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Design, fabrication and performance evaluation of solar dryer for banana

Vinay Narayan Hegde*, Viraj Shrikanth Hosur, Samyukthkumar K Rathod, Puneet A Harsoor and K Badari Narayana

Abstract

Background: An indirect, active-type, environmentally friendly, low-cost solar dryer was designed to dry various agricultural products. The dryer was built by locally available, biologically degradable, low-cost materials. The dryer consists of solar flat plate air heater with three layers of insulation, drying chamber and a fan with a regulator to induce required air flow in the system. Banana is the chosen crop for the experimentation since it is high in production and also has substantial loss in India. Also, dried bananas are having good nutritive value which makes it as essential diet.

Methods: The experiments were conducted to dry banana slices and to study its drying characteristics like rate of drying and quality of dried banana in terms of taste, colour and shape. The dryer has the following features: two different air flow configurations (air flow between glass cover and absorber plate called as the top flow and air flow between absorber plate and the bottom insulation of solar collector called as the bottom flow), forced flow with variable flow rates from 0–3 m/s and two different mounting schemes (conventional trays and wooden skewers).

Results: In the top and bottom flow experiments, the bottom flow provided about 2.5 °C higher chamber temperatures than the top flow for the same solar energy input. The efficiency of top flow configuration was found to be 27.5 %, whereas the efficiency of bottom flow configuration was found to be higher at 38.21 %. The results also agree well with the theoretical calculations performed as 60 W of energy can be saved for the same energy input.

Conclusions: The drying rate was found to increase when wooden skewers were used instead of conventional trays. At the end of the day, the total difference in moisture content is found to be 3.1 % which is considerable knowing that the rate of drying drastically decreases with time. Banana dried at 1 m/s air flow rate was of the best quality in terms of colour, taste and shape when compared to drying at 0.5 and 2 m/s air flow rate while the weather condition and ambient conditions were almost the same for all the cases with negligible difference.

Keywords: Solar drying; Design of solar dryer; Thermal analysis; Experimentation; Top flow and bottom flow; Conventional trays and wooden skewers; Varying air flow rate

Background

In many parts of the world, awareness is growing about renewable energy which has an important role to play in extending technology to the farmer in developing countries like India to increase their productivity. Poor infrastructure for storage, processing and marketing in many countries of the Asia-Pacific region results to a high proportion of waste, which average between 10 and 40 % [1]. Although India is a major producer of horticultural crops, many Indians are unable to obtain their daily requirement of fruits and vegetables and the Human Development Index (HDI) is very low. Considerable quantities of fruits and vegetables produced in India go to waste owing to improper postharvest operations and the lack of processing [1]. This results in a considerable gap between gross food production and net availability [1]. Reduction of postharvest losses is essential in increasing food availability from existing production [2]. Traditional techniques used in food preservation are drying, refrigeration, freezing, salting (curing), sugaring, smoking, pickling, canning and bottling. Among these, drying is especially suited for developing countries with poorly established low-temperature and thermal processing facilities. It offers a highly effective and practical means of preservation to reduce postharvest losses and offset the shortages in supply.

* Correspondence: vinumanu07@gmail.com
Department of Mechanical Engineering, RV College of Engineering, Bangalore, Karnataka 560059, India

Drying is a method of dehydration of food products which means reducing the moisture content from the food to improve its shelf life by preventing bacterial growth [3]. It is still used in domestic up to small commercial size drying of crops, agricultural products and foodstuff such as fruits, vegetables, aromatic herbs, wood etc. contributing thus significantly to the economy of small agricultural communities and farms [4–6].

Hii et al. [7] have shown that sun drying (laying the crops under direct sunlight) is economical, but the product obtained by it is of lower quality due to contamination by dust, insects, birds, pets and rain. Also, loss of vitamins, nutrients and unacceptable colour changes due to direct exposure to ultraviolet rays, and it takes long time to dry. Solar dryers are specialized devices that control the drying process and protect agricultural products from damage by insect pests, dust and rain. Umogbai et al. [8] made a comparison between sun drying and solar drying and obtained that solar dryers generate higher temperatures, lower relative humidity, lower product moisture content and reduced spoilage during the drying process than sun drying. Rajeshwari and Ramalingam [9] have demonstrated that the drying time in case of solar dryers compared to open air drying reduced by about 20 % and produces better quality dried products. Solar dryers are available in a range of size and design such as tunnel dryers, hybrid dryers, horizontal- and vertical-type dryers, multi-pass dryers and active and passive dryers [10–17]. Hii et al. [7] classified solar dryer according to their heating modes and the manner in which the solar heat is utilized, namely forced air circulation or active solar dryers and natural air circulation or passive solar dryers. Three distinct sub-classes of either the active or passive solar drying system can be identified depending upon the design or working principle of the dryer, mode of drying and type of product to be dried, namely integral or direct mode, distributed or indirect mode and mixed mode solar dryers. It should be noted that sunlight may affect certain essential components in the product, e.g. chlorophyll is quickly decomposed. If available places are scarce, indirect mode types of dryers are preferred for drying larger quantities. In such case of indirect mode, nutritive value of the food product and colour is retained.

