EXPERIMENT CONVECTION: EFFECT OF SOLAR DRYER ON BANANA

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ABSTRACT

Solar drying is convenient in several residential, commercial and industrial applications. Proper dryer design, operation and maintenance are essential for enhancing the dryer performance and better quality of the dried product. Solar dryer is beneficial as it protects the product from adverse climatic conditions and quickly economically dry the product. The dryer design has undergone significant shapes, dimensions, and storage features leading to better reliability. Researchers worldwide have reported higher energetic and exegetic performance through advanced design, measurement, and control features. Conventional dryer's efficiency deterioration is attributed to the lack of proper material selection and computational fluid flow techniques. Traditional dryer designs have focused on product drying rate while advanced sustainable solar dryer designs increased solar thermal utilization in a limited area with locally available materials based on fluid flow conditions suitable to the microclimatic conditions. Analysis using computational fluid dynamics (CFD) software has assisted in refining dryer designs to be compact with the complex flow and quick product drying features.

Keywords: *Solar Dryer, Classification of Solar Dryer, Natural convection, Solar air collector, Banana drying etc.*

1. INTRODUCTION

The conventional drying system to preserve fruits, vegetables, grains, fish, meat, wood and other agricultural products is sun drying which is a free and renewable source of energy. But, for large-scale production, there are various known limitations of sun drying as damage to the crops by animals, birds and rodents, degradation in quality due to direct exposure to solar radiation, dew or rain, contamination by dirt, dust or debris. Also this system is labour- and time intensive, as crops have to be covered at night and during bad weather, and have to be protected from attack by domestic animals. There is also a chance of insect infestation and growth of microorganism due to non-uniform drying. The advancement of sun drying is solar drying systems in which products are dried in a closed system in which inside temperature is higher. Major advantage includes protection against flies, pests, rain or dust. Several significant attempts have been made in recent years to harness solar energy for drying mainly to preserve agricultural products and get the benefit from the energy provided by the sun. Sun drying of crops is the most widespread method of food preservation in most part of India and world because of solar irradiance being very high for the most of the year. As this technique needs no energy during day time, it is more beneficial to the small scale farmers who can't afford the electricity or other fuel for drying. If it is necessary to dry product in night or in bad weather, an additional bio-fuelled heater can be used for heat supply

The high temperature dryers used in commercial countries are found to be economically viable in developing countries only on large agro sectors and generally it is not affordable by small and medium entrepreneurs because of high cost and process variability. Therefore, the introduction of low cost and locally manufactured solar dryers provides a promising alternative to reduce the grand postharvest losses. The opportunity to produce high quality marketable products appears to be a chance to improve the economic situation of the farmers. Taking into account the low income of the rural population in developing countries, the relatively high initial investment for solar dryers still remains a barrier to a wide application. However, if it is manufactured by locally available material such as wood, glass etc., it will be economically affordable by the farmers.

2. SOLAR DRYER

The objective of a solar dryer is to provide ample amount of heat i.e. more than ambient heat under given humidity. It increases the vapour pressure of the moisture confined within the product and decreases the relative humidity of the drying air so that the moisture carrying capacity of the air can be increased. Air is drawn through the dryer by natural convection or sometimes by a fan. It is heated as it passes through the collector and then partially cooled as it catches moisture from the material. The material is heated both by the air and sometimes directly by the sun. Warm air can hold more moisture than cold air to maintain relative humidity, so the amount of moisture removed depends on the temperature to which it is heated in the collector as well as the absolute humidity of the air when it entered the collector. The moisture absorption capacity of air is affected by its initial humidity and by the temperature to which it is subsequently heated.

3. CLASSIFICATION OF SOLAR DRYERS

In this section, Solar dryers are classified based on the solar radiation effect on the product and flow of heated air.

3.1. Solar radiation incidence

The subsections that follow deals with classifications of

3.1.1. Direct type solar dryers

Direct type solar dryer is differentiated from open sun drying by a transparent layer covering the product which is kept directly under the sun. The transparent layer absorbs heat and transfers it into the product. This transparent layer also prevents the transmission of radiations from inside the dryer to the outer parts. Thus, the dryer's efficiency increased as the temperature inside the dryer was greater than the temperature outside the dryer. One of the major disadvantages of this type of dryer is reducing nutrients and color deterioration of the product. This type of dryer is mostly used on a small scale to dry agricultural products. Sonu Sharma et al. dried the turmeric using a direct solar dryer and found that the product has a more uniform texture and better quality than open sun type dryer. Nabnean and Nimnuan used a direct type solar dryer to dry bananas. It reduces drying time by about 48% as compared to open sun drying. The overall product quality is also better than natural sun drying.

