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Investigation of the thermal performance of an indirect forced convection solar dryer for tapioca chips drying

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ABSTRACT

Tapioca (cassava) is rich in carbohydrates and is usually dried through the open sun drying method in rural areas, which ultimately reduces the quality of the dried products. Solar dryers are commonly preferred green structure for drying mostly food products under controlled environment by utilizing clean and eco-friendly solar energy. In this work, an indirect solar dryer powered by a solar air heater is fabricated with longitudinal fin arrangements for efficient heat exchange between the sensible heat storage material and absorber plate. The solar air heater is additionally facilitated with twin tilt adjustable mountings to maximize the absorption of solar insolation. Initial moisture content of tapioca was reduced from 64.45% (wet basis) to less than 10% (wet basis) in 90 min at 0.03 kg/s air flow rate with the average thermal efficiency of 34.75%. The effective moisture diffusivity value for solar drying was found to be varying between 6.769×10^{-11} and 9.298×10^{-11} m^2/s for different flow rates, whereas for the open sun drying it was determined as 3.572×10^{-11} m^2/s. The payback period of the solar drying system is obtained as just 1.30 y, which is much lower than the life of the system (10 y). The quality analysis of the dried samples indicated that the total colour change of the solar drying is better than the open sun drying. It is concluded that the solar drying substantially, reduces the drying time and can be utilized as an economic empowerment option for the rural women.

Keywords: Solar drying; Indirect solar drying; Tapioca chips; Thermal performance; Drying characteristics

1. Introduction

Cassava (Tapioca) is one of the major commercial crops cultivated in southern states of India such as Tamil Nadu, Andhra Pradesh and Kerala. It is also called as sago or sabudana. The plant is categorized as a woody shrub and belongs to spurge family. In Tamil, the roots are usually called as Kuchi Kizhangu or Maravalli Kizhangu and are used to prepare pappad & chips. There are many value-added products which are being obtained from cassava plants such as starch, sago, chips, flour from chips, thippi, peel, sago wafers etc. [1]. The processes involved in the extraction of tapioca from the cassava are peeling, washing, grating, soaking and drying. Drying is one of the important operations carried out in the extraction of tapioca. In most of the rural areas, open sun drying is adopted as it is very easy to adopt and there is no energy

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cost involved in it. However, pollution and other issues such as animals, birds and human intervention caused the processing of open sun drying more tedious. The quality of the dried cassava chips is influenced by the drying air temperature, velocity, humidity of the environment, surface area and size of the chips [2]. In the case of small-scale processing industries, the drying is usually practiced by means of mechanical or electrical dryers. They mostly use high-grade energy/fossil fuels, which makes the drying process more expensive. The best alternate for mechanical dryers is solar drying since solar energy is clean and free. The device, which utilizes the incoming solar radiation, that is, solar insolation for drying, is known as solar dryer and they may be classified as free or forced convection dryers on the basis of air circulation method. Sometimes, solar dryers may also be classified as direct, indirect and mixed-mode dryers based on the mode of utilizing the solar insolation. Ong [3] recommended that the forced convection solar dryers are the good choice for their desirable factors such as better control over drying, accelerated drying, etc.

Over the years, numerous forced convection solar dryers have been developed with various performance enhancement techniques such as the incorporation of energy storage materials, enhanced solar collector, etc. and their performances are reported for drying various agricultural products. A forced convection indirect solar dryer (ISD) with sensible heat storage for chilli was designed and investigated by Mohanraj and Chandrasekar [4]. The drying system was integrated with sand and aluminium scrap mixture as the sensible heat storage medium and inferred that the solar dryer with heat storage is preferable for achieving superior dried products. Seshachalam et al. [5] studied thermal behaviour of a triple pass ISD with thermal energy storage for drying carrot slices. The solar collector was incorporated with a wire mesh and sand (thermal energy storage) to improve the performance and they reported that the thermal efficiency varied from 12% to 66%. Similarly, some of the researchers have used rock or pebbles as a thermal energy storage material. An ISD with porous pebble bed in the airflow passage of the solar collector was designed and the thermal performance was studied for drying bitter gourd slices by Vijayan et al. [6]. They reported that sensible heat storage based solar dryer is capable of delivering more consistent performance. Lingayat et al. [7] presented a detailed review of the ISD construction, performance, types, etc. They observed that the thermal energy storage integrated solar dryer considerably reduced the drying time of the product.

Drying behaviour of the agro-produce has been reported by many researchers through different methods such as convective oven, microwave oven, solar dryer, open air drying, low temperature drying etc. The drying process of the products can be described using the theoretical, empirical or semi-empirical models. Many researchers have modelled the thin layer drying characteristics of the vegetables and fruits such as potato [8], bitter gourd [6], grapes [9], apricot [10], pear [11], sweet cherry [12], garlic [13], long green pepper, chilli pepper [14,15]. The modelling has also been extended to leafy vegetables and herbs; curry leaves [16], *Citrus aurantium* leaves [17], mint leaves [18], etc. Drying characteristics of cassava chips were analyzed to study the effect of temperature (60°C, 80°C, 100°C and 120°C) and the shape of chips (rectangular and circular). They modelled the thin layer drying behaviour of cassava chips and found that the Page model is a suitable one [19]. Energetic and exergetic investigation was carried out by Aviara et al. [20] for drying cassava starch under tray drying. Their results showed that the energy utilization increases while increasing the drying temperature and they also developed exergetic equations in terms of drying air temperature. Olalusi et al. [21] developed a mobile passive type ISD for cassava chips drying. Their set up comprised of a collector (200 mm × 300 mm) with reflector, drying chamber (8 trays) and wheels for mobility. Their investigative results indicated that the system dried 500 g in 6 h with the thermal efficiency of 58.4%. The drying behaviour of tapioca was investigated through various drying methods such as open sun drying, conveyor belt drying, bin drying, and fluidized bed drying. They noticed that the lowest drying time was 65 and 80 min for fluidized bed and conveyor belt drying methods, respectively. Finally, they concluded that all the drying methods produced good quality dried sago as per the SAVOSA quality estimation [22].