Mohanraj and Chandrasekar [18] and Banout and Ehl [19] concluded that forced convection solar dryer is more efficient than natural convection dryers. Also, products can be dried faster in the case of forced convection solar dryer than in the case of natural convection solar dryer, and end products obtained from forced convection drying have a superior quality.

From the literature survey, it is evident that though there are many dryer designs which involve the flow of air between glass cover and absorber plate in the collector [20] and also in some other designs, the flow is maintained between absorber plate and bottom insulation [21]. However, there is no comparison of the performance done between these two cases in a single setup. Hence, there is a requirement for comparative study to address the relative performance of the above-mentioned cases and hence to arrive at a better and efficient flow configuration.

Indian Horticulture Database 2013 [22] shows that banana is the most important fruit crop in India, accounting for 32.6 % of the total fruit production. Almost the entire production is used fresh, and hence, the entire production is subjected to the postharvest losses of 17.87 %. Banana is the chosen crop for the experimentation since it is high in production and also has substantial loss in India. Also, dried bananas are having good nutritive value which makes it as essential diet [23–25].

Most of the thin-layer drying of fruits is carried on using stainless steel meshed trays [26]. In practice, trays have many disadvantages which include sticking of the dried products to the trays, difficulty in loading and unloading, hygiene among others. Hence, an innovative way of placing the bananas in the trays is devised in which wooden skewers are used to hold the fruits. Though the various literatures on drying banana included the studies on the optimum slice thickness, solar-assisted dryer for bananas and effect of various pre-treatments and temperatures on banana among others [26–29], the effect of the air velocities on the moisture removal rate and quality of the dried bananas obtained has not been studied. As air velocity also plays an important role in drying of food products [30–33], there is a need to address the effect of air velocity on drying of banana.

In the present study, low-cost indirect-type solar dryer was designed and constructed using locally available environmentally friendly materials to compare the performance of the flat plate collector for the top flow and the bottom flow of air both theoretically and experimentally, to compare the performance in the form of moisture removal rate and dryer efficiency for different banana mounting methods such as wooden skewers and on conventional trays and to dry banana using different air velocities 0.5, 1 and 2 m/s and to compare the quality of the end product in terms of taste, texture, colour and final moisture content.

Methods

The design process of the dryer first involved the collection of the climatic data of the study location, i.e. Bengaluru. Further, the other important data such as insolation was studied and calculated as per the collector configuration. For the initial phase of dryer design, many existing designs were studied and some of the design parameters were determined. The performance of the dryer was then analysed [34–37]. Once the dimensions of the dryer were fixed, an appropriate axial fan was selected to obtain the required flow rates.

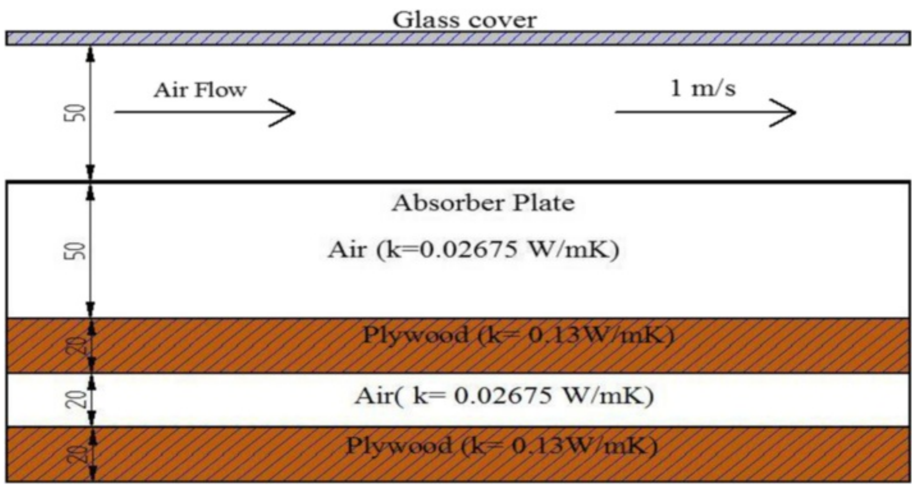

Fig. 1 Top flow

Climatic data collection

Bengaluru is located in Karnataka, India, at a latitude of 12° 58′ North and longitude of 77° 34′ East. Solar radiation over the year on horizontal surface in Bengaluru is found to be 666.635 W/m^2 [38]. Total solar radiation on a 13° tilted surface is calculated as 676.367 W/m^2.