3.1.2. Indirect type solar dryers

In this type of dryer, an opaque surface is made to absorb the sun's radiations and transmit the heat to the product through convection. Compared to the direct type, these are easier to control, and the drying rate can be further improved by involving forced convection instead of natural convection. These dryers also overcome the quality and discoloration issues faced in the direct type of solar dryers. Shalaby at al. reported that indirect mode forced convection solar dryer usage is much better than natural drying. It reduced the drying time by 48.33% of sweet basil without affecting the essential oil in it. Abhay Bhanudas Lingayat et al. experimented with various kinds of indirect type solar dryers. It was found that passive and indirect type solar dryers are easy to install and economical. However, the drying rate is not controlled in passive-type solar dryers, whereas it can be efficiently controlled in inactive type indirect solar dryers. Hence, the thermal efficiency is higher than that of the passive type.

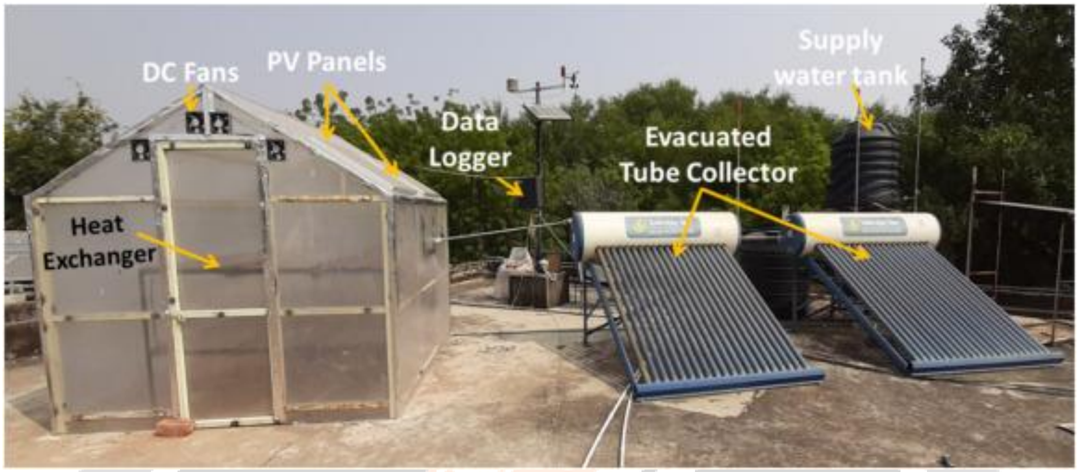
3.1.3 Mixed mode solar dryers

Mixed mode dryers works on the principle of both direct and indirect solar dryers. A transparent panel dries the product directly and in addition air is preheated before it enters the drying chamber. This has a higher thermal efficiency than both direct and indirect type solar dryers. In this type of dryer, the heat transfer occurs through convection and radiation from the drying chambers. Subbian et al. evaluated the performance of mixed-mode solar dryers for drying coconuts. The results showed that the drying rate increases with a decrease in mass flow rate. Vengsungnle et al. investigated the thermal performance of photovoltaic ventilated mixed-mode greenhouse solar dryer for ganoderma drying. It was concluded that mixed-mode solar dryer improved the drying rate and improved with increased ventilation and higher drying temperatures.

3.2. Heated airflow

3.2.1. Active type solar dryers

Inactive type solar dryers, heat transfer rate, can be achieved through the forced movement of air by external means like blowers, fans or pumps. Due to higher air circulation, active-type solar dryers provide better drying rates than passive-type solar dryers. Off sun heating systems can be integrated with this type of dryer which is helpful in rainy climates. Pushpendra Singh and Gaur studied the sustainability of integrated active type greenhouse solar dryers in the experimental set up shown in Fig.1 with evacuated solar collectors. It was reported that tomatoes dried from 94.6% moisture content to 10% in 10 hours. It was also reported that though the initial investment is high, the return payment is in 1.73 years, whereas the dryer's lifetime is about 30 years. Therefore, an active type solar dryer is a promising alternative to other types, although higher investment cost. Etim et al. studied the design and development of an active indirect solar dryer to cook bananas and found that the air inlet area plays a major role in the drying after optimizing every other factor. A higher inlet area increased the drying rate and vice-versa. Arun et a. studied the active mixed-mode type solar cabinet dryer to dry unripe bananas. It was found that the dried banana flakes were of good colour, texture, and natural aroma compared to open sun-dried flakes. Also, the payback time for this dryer is 9 months compared to its 15 years lifetime.



