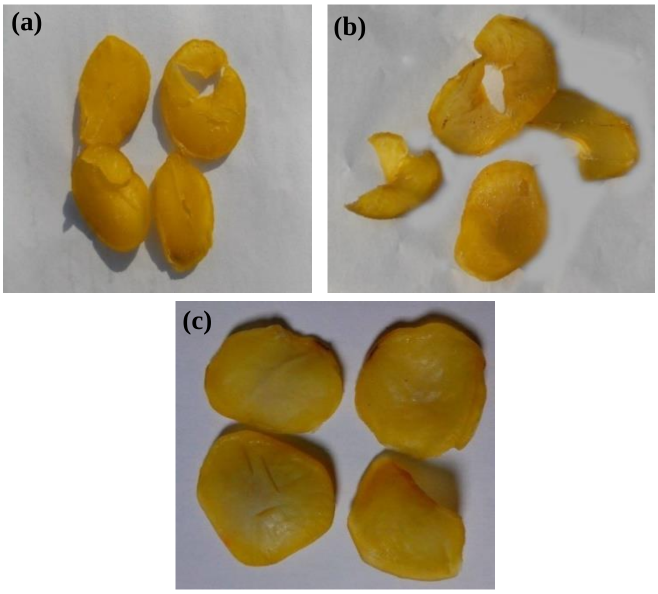

Fig. 10. Photographs of the potato samples dried using (a) passive solar, (b) direct solar and (c) open sun drying methods.

4. Conclusion

In this research work, a simple and inexpensive passive solar dryer was developed and tested for drying performance. A decrease in the exhaust area of the passive solar dryer result in reducing the flow rate and relative humidity of the air while increasing the air temperature. For an exhaust area of 0.0011935 m^2, the maximum temperature and minimum relative humidity were about 54.2 °C and 13%, respectively. An increased air flow rate was observed to improve collector efficiency. The drying rate was found to decrease as the moisture content decreases. Due to the higher moisture content of the loaded products, dryer efficiency increases with the number of samples loaded in the drying chamber. When compared to open sun drying and direct solar drying, the solar passive dryer saved 20% and 11.11% of the drying time. The colour, taste, appearance, and flavour quality attributes of solar passive dried samples were found to be superior to those of direct solar and open sun dried samples. Furthermore, the dried potato samples were seen to be free of dust, sand, and other contaminants. These findings can be improved further by using numerical simulation to design cost-effective solar dryers for agricultural products.

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