Design consideration

The dryer was constructed using plywood, stainless steel mesh, wooden skewers, clear glass, galvanized iron sheet and axial fan for operation of the dryer which are locally available with low cost.

The thickness of banana slices was selected to be 4–5 mm [17, 27, 29]. An indirect type of solar dryer was considered as it does not affect the colour and nutrient content of the produce as in the case with a direct type. Also, the drying is uniform without any localized heating. Flat plate collector is used since it is easy to fabricate and also economical. The collector is made up of GI sheet of 0.6 mm thick as it is a good conductor and economical. It was painted black to increase the absorption of heat [39, 40]. The recommended glass thickness for collector is 5 mm [37]. Air gap of 5 cm is recommended for a tropical climate [37]. The insulating material was selected to be plywood as it is a good insulator as well as environmentally friendly. It also does not have any carcinogenic effects which other popular insulating materials like glass wool have. To reduce the heat loss, a layer of air sand witched between two plywood sheets (Figs. 1 and 2). To further reduce the heat loss by radiation and to avoid moisture absorption by wood, aluminium foil is wrapped on the inside of the chamber [41]. Food grade stainless steel mesh for the trays and food grade wooden skewers were selected for placing of

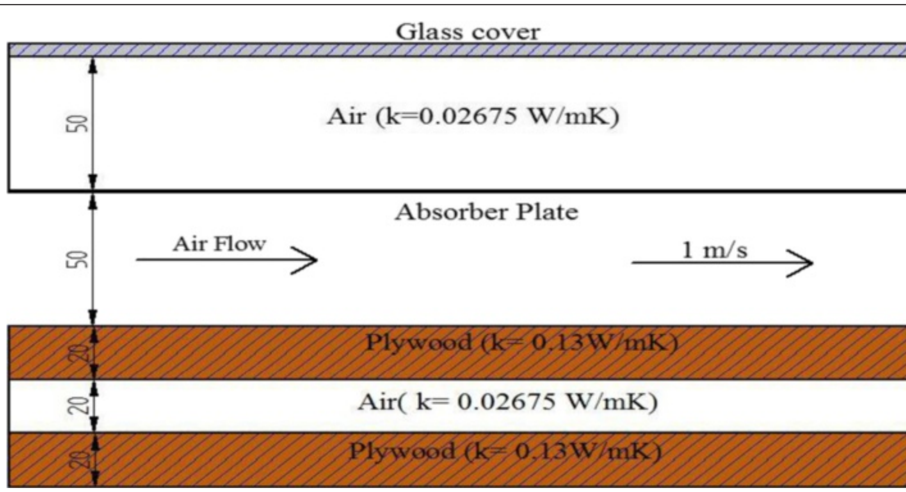

Fig. 2 Bottom flow

Table 1 Heat losses

	Top loss (*W*)	Side loss (*W*)	Bottom loss (*W*)	Total (*W*)
Top flow	259.2	7.058	25.879	292.137
Bottom flow	215.657	6.931	1.818	224.406

banana. To ensure the constant flow rate of air during the experimentation, an axial flow fan was selected based on the calculations of pressure drop in the system and the required flow rate limit of air at 3 m/s. For the purpose of experimentation, 1.5 kg of banana of Poovan variety which is locally available is used.

Thermal analysis

In the design, a flat plate collector with an area of 1.6 × 0.6 m^2 is considered. The performance of the collector is described by an energy balance that indicates the conversion of solar radiation into useful energy gain and losses. The thermal analysis was done to calculate the heat gain and losses for flow of air between glass cover and absorber plate which is the top flow and flow of air between absorber plate and bottom insulation which is the bottom flow [3, 36, 41]. Figures 1 and 2 show the typical configuration of top flow and bottom flow, respectively.

Table 1 consolidates the results from the thermal analysis. It is seen that heat loss from the top, side and bottom of the collector is more for top flow configuration compared to bottom flow configuration. This is due to the reduced temperature difference between the collector and the ambient.

Specification of the dryer

Table 2 gives the specification of the dryer.