3.2.2. Passive type solar dryer

The air is circulated naturally without any external aid in this type of solar dryer. The passive type of dryer is eco-friendly and does not require any external energy except for solar energy. These dryers have ventilation holes both at the entrance and exit of the dryer. Duran et al. simulated a passive solar dryer to charqui production using temperature and pressure networks. The drying time was decreased by two days and the drying rate improved when the wind turbine was directly placed at the solar chimney's outlet. The drying time was reduced due to the dryer's constructional features, thermal isolation, and airflow in the dryer. Quonset shaped drier generated higher temperature compared to other shaped driers shown in Fig.2 in their investigations by Jagadeesh et al.

4. DRYING

Drying is commonly described as the operation of thermally removing water content to yield a solid product. Moisture held in loose chemical combination, present in the product matrix or even trapped in the microstructure of the solid, which exerts a vapour pressure less than that of pure liquid is called bound moisture. Moisture in excess of bound moisture is called unbound moisture. When a solid is subjected to thermal drying, two processes occur simultaneously:

A. Transfer of energy (mostly as heat) from the surrounding environment to evaporate the moisture from the surface.
B. Transfer of internal moisture to the surface of the solid and its subsequent evaporation due to application of energy.
The drying rate can be governed by the rate at which the two processes proceed. Energy transfer as heat from the surrounding environment to the wet solid can occur as an outcome of convection, conduction, or radiation and in some cases as a result of a combination of these effects. Various dryers differ in type and design, depending on the principal method of heat transfer applied. In most cases, heat is transferred to the surface of the wet solid and then to the interior. However, in dielectric heating, radio frequency (RF) or microwave drying, energy is supplied to generate heat within the solid and flows to the exterior surfaces.

Process A, the removal of moisture as vapour from the material surface, depends on the external conditions such as temperature, air humidity and flow, area of exposed surface, and pressure. Process B, the movement of moisture within the solid, is a function of the physical nature of the solid, diffusion rate, and its moisture content.

Apart from weather conditions the drying behaviour of agricultural crops during drying depends on the:

- Product
- Size and shape
- Initial moisture content
- Final moisture content
- Bulk density
- Thickness of the layer
- Turning intervals
- Temperature of grain
- Temperature, humidity of air in contact with the grain
- Mechanical or chemical pre-treatment
- Velocity of air in contact with the grain

In a drying operation, any one of these processes may be the limiting factor regulating the rate of drying, although they both continue simultaneously throughout the drying cycle.

5. EXPERIMENTAL METHOD

5.1. Instruments used

The experimental setup utilized various instruments to gather data and measure key parameters within the dryer. The following instruments were employed, along with their respective accuracy and specifications:

1. LCD digital thermometers: these thermometers were used to estimate temperature values at different positions within the dryer, which includes the SAC inlet and SAC outlet, trays, and the dryer outlet. The accuracy of these thermometers was ±0.1 °C.
2. Anemometer: an anemometer with a model LIN-32967 was used to determine air velocity with a scale of 0–30 m/s was used. The anemometer had an accuracy of ±5 %.
3. Pyranometer: a pyranometer was employed to gauge sunlight radiation levels. The pyranometer had an accuracy of ±5 W/ m2.
4. Hygrometers: hygrometers were employed to measure air relative humidity of the air both inside and outside the dryer with an accuracy of ±1 %. These instruments enabled precise monitoring of RH levels, aiding in the evaluation of drying conditions and the effectiveness of moisture removal.
5. Electronic scale: an electronic scale with a model Sartorius and a capacity of 3000 g, with a precision of ±0.01 g, which was used to estimate the loss of weight in the product. This scale allowed for precise measurements of the change in mass during the drying process.
6. Hot air oven: A hot air oven with a temperature scale of 0–200 °C and a model name Memmert was employed to estimate the product mass post-drying. This oven facilitated the dehydration of the product, allowing for the determination of its final dried mass.