The extensive literature survey on indirect solar drying studies revealed that the forced convection solar dryer is the most preferable to retain the maximum nutrients and to have better control over the drying process and further, the integration of sensible heat storage also enhances the performance of the dryer. Sensible heat storage materials are simple and easy to incorporate in the air flow path for achieving consistent hot air to the drying chamber. It is also noticed that only very few articles on the drying of tapioca chips using convection dryers. However, solar drying characteristics of tapioca chips have not been reported. Therefore, in this work an indirect forced convection solar dryer was used that consisted of an efficient solar air heater with porous medium of copper scrap thermal storage material in the flow path and longitudinal fins provided in the collector for efficient heat exchange between the sensible heat storage material and absorber plate. The solar air heater is additionally facilitated with twin tilt adjustable mountings to maximize the absorption of solar insolation. The thermo-economic performance and drying characteristics of the developed system were studied for drying tapioca chips.

2. Materials and methods

The experimental setup was fabricated and installed on the terrace of a building. The experimental studies have been conducted at various mass flow rates in the meteorological conditions of Namakkal (latitude of 11.25°N; longitude of 78.15°E) during the months of October – November 2020.

2.1. Description of the experimental setup

The experimental setup comprised of two major components such as a solar collector and drying chamber. In addition, a blower is also used to circulate the air from the ambient through the system. The detailed description of the components is given below.

2.1.1. Solar collector

Flat-plate solar collector is a distinct type of heat exchanger that contains a radiation-absorbing flat plate underneath the transparent cover; it uses both beam and diffuse solar radiation to heat the air as a working fluid. It delivers at moderate temperatures, up to 100°C. It is comparatively simple in construction and less expensive to fabricate, install, and maintain.

In this work, flat plate solar collector was designed with the dimensions of 700 mm × 400 mm × 180 mm. The bottom plate and sides were made using a galvanized iron sheet (GI) of 1 mm thick. A black coated 0.8 mm thick copper plate was used as absorber plate (It was designed in such a way that other types of absorber plate materials such as aluminium or galvanized iron sheet of 0.8 mm thickness that may be used for research purpose, can be easily assembled or disassembled by means of temporary joints using screw, washer and nuts). The holes provided on the absorber plate for fastening purpose were sealed with asbestos washer and Polystyrene foam. All the four sides of the solar collector box were insulated using thermocol (other types of insulating materials such as coconut fibre or glass wool may be used for research purpose) of size 25 mm thickness, and 50 mm thickness at the bottom side of the collector box. The top of the solar collector box was covered using a window glass of 4 mm thickness (the glass cover can be replaced easily by means of the duct tape around it for the purpose of research using different thickness of glass cover, for example 5 mm or 6 mm) at a distance of 30 mm from the absorber plate to minimize the convective heat loss to the ambient. The detailed drawing is shown in Fig. 1. The top four edges of the collector box provides cushioning effect to the glass cover, due to the soft packing materials such as polystyrene foam fitted to the collector. The four corners of the collector box after fixing the glass cover were sealed with air tight duct tape to get the desired air flow rate without leakage.

In order to effectively transfer the heat from the absorber plate, two additional unique copper fins of size, 0.8 mm thickness having 60 mm width at the top portion and 30 mm width at the bottom portion and the height of 100 mm, length of 650 mm, which are mounted along the lengthwise with the bottom plate (30 mm side of the fins) of the inner collector box, it also provide additional support to the copper absorber plate at the top side (60 mm side of the fins) and fastened by means of screw, washer and nuts, as shown in Fig. 2. These fins are the most efficient arrangement to extract the maximum fraction of solar irradiance falling on the absorber plate and transferring it to copper scraps, the sensible heat storage materials (the other types of sensible heat storage materials are similar to aluminium scraps or iron scraps for the purpose of research work) provided in the air passage between the absorber plate and the bottom plate of the inner solar collector box.

Copper scrap was filled to a height of 80 mm in all the three compartments to act as sensible heat storage medium. The heat storage material is provided to supply consistent hot air to the drying chamber [6]. The entire setup was completely covered using 1 mm thick GI sheet to extend the life of the system. The drying chamber and the total system with solar collector were arranged as shown in Fig. 3. Rubber beadings, polystyrene foam and duct tape were provided at all the junctions to minimize the air leakage.

To achieve the good air flow at the entrance of the collector, a diverging portion (rectangular opening of 125 mm × 45 mm from 50 mm diameter circular duct) was attached between the collector and the air supply unit. Similarly, for ensuring the better hot air supply to the drying unit, a converging portion (50 mm diameter circular duct from 125 mm × 45 mm) was attached in between. A small handheld heavy duty 325 watts blower