Experimental procedure

The solar dryer was placed over the roof top of a building based on the design (Fig. 3). Axial flow fan was fixed at the top of the drying chamber and tested. The experiments were conducted in the month of March, from daily

Fig. 3 Solar dryer setup

9 am to 5 pm. The solar radiation was measured using pyranometer. The K-type thermocouples were used for the measurement of temperature in the collector assembly. The temperature was measured for each hour from 9 am to 5 pm at three points, namely entry, middle and exit of the glass cover, absorber plate and bottom insulation as it can be seen in Fig. 4. The temperature of the air in the drying chamber and the atmosphere were measured by the thermometer. A vane-type anemometer is used to measure the air velocity. The weight of the banana is

Table 2 Specification of the dryer

Overall length	2.04 m
Overall height	1.38 m
Absorber plate dimension	1.6 × 0.6 m
Glass cover thickness	0.005 m
Insulation total thickness (bottom)	0.06 m
Gap between absorber plate and glass cover	0.05 m
Gap between absorber plate and insulation	0.05 m
Number of trays	3
Tray dimension	0.3 × 0.6 m
Distance between trays	0.15 m
Tilt angle of the collector	13° due south

Fig. 4 Top flow

Fig. 5 Bottom flow

measured using a digital weighing pan. All the experiments were repeated to confirm the repeatability of the data obtained. The following experiments are carried out:

Flow over the absorber plate (top flow) and flow beneath the absorber plate (bottom flow)

Case A: Air is allowed to pass between the absorber plate and glass cover (Fig. 4). The air passage between absorber plate and bottom insulation is blocked using a cardboard with adhesive tape and glue.

Case B: Air is allowed between the absorber plate and the bottom insulation (Fig. 5). The air passage between glass cover and absorber plate is blocked using a cardboard with adhesive tape and glue.

The temperature readings were taken, and the losses and gain are calculated and compared.

Conventional trays and wooden skewers

In this case, the banana was placed on conventional trays (Fig. 6) and wooden skewers (Fig. 7) and allowed to dry for 8 h from 9 am to 5 pm. The air flow velocity is maintained as 1 m/s in the collector. The moisture content removed from the banana slices was compared.

To calculate the final moisture content, the following formula is used:

$$\text{Percentage moisture content} = \frac{77.2 \times w_i - 100 \times w_l}{w_i - w_l} \tag{1}$$

where 77.2 % is the initial moisture content of banana variety selected.

Efficiency for the dryer system is given by [41].

Fig. 6 Banana kept on trays

Fig. 7 Wooden skewers

$$\eta = \frac{mL_w}{AIt}$$

Varying air flow rate

The air flow though the dryer was varied using a speed regulator for the axial flow fan. The experiments are conducted, and repeatability tests are also made. As the experiments have been done on consecutive days, there is a very little change in atmospheric temperature and solar radiation.

Based on the test results of drying banana slices kept in trays and wooden skewers, varying velocity tests were conducted only on banana slices attached to skewers. The velocity of air flow is maintained as 0.5, 1 and 2 m/s in the collector region (0.0169, 0.0338 and 0.0676 m^3/s volume flow rate) for a duration of 16 h of drying time for consecutive days with each day 8 h from 9 am to 5 pm. Every hour the weight of the banana slices was measured, and the moisture content and the efficiency of the dryer were calculated. At the end of the day, banana slices were stored in air-tight bags. After drying for 16 h, the dried banana samples obtained from using 0.5, 1 and 2 m/s were compared in terms of taste, texture, colour and final moisture content.

Results and discussions

The average solar insolation in Bengaluru in the month of March as measured with a pyranometer is shown in Fig. 8. It can be noticed that the insolation increases by the day from 9 am to 1 pm and then starts to drop. The maximum radiation received was 1033 W/m^2 at 1 pm, whereas it was 293 W/m^2 at 5 pm.