5.2. Preparation of the product

In our experiences, we have used bananas produced in Morocco. We have chosen bananas that have almost a similar shape, we have cut these bananas into similar slices with a thickness of L = 4 ± 1 mm and a diameter of D = [3.5; 4] ±0.2 cm. The shape of banana slices was shown in Fig. 3.

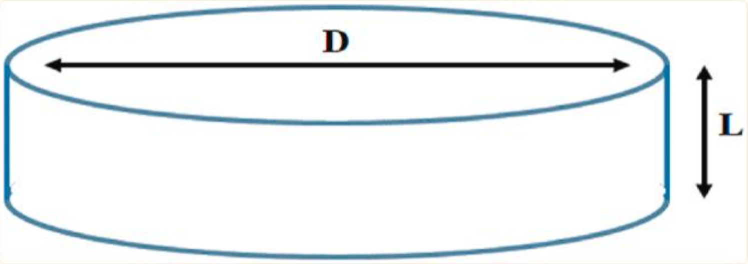


Fig. 3

Banana shape used for drying.

5.3. Determination of moisture and dried mass of banana

To determine the dried mass of banana slices, a hot air oven was used, and some of mass were dried under 105 °C during 24 h.

In Table 1, we have dried nine samples of banana slices (M1 to M9). By calculating the initial, the final mass of each sample and the percentage of moisture, and using equation (4), the average MC of banana in dry basis (db) was estimated and it was found to be 3.5771 kg/kg and the average percentage of moisture value presented in the product was 78.15 %.

Table 1: **Moisture measured for various masses to calculate the initial moisture content of banana.**

Mass	**Banana**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Initail mass (g)	3,9750	5,2229	3,4760	4,0313	3,7655	3,9885	16,4962	13,6461	31,9940
Final mass (g)	0,8694	1,1527	0,7700	0,8741	0,8209	0,8834	3,5579	2,9810	6,8822
MC (db)	3,5721	3,5310	3,5143	3,6119	3,5870	3,5149	3,6365	3,5777	3,6488
Moisture (%)	78,1283	77,9299	77,8481	78,3172	78,1994	77,8513	78,4320	78,1549	78,4891
Average of moisture (%)	78,1500								
Average	3,5771								

Experiments were done in month of December under better conditions of weather, from 9 a.m. to 18:30 (5:15 a.m.).

6. THEORETICAL ANALYSIS FOR DRYING

Drying efficiency refers to the percentage of energy supplied by the wet product itself to remove moisture during the drying process. It is a measure of the efficiency with which the energy contained in the wet product that is used to evaporate moisture. In natural convection, drying efficiency is given by the following equation :

$$(\%)\eta d = mw.hfg/Ac.Ic.t \qquad (1)$$

The amount of heat for drying is given by equation .

$$Qa = ma..Cpa(Tco - Tci) \qquad (2)$$

where, a means air fluid, ci is the SAC inlet, co is the SAC outlet.

Collector efficiency refers to the ratio of the heat available for the drying inside the SAC to the total value of incident solar radiation at the solar collector. It depends on time and insolation collected at SAC. By using equation (3), the value collector efficiency was estimated .

$$(\%)\eta c = ma..Cpa(Tco - Tci)/AcIc \qquad (3)$$

The MC values of banana slices was estimated using equation.
In dry basis:

$$MC=\frac{(m-md)}{md} \qquad (4)$$

Where m refers to initial mass of samples (kg) and md is the dried mass of product (kg).
The drying rate (DR) is estimated by calculating the difference of MC value at two successive times of drying divided by duration time with using the following equation:

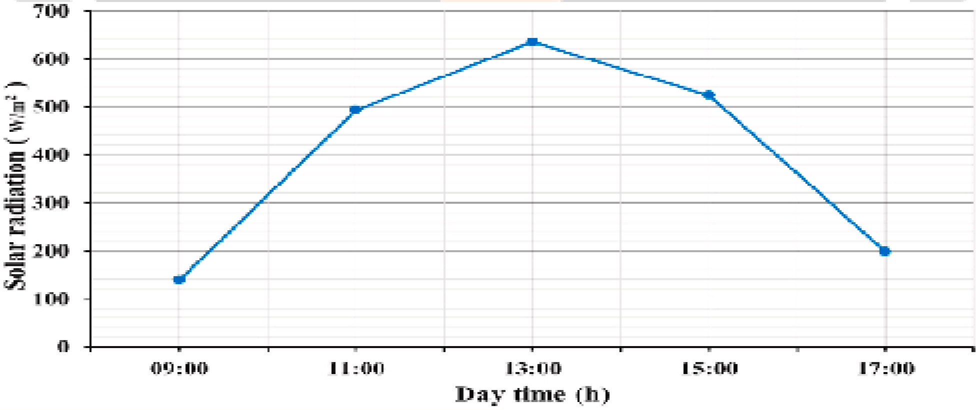
$$DR=\frac{dMC}{dt}=\frac{MCt+dt-MCt}{dt} \quad (5)$$

where dt is the difference in time.