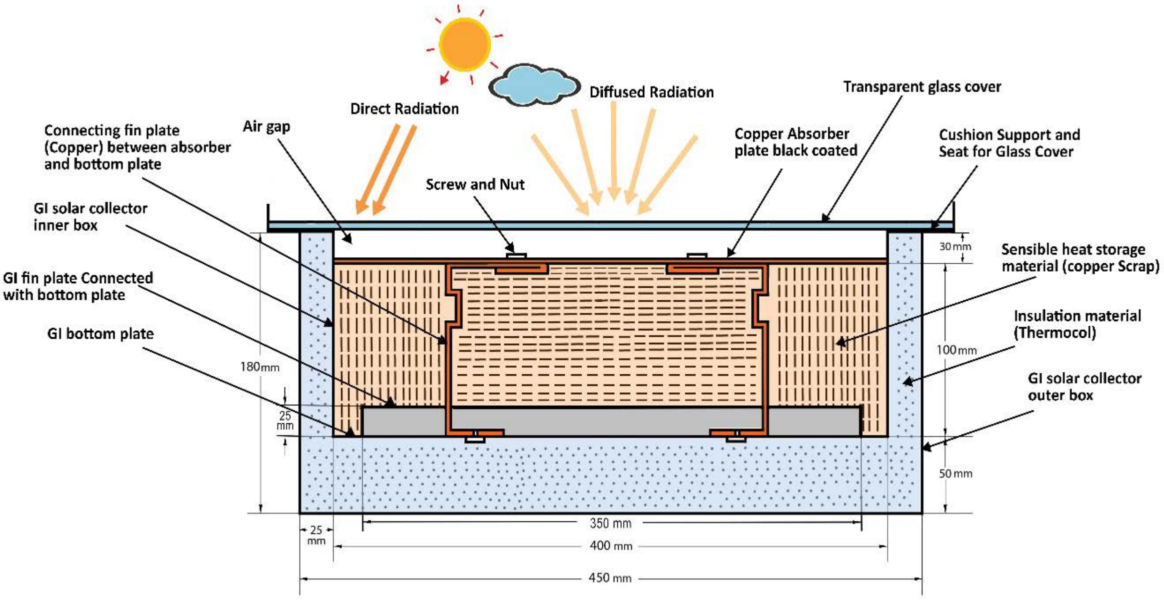

Fig. 1. Cross sectional view of solar collector.

Fig. 2. Solar collector without and with sensible heat storage material (copper scrap).

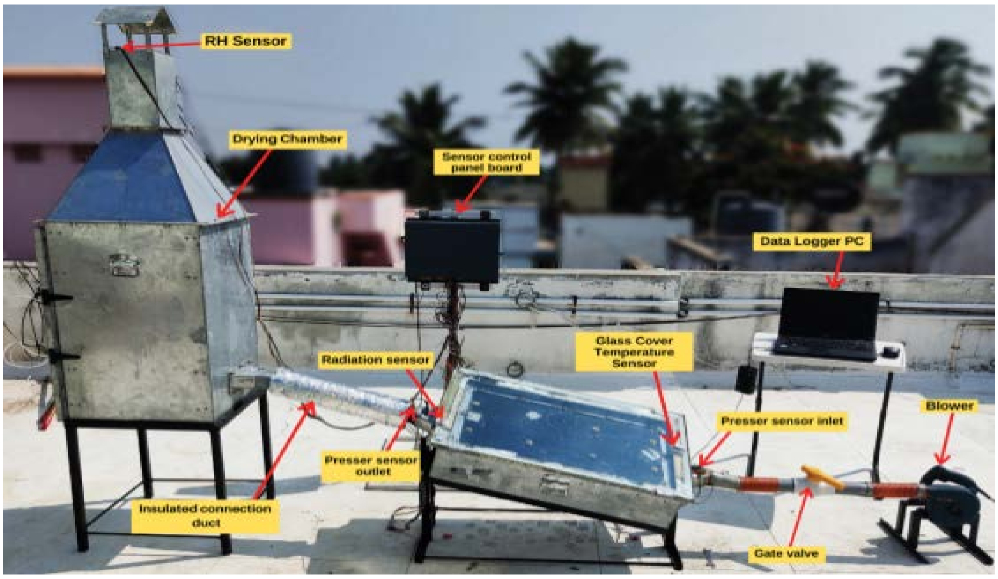

Fig. 3. Experimental setup.

was connected with a flexible hose to supply the air to the solar collector along with a ball valve to vary the airflow rate. To maximize the solar insolation collection, the collector has to be positioned on an adjustable stand and it can be varied from an angle equal to the latitude of the location [6]. In this work, for quick positioning (East to West), the collector was mounted on an adjustable stand and varied from 12° to 16° with the help of additional provision made at the lower portion of the stand (to vary the inclination according to the sun positions during a year). The supporting stand of the solar collector was fabricated with equal L angle of size 20 mm × 20 mm × 3 mm along with the angle adjustment as well as tilting arrangements for solar tracking.

2.1.2. Drying chamber

To place the products for reducing the moisture, a separate unit called drying chamber was fabricated with five trays and was separated by 100 mm in between. The drying unit (400 mm × 400 mm × 1,500 mm) was fabricated and insulated with thermocol of 25 mm thick on each side to reduce the heat loss to the surroundings. For spreading the products and to have better air circulation, the trays were formed using the food quality perforated sheet of aluminium material with an area of 0.144 m^2 (0.380 m × 0.380 m). The trays can be easily removed to load and unload the drying product through the door, which represents one side of the drying chamber. The drying chamber is facilitated with the chimney for a height of 500 mm to ensure the quick removal of the moist air from the chamber. A flexible insulated metal pipe was provided in between the collector and the convergent portion of the drying chamber.

2.2. Experimentation

The experimental setup is provided with the required measuring instruments to record the data for performing the analysis. The temperature of various elements such as ambient air, solar collector glass temperature, absorber plate, back plate, collector inlet, outlet, drying chamber inlet and outlet temperature of air was measured by means of k-type thermocouples. The thermocouples were connected to a data acquisition system and the observations were recorded for every 10 min interval. Solar irradiance on the collector was measured using a solar power meter. Airflow rate was measured by means of a vane type anemometer having a measuring range of 0–45 m/s. The weight of the samples was measured using a digital weighing machine capable of measuring up to 10 kg. The detailed specification of the instruments used is indicated in Table 1.

The observations were noted during the day time from 09:00 to 17:00. The wet products (tapioca chips) were loaded at 10:00 and continued till the stagnation in the drying process. The cassava roots (tapioca) opted for the drying was of identical in size to ensure the uniform drying. The soil and dirt deposited on the skin of the cassava root were washed with the help of tap water at room temperature. Then the skins of all the roots were peeled off using a knife and sliced by means of a vegetable slicer, to get uniform thickness (1–1.5 mm) of all the slices. The initial moisture content of tapioca chips was determined through the convective oven drying method [8]. The average initial moisture content of 64.45% (wet basis) was obtained from three trial studies. The tapioca slices were spread on the trays such that all the slices are exposed to the hot air on both the sides. Sliced tapioca chips were of diameters 40–50 mm; 200 g of wet tapioca chips were placed on each tray for drying. In order to estimate the amount of moisture removed from the products, the weight of the samples was found at every 30 min during initial periods and 15 min on later periods. For all the experiments, 1 kg of tapioca chips (200 g on each tray) was used. It was also noticed that the products on the lower tray experienced more hot air; therefore the weight reduction was more than in the other trays. To avoid over drying, the trays were swapped with the other trays (on top) while taking out for weight measurement. The stages in the cassava chips drying process are shown in Fig. 4.