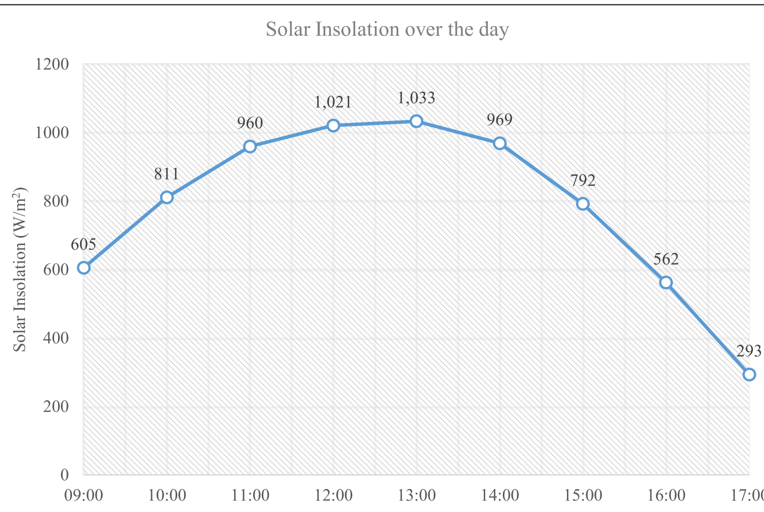

Fig. 8 Solar insolation over the day

Comparison of the top flow and bottom flow

Figure 9 shows the temperatures of the ambient air and chamber temperatures over the entire day from 9 am to 4 pm. The experiments were conducted on consecutive days and observed that the ambient temperatures were quite similar. Hence, the average ambient temperatures of 2 days were used to plot the comparison. In Fig. 9, for the case of the bottom flow, it can be seen that when the air inlet velocity is maintained at 1 m/s, the maximum temperature of the air outlet is 45 °C at an ambient temperature of 34 °C which is 11 °C above the ambient temperature. In case of the top flow experiment conducted at the same air inlet velocity, the maximum air outlet temperature reached is 42.5 °C at an ambient temperature of 34.5 °C which is about 8 °C above the ambient temperature. It can also be seen from the figure that the air temperature rise and fall closely follow the insolation curve except at the end of the day for the case of the bottom flow. This is due to the heat storage effect of the insulation which helps to maintain the air temperatures in the evening even though the insolation drastically drops. So it is evident that the configuration with the air flow below the absorber plate gives higher air outlet temperature, i.e. about 2.5 °C more than the one with the air flow above the absorber plate for same solar energy input at the peak insolation. A maximum difference of 3.5 °C was obtained at 11 am and 4 pm between these two configurations. Another point to be noted is that though the solar insolation drops quite drastically in the post noon period, i.e. from 12 pm, the ambient air temperature does not drop that drastically as it retains the heat being a good insulator. Also, it absorbs the heat radiated by the earth.

The collector efficiency indicates the utilized heat against the heat input in the form of solar insolation. Figure 10 compares the efficiency for the two configurations. Lower efficiency at 9 am is due to the fact that the experiment was started at 9 am and the setup had not yet stabilized. The increase in efficiency during the evening in the case of the bottom flow may be attributed to the heat storage by the insulation. When insolation drops, the stored heat is retrieved, thus maintaining higher air temperature and hence higher efficiency. The efficiency of the system was least at the peak insolation hour of 12 pm. This is because the plate temperature rises rapidly in the noon with higher insolation, but the heat removal capacity of the air does not meet this additional load due to its fixed velocity. Thus, the air does not take away the heat which stays in the collector chamber and is hence lost to the surroundings in the form of various losses leading to lower efficiencies of the system. If the air velocity is increased in order to improve the efficiency, the air outlet temperature from the collector would decrease. Hence, a balance has to be maintained between collector efficiency and air outlet temperatures. The total loss for the top flow is 201.9 W, whereas it is 139 W for the bottom flow. This saves nearly 62.9 W in total if bottom flow configuration is used. The mean efficiency for top flow configuration is 27.5 %, whereas it is 38.21 % for bottom flow for a day.

Thus, it can be concluded from this experiment that the bottom flow configuration is more efficient than the top flow configuration.

Comparison of conventional trays and wooden skewers

Figure 11 shows the variation of moisture content with time for the two mounting configurations, i.e. one with conventional trays and the other with wooden skewers.

It is clear from Fig. 11 that the rate of moisture removal is better with the skewers at every stage of time.