7. RESULTS AND DISCUSSIONS

7.1. Performance of the indirect solar dryer

This section presents the temperature distribution inside the indirect solar dryer, highlighting its sensitivity to variations in solar radiation. The temperature distribution plays a crucial role in understanding the overall performance of the dryer and its efficiency in utilizing solar energy. By closely examining the impact of changing solar radiation levels, we acquire valuable understanding of the system's dynamic behavior.
In Fig. 4, the solar radiation was measured over a period of 8 h during the drying process from 9:00 to 17:00. The measurements indicate that there is a significant fluctuation in the solar radiation levels during this period. At the start of the process, at 9:00 in the morning, the solar radiation was measured at its lowest value of 341 W/ m2. This low level of radiation can be attributed to the fact that the sun is still low on the horizon at this time of the day. As the day progressed, the solar radiation levels gradually increased, and by 13:00, the solar radiation had peaked at a maximum value of 635 W/ m2. This high level of radiation can be attributed to the fact that the sun is at its highest point in the sky at this time of the day, which leads to maximum exposure to the sun's rays. The average solar radiation measured during the day was 397.8 W/ m2. This average value takes into account the fluctuations in solar radiation values levels throughout the day, and provides a good representation of the overall solar radiation levels during the drying. The peak radiation value observed at 13:00 indicates the optimal conditions for drying during this period. However, it's crucial to highlight that diminished radiation levels in the morning and late afternoon may lead to slower drying rates during these times.



Variation of solar radiation values versus day time (W/m2).

Fig. 5 provides valuable insights into the temperature changes within the dryer through day time. Inside the dryer, the measurements show that the temperature varies depending on the location within the system. Specifically, the temperature was found to be higher at the SAC outlet and gradually decreased as the air flowed through trays 1, 2, 3, and 4. This pattern can be attributed to the fact that the air passes through each tray and transfers heat to the material being dried, resulting in a decrease in temperature as it flows through the trays. The highest temperature value of 58.4 °C was recorded at 13:30 at the SAC outlet, indicating that this is the point at which the air is hottest. Additionally, temperature values of 45.9, 44.4, 43.8, 43.1, and 42.6 °C were recorded for trays 1, 2, 3, 4, and the outlet of the dryer, respectively. Within the drying chamber, tray 4 had the minimum temperature value, indicating that the air was at its coolest as it flowed through this tray because as the air loses heat in favor of the racks which causes it to cool.

Conversely, tray 1 achieved the maximum temperature value, indicating that the air was hottest at this point [35]. This temperature gradient highlights the importance of tray placement within the dryer. These temperature measurements provide a clear indication of the temperature variations that occur within the dryer and highlight the importance of accurate temperature monitoring during the drying process. Understanding temperature distribution within the dryer is crucial as it directly influences the drying kinetics and product quality