Experimental uncertainty analysis is important as it determines the value of possible errors in the measured and calculated parameters, because errors in the experimental observations are inevitable. In this experimental study, the measured variables are solar irradiance, temperature, relative humidity, air velocity and weight of the samples. The uncertainty was estimated using (Eq. (1)): suggested by Holman [23]

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{1/2} \tag{1}$$

where w_R is the uncertainty in the calculated variable and w_1, w_2…… w_n are the uncertainties in the measured variables. The uncertainty values in the calculated parameters such as thermal efficiency, drying efficiency and SMER are ±0.2025, ±0.051 and ±0.051, respectively.

3. Data analysis

The thermal performance of the solar dryer is usually expressed with the key performance indicators of the major components of the system such as thermal efficiency, outlet air temperature, and useful heat gain for solar collector and overall dryer efficiency, specific moisture extraction rate (SMER), specific energy consumption (SEC), etc. The significant component of ISD is solar collector and the key parameters are thermal efficiency, useful heat gain, outlet air temperature, etc. The thermal efficiency can be estimated through Eq. (2) [24] as follows:

$$\eta_c = \frac{\dot{m} C_p \left(T_o - T_i\right)}{A_p I} \tag{2}$$

where $\dot{m}$ is the mass flow rate of the air, T_o and T_i are the collector outlet and inlet temperature, A_p is the aperture area of the collector and I is the solar insolation falling on the collector in W/m^2. Another important parameter is overall dryer efficiency, which can be defined as the ratio between the amount of energy effectively utilized to dehydrate the product to the total energy provided to the system. In the case of forced convection solar dryer, the energy supplied to the blower may also be accounted, using Eq. (3) suggested by Usub et al. [25]

$$\eta_d = \frac{WL}{A_p I + P_f} \tag{3}$$

Drying is an energy-intensive process; therefore, the energy utilization is accounted with the parameters

Table 1
Specifications of instruments

Name of the instrument	Purpose	Make/model	Range	Resolution	Accuracy
Solar power meter	To measure solar irradiance	TES-1333	2,000 W/m^2	1 W/m^2	±10 W/m^2
Vane anemometer	To measure the velocity of air entering and leaving the system	HTC AVM-06	0°C–50°C 0–45 m/s	0.1°C 0.01 m/s	±0.5°C on 0°C–45°C ±3% on velocity
Weighing machine	To weigh the samples	Accurate electronics/ ATC-10W-Rear	0–10 kg	1 g	±1 g

Raw cassava After peeling After slicing After drying

Fig. 4. Sample preparation stages.

namely SMER and SEC. They are estimated using Eqs. (4) and (5) [26,27] as follows:

$$\text{SMER} = \frac{\text{Total mass of water removed in kg}}{\text{Total Energy supplied}} \tag{4}$$

$$\text{SEC} = \frac{\text{Total Energy supplied}}{\text{Mass of water removed in kg}} \tag{5}$$

The initial moisture content of the tapioca chips (M_i) on wet basis was calculated using Eq. (6):

$$M_i = \frac{W_o - W_d}{W_o} \times 100 \tag{6}$$

where W_o is the weight of the sample at $t = 0$ in kg, W_d is the dry mass of the sample in kg. Moisture ratio (MR) is a dimensionless indicator used to express the ratio of moisture content at any time (t) and the initial moisture content, which can be calculated using Eq. (7) [25]:

$$\text{MR} = \frac{M_t}{M_i} \tag{7}$$

The drying rate (DR) of the samples may be expressed in Eq. (8) [28]:

$$\text{DR} = \frac{dM}{dt} = \frac{M_{t+\Delta t} - M_t}{\Delta t} \tag{8}$$

Effective moisture diffusivity of the tapioca chips for solar drying process can be determined using Eq. (9), which relates D_{eff} with MR as [28]:

$$\text{MR} = \frac{M_t - M_e}{M_i - M_e} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 \cdot D_{\text{eff}}}{4r^2} \cdot t\right) \tag{9}$$

$$\ln(\text{MR}) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 \cdot D_{\text{eff}}}{4r^2} \cdot t\right) \tag{10}$$

The above equation can be compared with a straight-line equation ($y = mx + c$). Then the effective moisture diffusivity of the product during the drying can be estimated from the slope of a line drawn between ln(MR) and the drying time (Eq. (10)): Slope (k_0) of that line can be expressed by the following equation:

$$k_0 = \frac{\pi^2 D_{\text{eff}}}{4r^2} \tag{11}$$

3.1. Economic analysis

Economic feasibility of the developed solar drying system is analyzed for drying of tapioca chips, which considers all the costs involved such as capital cost, maintenance cost, labour cost, operation cost, and the product cost. The payback period is an important parameter in economic analysis and is estimated using Eq. (12) [29] as follows:

$$\text{Payback Period} = \frac{\ln\left(1 - \frac{C_{\text{cc}}}{S_1}(d - i)\right)}{\ln\left(\frac{1+i}{1+d}\right)} \tag{12}$$

where C_{cc} – capital cost of the drying system, d – rate of interest, i – rate of inflation, and S_1 – savings gained in first year.

4. Results and discussion

The drying characteristics of tapioca chips were studied under forced convection solar dryer and the key parameters identified for the performance evaluation of the experimental setup are the outlet air temperature, thermal efficiency, SEC, etc. Fig. 5 explores the variations of solar irradiance, solar collector components such as glass, absorber plate, back plate temperatures and air outlet temperature for 0.01 kg/s flow rate of air. From the graph, it is noted that the temperature of the solar collector components is following the solar insolation profile, that is, temperature raises with an increment in solar insolation and vice versa.