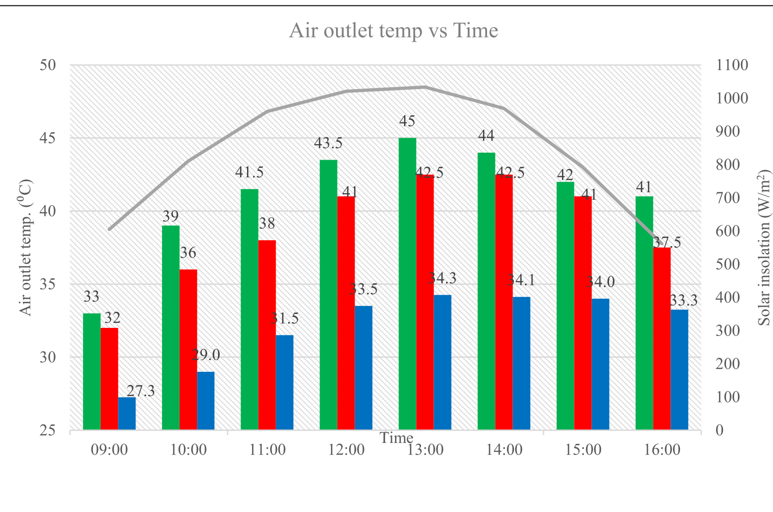

Fig. 9 Comparison of air outlet temperature for top and bottom flow over the day

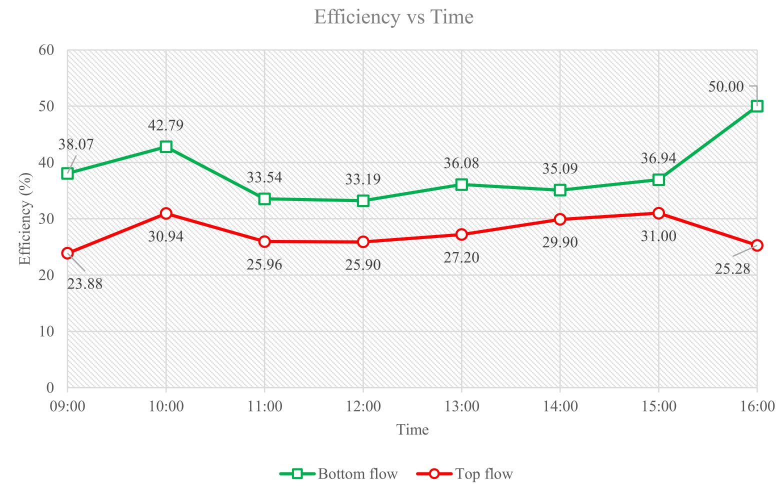

Fig. 10 Efficiency for top and bottom flow configuration

At the end of the day, the total difference in moisture content is found to be 3.1 % which is quite considerable knowing that the rate of drying drastically decreases with time. In terms of the weight of moisture removed, it is 825 g for trays while it is 864 g for skewers, the difference being 39 g.

Figure 12 shows the cumulative dryer efficiency for the above two mounting configurations. The cumulative efficiency is the ratio of the total moisture removed in the form of latent heat to the total energy supplied calculated up to specified time. It can be noted that initially, the difference in efficiencies is higher compared to the later periods, as initially, it is the unbound moisture that is being removed and just depends on the surface area. As the time goes by, the difference between the two curves reduces as the rate of moisture removal becomes much less dependent on the surface area and due to the start of the falling rate phase of drying.

The cumulative efficiency continuously drops as the rate of moisture removal drops even though the input energy is the same because of this falling rate period. Starting off with better efficiency, the skewer configuration maintains the higher efficiency throughout the day over the tray-type configuration. At the end of the day, the efficiencies are 8.45 and 8.06 % for skewer and tray type, respectively.

Flow rate for drying of banana

Figure 13 shows the comparison of moisture content for different flow rates (0.5, 1 and 2 m/s) over drying time.

The maximum temperatures achieved with 0.5, 1 and 2 m/s are 49.5, 45 and 41 °C, respectively, with almost similar ambient air temperature for all the velocities. At the end of 2 days of drying, i.e. 16 h, the moisture content in the bananas is 34.98, 29.63 and 36.04 % for 0.5, 1 and 2 m/s, respectively. If the absolute moisture removal