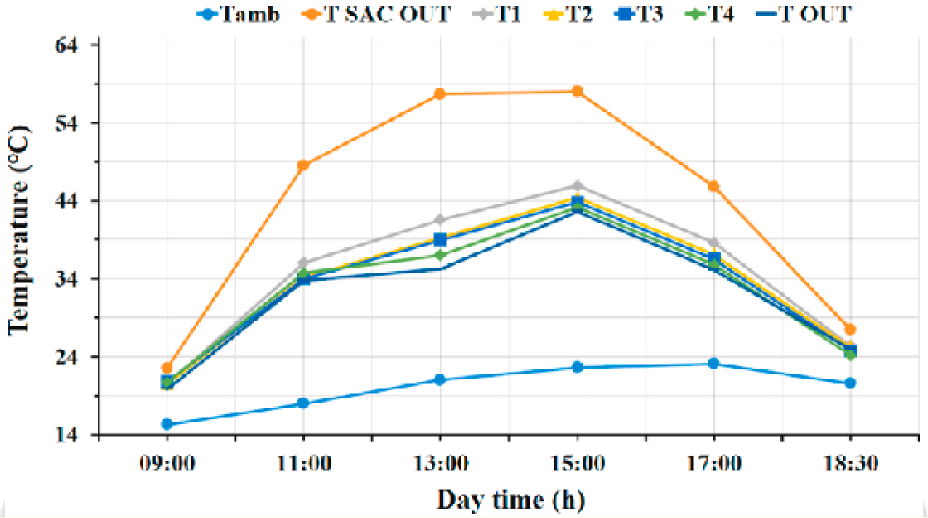
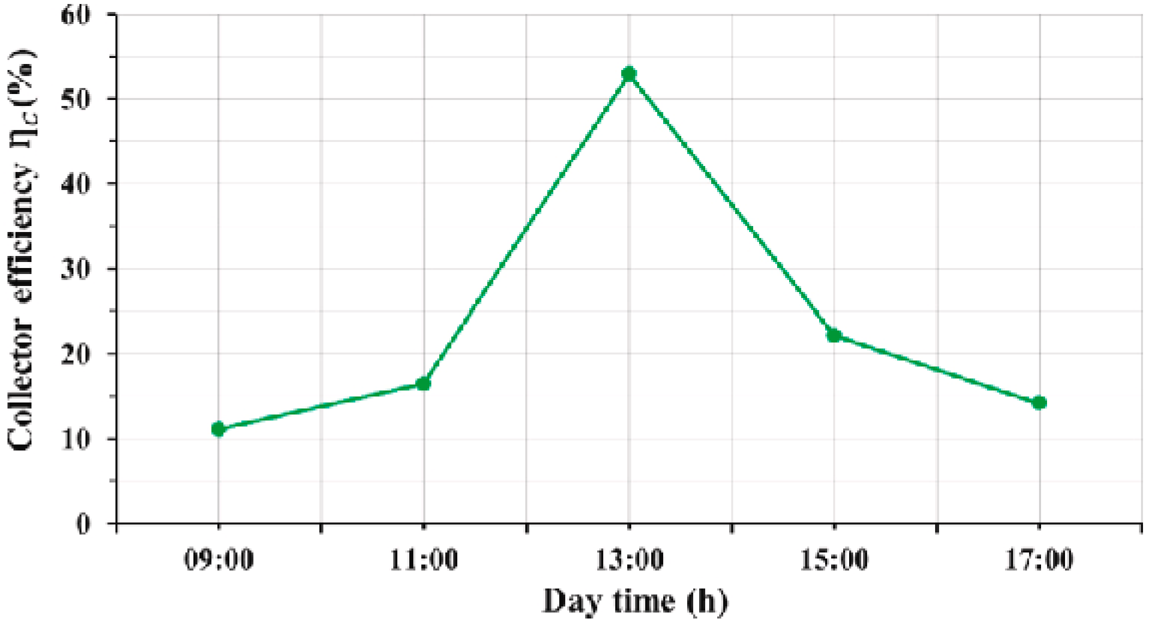


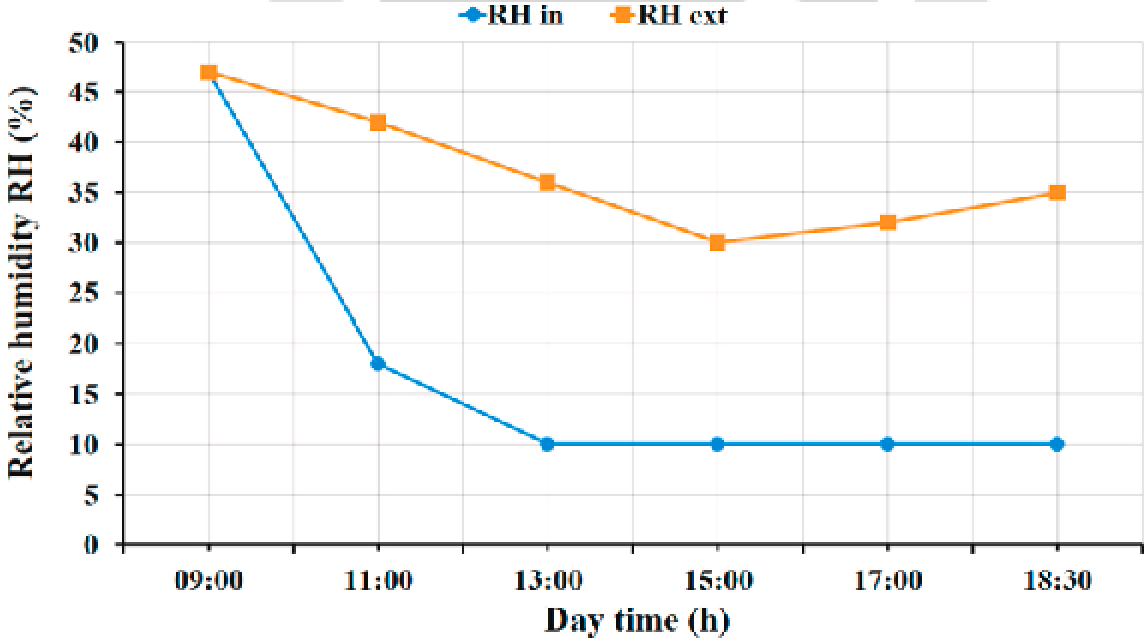
Fig. 5: Variation of temperature inside dryer (ISD), (°C).