The ambient temperature of the day (14/10/2020) was noticed in the range of 30.8°C–36.2°C. The peak solar irradiance of 1,042 W/m^2 was observed at 12.40 h. The maximum collector outlet air temperature was noted as 46.7°C

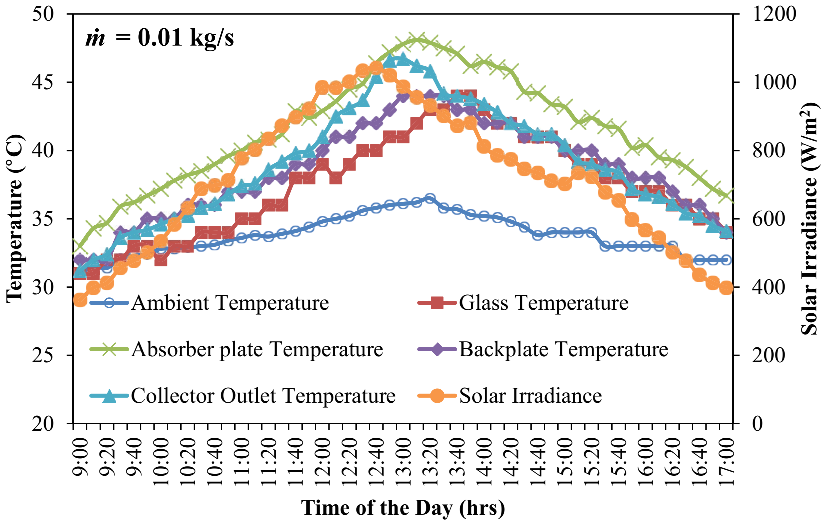

Fig. 5. Variations of solar collector component temperatures for the flow rate of 0.01 kg/s.

at 13.00 h. Absorber plate temperature was 2°C–6.8°C more than the outlet air temperature. The experimental studies were conducted at different flow rates of air and the days with equivalent insolation profile are only taken for the further analysis and comparison as to minimize the errors associated with it. The average solar insolation values are 717.49, 745.92, 738.87 and 725.16 W/m^2 for the mass flow rates 0.01, 0.02, 0.03 and 0.04 kg/s, respectively.

Fig. 6 shows the variations of solar collector outlet air temperature for different flow rates of air from 0.01 to 0.04 kg/s. The maximum and minimum outlet air temperatures were observed for 0.01 and 0.04 kg/s flow rates. From the graph, it is noted that the outlet air temperature diminishes with increment in the flow rate of air due to the fact that the rise in flow rate results in enhanced air velocity, which drastically reduces the residence time of air inside the collector. The sensible heat storage medium has influenced the consistent outlet air temperature. The outlet air temperature was maintained slightly higher (1°C–5.7°C) than the ambient temperature during the periods from 16.00 to 17.00 h. The discharging period of sensible heat storage was very short for the peak flow rate of air and also caused the low-temperature rise.

The thermal efficiency of the solar collector is an important performance indicator, which shows how effectively the solar insolation is utilized to heat the flowing air. Fig. 7 indicates the variations of the thermal efficiency of the solar collector for different flow rates of air during the experimental observations. The thermal efficiency profile of all the mass flow rates imitates the solar insolation trend of the day. During the low sunshine (evening) periods, the thermal energy stored in the copper scraps were released through the flowing air, which results in enhanced thermal efficiency as indicated in the graph. The maximum thermal efficiency of 62.14% was achieved at 13.40 h with 0.04 kg/s flow rate of air.

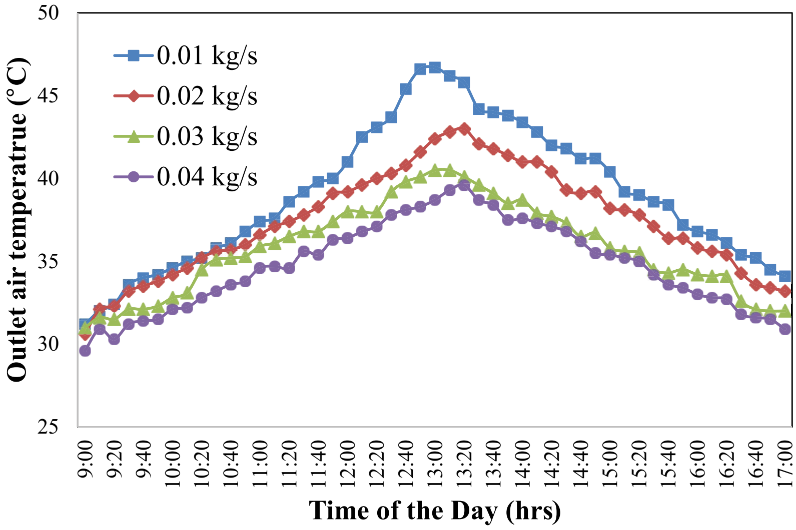

Fig. 6. Variations of collector outlet air temperature for different mass flow rates of air.

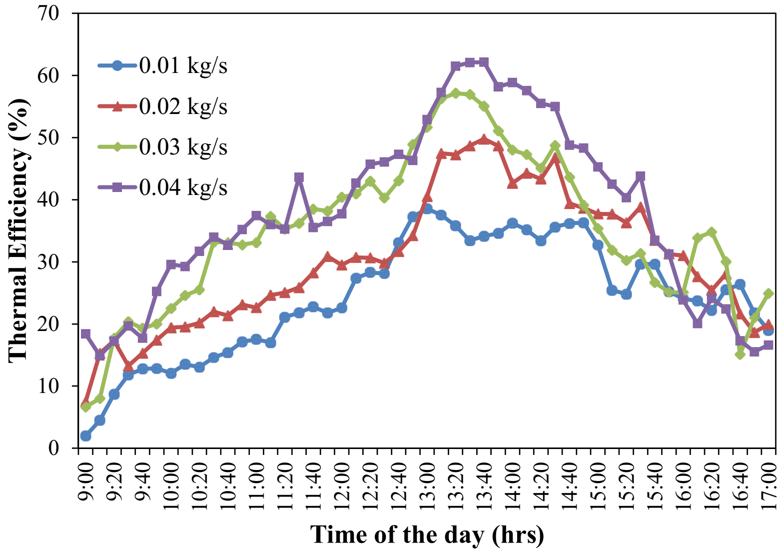

Fig. 7. Thermal efficiency as a function of time of the day for different mass flow rates of air.