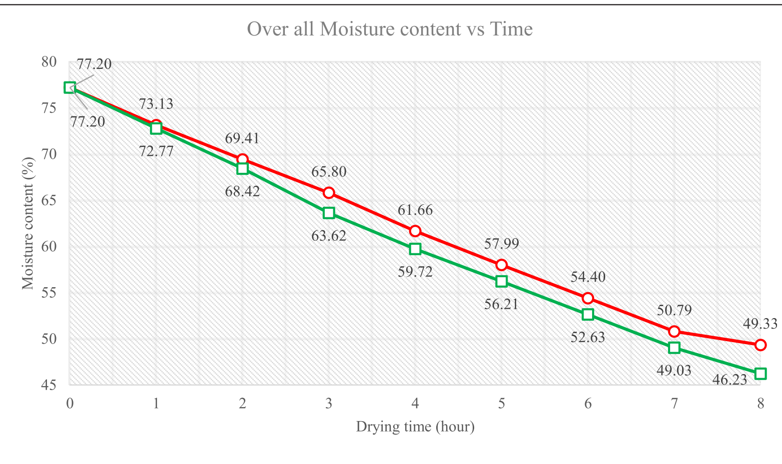

Fig. 11 Moisture content in trays and skewers over a day

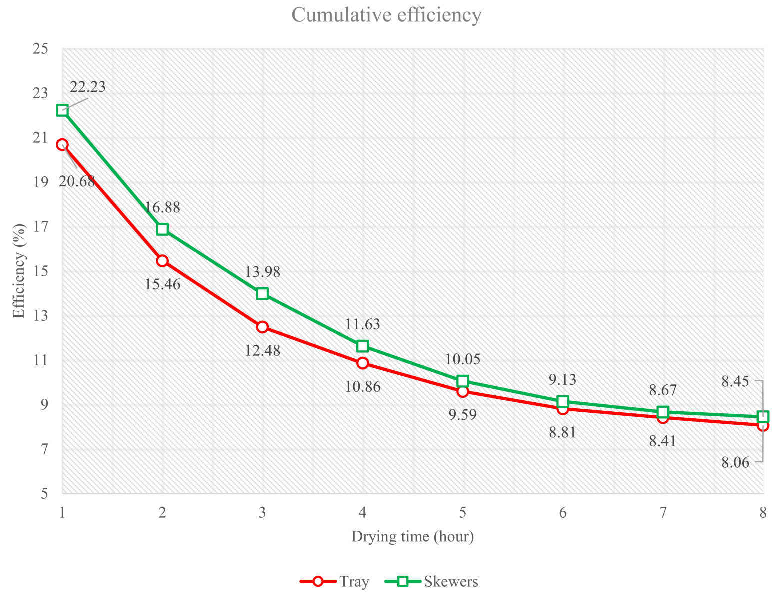

Fig. 12 Cumulative dryer efficiency for trays and skewers

rate is considered then the moisture removal rate is fastest with the velocity of 1 m/s, followed by 0.5 and 2 m/s as seen in Fig. 13.

The dryer efficiency at the end of 16 h of drying is 5.75, 4.96 and 5.05 % for 0.5, 1 and 2 m/s, respectively. The reason for slight increase in dryer efficiency for 2 m/s over 1 m/s is that the bananas dried at 1 m/s have reached the falling rate stage of drying for the given time which has impacted the dryer efficiency for the time frame considered. It is seen in Fig. 14 that the drying efficiency is clearly higher with air inlet velocity of 0.5 m/s, followed by 2 and 1 m/s. This indicates that higher air temperatures are much more effective in increasing the drying rate with the air velocity playing a minor role. But it is also to be noted that it is just not the drying rate that is important, the quality of the products obtained is more important. It is noted that with velocity of 0.5 m/s, the dried banana obtained has cardboard-like structure, hard outer surface, too light and looks like not ripened which is unacceptable. Because of the faster rate of moisture removal with 0.5 m/s, the rate of evaporation increased which resulted in hardening of the surface. The dried banana samples are shown in