Fig. 6 provides a representation of the collector efficiency values for different hours of the day. The measurements show that the collector efficiency fluctuates throughout the day due to variations in solar radiation levels. This variation in solar radiation leads to variations in energy obtained at the collector, which in turn affects the efficiency of the collector. At 9:00, the minimum value of collector efficiency was recorded at 11.11 %. This low efficiency value can be attributed to the solar radiation levels that are still low at this time. As the day time progresses and solar radiation levels increase, the collector efficiency also increases. The maximum value of collector efficiency was recorded at 13:00, which corresponds to the time of maximum solar radiation, as shown in Fig. 4. At this point, the collector efficiency was measured to be 52.92 %, indicating that the air fluid could absorbs a maximum amount of energy from the SAC



Using equation (1), the dryer average thermal efficiency was estimated, resulting in a value of 18.8 %. The obtained thermal efficiency serves as an important indicator of the system's performance and its ability to optimize energy utilization while achieving desired drying outcomes. The obtained thermal efficiency value of 18.8 % demonstrates the efficient harnessing of solar energy during the drying procedure. This value provides insights into the system's overall energy performance and highlights its potential for efficient and sustainable food preservation.

Fig. 7 presents the relative humidity (RH) values during drying time. During the drying process within the drying chamber, there was an observation revealed that the minimum relative humidity (RH) value reached a level as low as 10 %. This significant drop in RH indicates that the drying conditions prevailing inside the chamber were highly favorable to moisture removal from the product. The low RH creates an environment where moisture is encouraged to evaporate from the product, facilitating the drying and contributing to the efficient reduction of moisture. It is worth noting that the RH values are influenced by a variety of factors, including air flow rate, temperature, and the MC of the product. The mean relative humidity (RH) of the air within the drying chamber was measured to be 17.5 %, which is significantly lower than the average RH of the ambient air, which was 37 %. This suggests that the air within the drying chamber was drier than the surrounding environment, which is beneficial for the drying process. Dry air has a greater capacity to absorb moisture from the product, which facilitates to remove moisture from the product throughout the drying process. The low RH values observed in the drying chamber indicate also that the design and operation of the dryer were effective in creating optimal drying conditions.



7.2. Drying characteristic of banana using the ISD

In this section, the results of drying banana slices are analyzed. Fig. 8 shows the mass loss of banana slices as a function of time. It can be observed that the mass of the product starts to decrease once the absorber transfers its energy to the drying air. During the 9.5 h of indirect drying, the mass of the banana slices at all trays (1, 2, 3 and 4) decreased from 549.76 g to 138.41 g. This significant reduction in mass is a result of the loss in moisture from the product throughout the drying process. As the drying air absorbs moisture from the product, the water content of the slices decreases, leading to a reduction in mass. The mass loss observed in Fig. 8 can be attributed to the evaporation of moisture from the banana slices driven by the temperature and airflow conditions within the drying chamber.