The average and maximum thermal efficiencies for the different flow rates of air are presented in Fig. 8. The average thermal efficiencies were 24.37%, 30.21%, 34.75% and 37.76%, respectively, for 0.01, 0.02, 0.03 and 0.04 kg/s mass flow rate of air.

The drying characteristics of tapioca chips were evaluated based on drying time, drying rate, energy consumption, drying efficiency and effective moisture diffusivity values. The drying time to lessen the initial moisture content of 64.45% (wet basis) to less than 10% (wet basis) was noticed as 2 and 3.5 h, respectively, for solar and open sun drying. Variations of MR with the drying time are revealed in Fig. 9. For all the flow rates, the drying was continued till the stagnation in the drying process, but for the comparison, the moisture reduction less than 10% (wet basis) was considered, the time taken was 105, 105, 90 and 120 min for the mass flow rates 0.01, 0.02, 0.03 and 0.04 kg/s, respectively. In the case of open sun drying, the drying time was around 210 min. Solar drying has reduced the drying time by about 90 min when compared with the open sun drying, due to the reason of forced convective drying using the warm air.

The result of the drying characteristics of the solar drying system is compared with the multipurpose convective tray dryer and reported by Argo and Ubaidillah [30]. They conducted the experimental study of drying cassava chips by means of a convective dryer powered by two LPG burners and the hot air supplied at 2.5 m/s to the drying chamber. They observed that the initial weight of 12 kg was reduced to 5.46 kg in 345 min, whereas in the present study it took only 120 min due to the reason of very low thickness (1–1.15 mm) of the samples. It clearly indicates that the thickness of the sample plays an important role in the drying.

The change of drying rate (DR) as a function of drying time is demonstrated in Fig. 10. The highest drying rate of 8.83 g of water/min for the mass flow rate of 0.03 kg/s is noted. Similar to other agricultural products, tapioca chips too showed the declining DR period. The drying

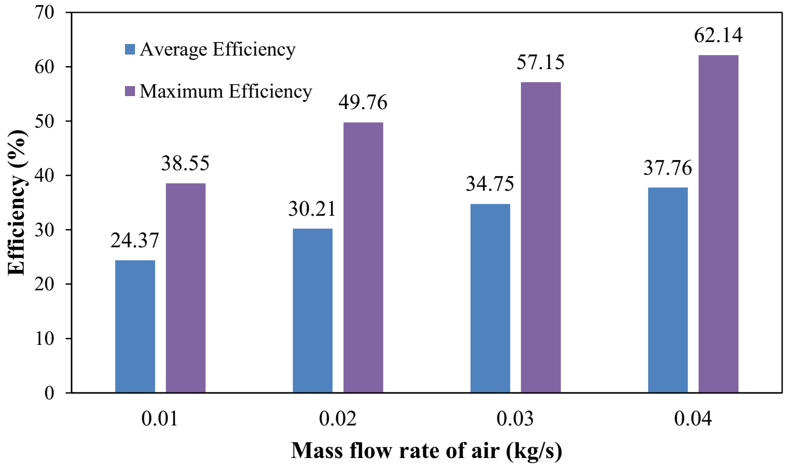

Fig. 8. Average and maximum thermal efficiencies.

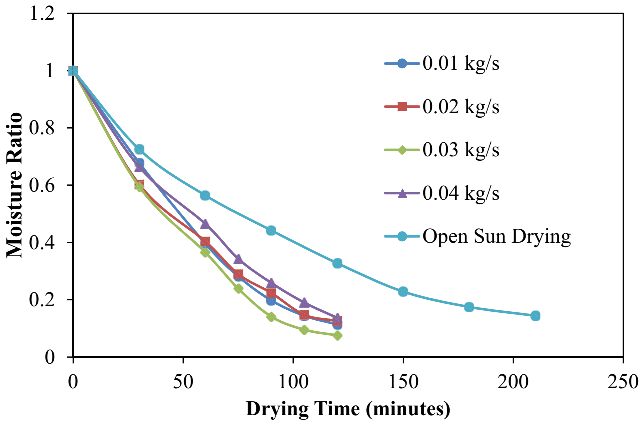

Fig. 9. Moisture ratio as a function of drying time.

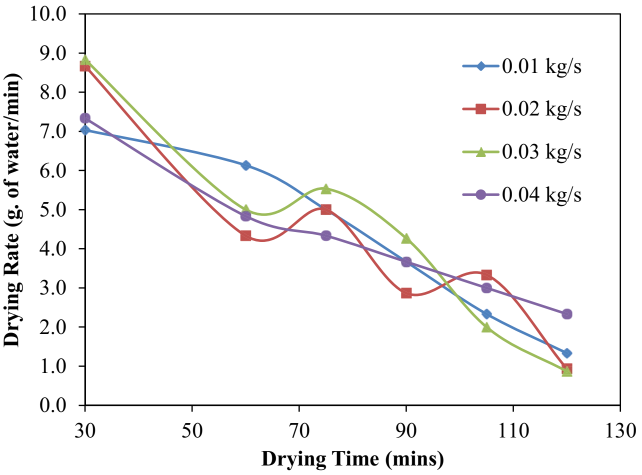

Fig. 10. Drying rate vs. drying time.

rate is higher during the first 30 min and a further increment in drying time reduces the moisture removal rate. Moreover, the surface area exposed to the convective air is very high when compared with the thickness of the chips. This caused higher removal at the initial period as it contains more free moisture on its surface. When the drying progresses, the drying rate decreases due to the slower migration of moisture from the interior to the surface.

Drying rate as a function of moisture content is shown in Fig. 11. It indicates that the drying rate is more when the moisture content is high and reduction in moisture content led to decreased drying rate as shown in the graph.