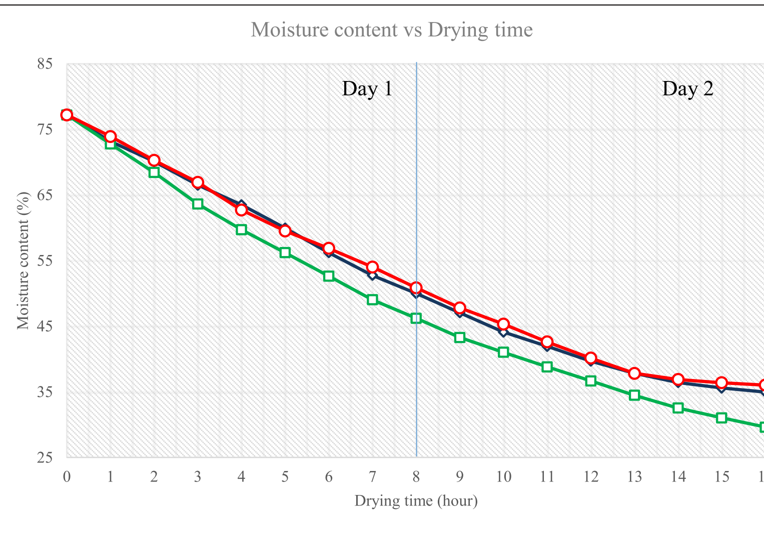

Fig. 13 Comparison of moisture content for different flow rates over drying time

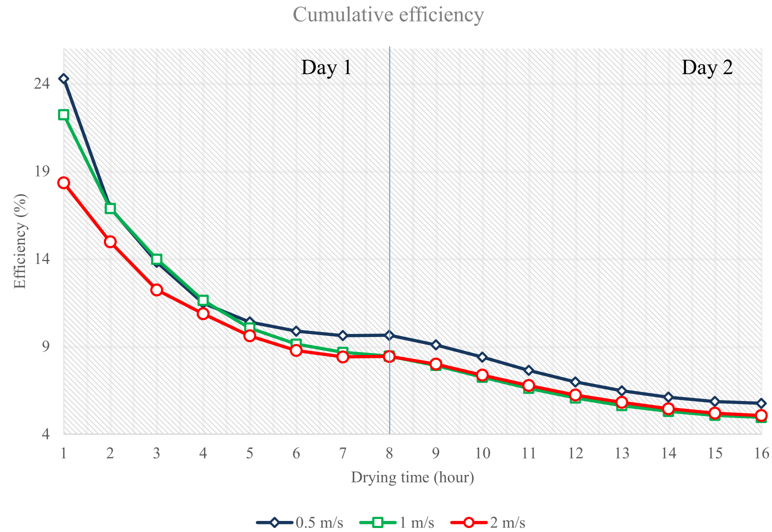

Fig. 14 Cumulative efficiency for different flow rates

Fig. 15. On the other hand, the rapid cooling of the surface of banana slices due to faster air velocity with the air inlet velocity of 2 m/s resulted in dark colour with blackening of the surface, and the surface became hard. Due which the banana obtained is of unacceptable quality. This also impacted the rate of drying as can be seen in Fig. 13. But the banana samples obtained by drying at a velocity of 1 m/s at the collector inlet are having more consistent quality of dried banana with good colour, texture, no dusty appearance, chewy and natural aroma. So with 1 m/s, good quality of banana can be obtained with quite high drying rates. The dried banana samples obtained with different air velocities were also compared with the dried banana samples obtained by Wakjira et al. [29] and Brett et al. [42]. These also confirm that the dried banana samples obtained by a velocity of 1 m/s are acceptable.

Conclusions

In the top and bottom flow experiments, the bottom flow provided about 2.5 °C higher chamber temperatures than the top flow for the same solar energy input. The efficiency of top flow configuration is found to be 27.5 % and the total heat loss or the case is found to be 201.9 W, whereas the efficiency of bottom flow is found to be higher at 38.21 % and the total heat loss is found to be 139 W. The experimental results are in excellent agreement with the theoretical values with the savings of 62 W energy. Hence, the bottom flow configuration is

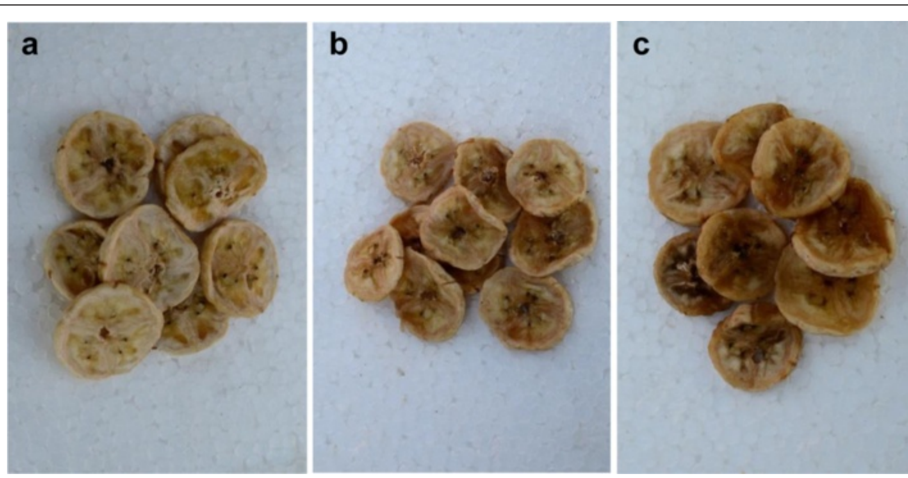

Fig. 15 Dried banana sample. **a** 0.5 m/s. **b** 1 m/s. **c** 2 m/s

more efficient. The drying rate is found to be increased when skewers are used instead of conventional trays with ease of loading and unloading of banana in the case of skewers. At the end of 16 h of drying, about 3.1 % difference in moisture content is obtained between the two configurations which is significant. The result also shows that the banana dried at 0.0338 m^3/s volume flow rate (velocity of 1 m/s over the collector) is of the best quality in terms of colour, taste and shape when compared to drying at 0.5 and 2 m/s flow rate for the same solar energy input and atmospheric conditions.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
This article is based on the student project done at the RV College of Engineering Bangalore as a part of curriculum for final semester under the guidance of Dr. KBN, Professor in the Mechanical Engineering Department at the RV College of Engineering Bangalore. Vinay, Viraj, Samyukth and Puneet are the students involved in this project. VNH contributed to the conception and design, fabrication of the model and interpretation of the data collected from the experiments. VSH contributed to the data analysis, calculations and interpretation of the data. SKR contributed to the acquisition of the data and data interpretation and fabrication of the model. PAH contributed to the experimentation and data collection and fabrication of the model. Dr. KBN involved in drafting the manuscript and revised it properly for important technical content. He is also involved in the data interpretation. All authors read and approved the final manuscript.

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