Energy utilization for the drying process can be estimated with the parameters similar to SMER and SEC. SMER and SEC varies with respect to the amount of energy consumed and the total mass of the moisture removed from the wet product. In this study, SMER values are estimated as 0.7751, 0.7412, 0.7886 and 0.7608 kg of water/kWh. Similarly, the SEC is the reciprocal of SMER and estimated in the range of 1.268–1.349 kWh/kg of water. The moisture extraction rate is slightly higher for the flow rate of 0.03 kg/s; this may be due to the reason of optimal temperature as well as the velocity of the air for drying process.

Overall drying efficiency of the forced convection integrated with sensible heat storage solar dryer for drying tapioca chips is shown in Fig. 12. The drying efficiencies were estimated for the duration of 120 min and noticed that the highest drying efficiency of 49.5% was noticed for the mass flow rate of 0.03 kg/s.

Effective moisture diffusivity value for solar and open sun drying of tapioca chips can be estimated using Eq. (11): Variation of ln(MR) as a function of drying time is depicted in Fig. 13, for solar drying and open sun drying.

The effective moisture diffusivity value for solar drying is varying from 6.769×10^{-11} to 9.298×10^{-11} m^2/s for different flow rats of air, whereas for the open sun drying determined as 3.572×10^{-11} m^2/s. Table 2 lists the linear equation, R^2 value and the effective moisture diffusivity for different drying conditions of tapioca chips.

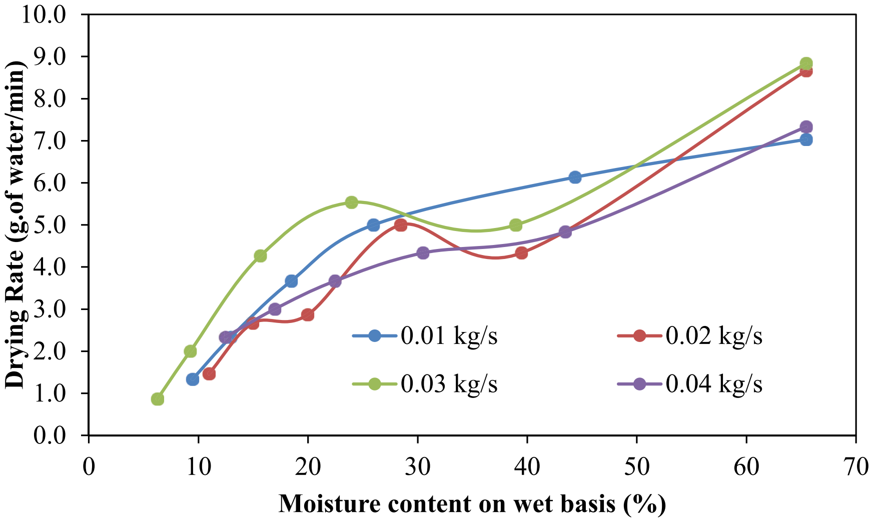

Fig. 11. Drying rate as a function of moisture content (wet basis).

4.1. Economic analysis

The solar drying system used for drying tapioca chips was analyzed for its economic benefits. The parameters used in the study are listed in Table 3.

The quantity of tapioca chips that can be dried in a batch is of 1 kg and the solar drying system took 2 h to complete one batch. The number of batches per day is estimated as 3 by accounting the time for loading, unloading of products and poor climatic conditions. The effective life span of the solar drying system is assumed as 10 y. The maintenance cost is taken as 5% of the capital cost, which includes the operations similar to cleaning, replacing rubber gaskets, painting, etc. The selling price of branded dried tapioca chips is noted as Rs. 214 per kg from a popular e-commerce site but for the analysis, which is taken as Rs. 180 per kg only. The total cost involved in solar drying process per kg of dried product is around Rs. 80/-and the total savings per year is calculated as Rs. 20,802/-. The payback period of the developed solar dryer integrated with energy storage for drying tapioca chips is determined as 1.30 y. When compared with the total life of the solar dryer, the payback period is much lower. Hence, this system can be effectively utilized as an income generation option for rural women.

4.2. Quality analysis of the samples

The quality of the dried samples of tapioca chips was evaluated based on the colour and carbohydrate retention percentage. Drying conditions influence the quality of the dried product and therefore it is necessary to study

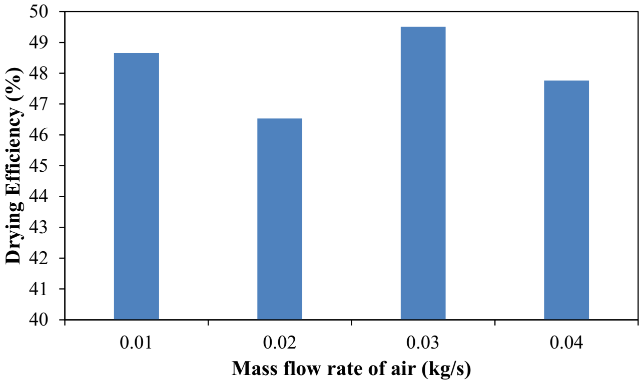

Fig. 12. Drying efficiency vs. mass flow rate of air.

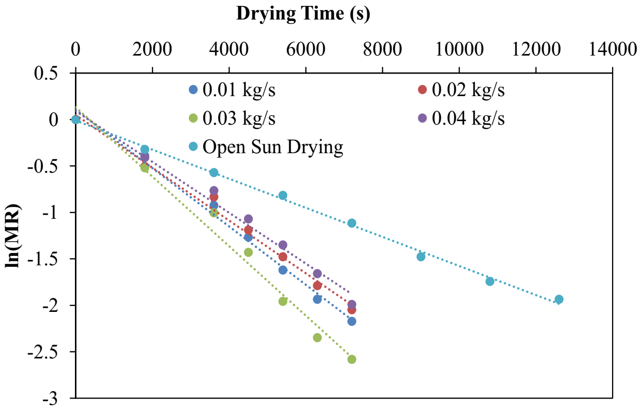

Fig. 13. ln(MR) vs. drying time.

Table 2
Effective moisture diffusivity values for tapioca chips drying

Mass flow rate of air (kg/s)	Linear equation	R^2	Effective moisture diffusivity (m^2/s)
0.01	$y = -0.0003404x + 0.1043$	0.9914	7.767×10^{-11}
0.02	$y = -0.0002966x + 0.0491$	0.9903	6.769×10^{-11}
0.03	$y = -0.0004075x + 0.1322$	0.9824	9.298×10^{-11}
0.04	$y = -0.0002967x + 0.0907$	0.9850	6.770×10^{-11}
Open sun drying	$y = -0.0001566x - 0.0112$	0.9969	3.572×10^{-11}

Table 3
Economic evaluation of solar dryer

S. No.	Description	Values
1	Total capital investment on solar dryer	Rs. 25,000/-
2	Operational cost per year – electricity @ Rs. 5.00/kWh (8 h per day for 250 d in a year)	Rs. 3,200/-
3	Loading capacity	3 kg/d
4	Raw material cost (fresh tapioca)	Rs. 20/kg
5	Dried product selling price	Rs. 180/kg
6	Interest rate *(d)*	8%
7	Rate of inflation *(i)*	5%
8	Life span of the dryer	10 y
9	Number of days of operation	250 d

Table 4
Colour measurement and carbohydrate concentration

Type of sample	Lightness L*	Green-red a*	Yellow-blue b*	Total colour change ΔE	Carbohydrate concentration
Fresh tapioca chips	84.77	–1.61	10.16	–	24.25%
Open sun dried	90.40	–0.14	6.92	6.659	58.5%
Solar dried (0.01 kg/s)	90.58	–0.35	7.42	6.544	63.86%
Solar dried (0.03 kg/s)	91.07	–0.56	8.74	6.543	65.78%

the quality of the samples to select the suitable drying method. In this investigative study, the colour change and carbohydrate retention of the open and solar dried samples were evaluated at Food Quality Testing Laboratory, Tamil Nadu Agricultural University, Coimbatore (India). The instrument used for the colour measurement was Tintometer RT200 (Lovibond) and CIE L*a*b* colour space was followed during the measurements. The total colour change of the dried samples was evaluated by considering the fresh sample as reference [31].

$$\Delta E = \sqrt{\left(L_f^* - L_d^*\right)^2 + \left(a_f^* - a_d^*\right)^2 + \left(b_f^* - b_d^*\right)^2} \qquad (13)$$

The colour measurements of the fresh and dried samples of tapioca chips are indicated in Table 4. The total colour changes of the open and solar dried samples are estimated using Eq. (13) as 6.66 and 6.54, respectively. The change of colour is slightly lower for solar dried samples in comparison with the open sun-dried samples; this may be due to the reason of direct exposure to solar insolation. Carbohydrate concentration percentage in the samples is also indicted. It clearly shows that the carbohydrate concentration percentage is higher for solar dried samples. Usually, carbohydrates decompose when they are exposed to the higher heating environment and this would have caused the lower carbohydrate concentration in open sun-dried samples, even for the samples dried at 0.01 kg/s that is having slightly lower carbohydrate concentration percentage than the samples dried at 0.03 kg/s. This is because the drying air temperature at 0.01 kg/s is higher than 0.03 kg/s flow rate of air.

5. Conclusions

In the present study, the drying characteristics of tapioca chips were investigated through open sun drying as well as through indirect forced convection solar drying methods. A special type of solar collector was designed with copper fins and sensible heat storage for small-scale drying of tapioca chips. The important findings of the study are listed below:

- The sensible heat storage medium has influenced the consistent outlet air temperature. The outlet air temperature was maintained slightly higher (1°C–5.7°C) than the ambient temperature during the periods from 16.00 to 17.00 h.
- The average thermal efficiencies were 24.37%, 30.21%, 34.75% and 37.76%, respectively, for 0.01, 0.02, 0.03 and 0.04 kg/s mass flow rate of air.
- The initial moisture content of 64.45% (wet basis) was reduced to less than 10% (wet basis) in 105, 105, 90 and 120 min for the mass flow rates 0.01, 0.02, 0.03 and 0.04 kg/s in solar drying, whereas open sun drying took 210 min of drying time.
- The overall drying efficiencies were in the range of 47.76%–49.51% for the different mass flow rates of air.
- The effective moisture diffusivity value for solar drying is varying from 6.769×10^{-11} to 9.298×10^{-11} m^2/s for different flow rates of air, whereas for the open sun drying it was determined as 3.572×10^{-11} m^2/s.
- Economic analysis indicates that the payback period is just 1.30 y, which is much lower than the total life of the drying system. Therefore, this can be effectively employed for empowering rural women and small scale farmers.
- The quality analysis of the dried samples showed that solar drying is superior to the open sun drying method.

It is concluded that the new efficient ISD can be preferred for drying tapioca chips and may be suggested as an option for income generation.

Symbols

T_a — Ambient temperature, %
A_p — Aperture area of the solar collector, m^2
C_{cc} — Capital cost of dryer, Rs.
T_i — Collector inlet air temperature, %
T_o — Collector outlet air temperature, %
η_c — Collector thermal efficiency, %
W_d — Dry mass of the sample, kg
η_d — Drying efficiency, %
DR — Drying rate, g of water h^{-1}
D_{eff} — Effective moisture diffusivity, m^{2}s^{-1}
M_e — Equilibrium moisture content, %
I — Global solar insolation, Wm^{-2}
r — Half thickness of the wet product, m
M_i — Initial moisture content, %
W_o — Initial weight of the sample, kg
L — Latent heat of vaporization of water, kJ kg^{-1}
W — Mass of water removed from the wet products, kg
M_t — Moisture content at any time of drying, %
i — Rate of inflation
d — Rate of interest on long term investment
S_1 — Saving gained at the end of first year, Rs.
C_p — Specific heat of air, J kg^{-1} K^{-1}
W_R — Uncertainty value of variables, %

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