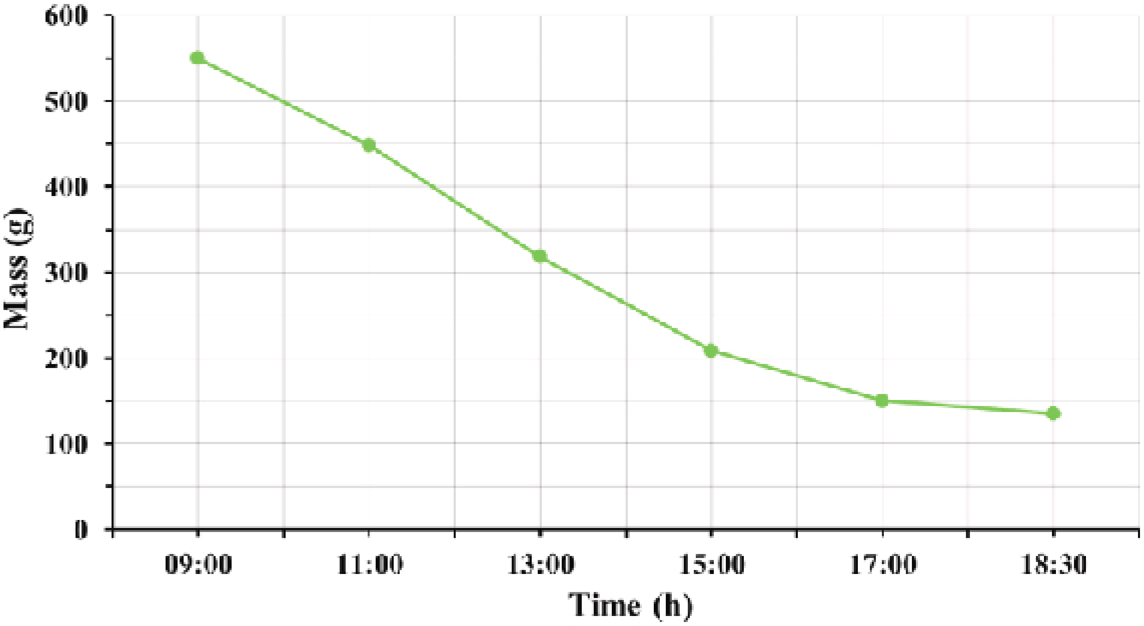


Fig. 8 Mass loss of samples vs. day time

Fig. 9 shows texture change of banana slices before and after drying under natural convection. In Fig. 9-a, the banana slices are shown before drying, while Fig. 9-b and 9-c show the same slices after the drying process. It is evident that the slices have undergone a significant transformation, with the drying process resulting in a reduction in MC and a change in texture. In addition, it can be observed that the slices have maintained a good color after the drying process. Changes in color can be an indicator of the extent of chemical and biochemical changes that have occurred in the product during the drying process. Furthermore, Fig. 9 highlights that the drying process has been successful in maintaining the color of the banana slices. The slices exhibit a desirable color even after the drying process

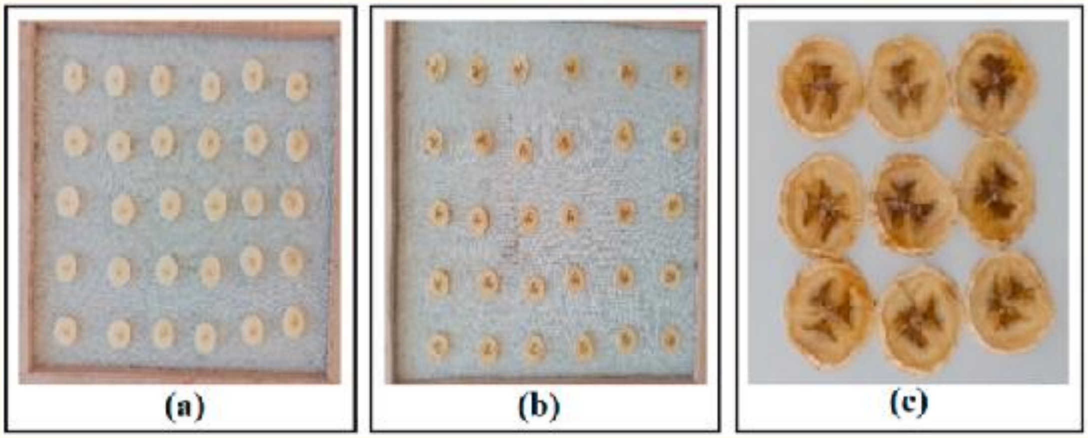


Fig. 9 Banana slices before (a) and after indirect drying (b), (c) under natural convection.

Fig. 10 presents the evolution of moisture removed from banana at trays in function of drying time. The results reveal that the moisture removal from banana slices increased with time for all four trays in the dryer. The maximum percentage of moisture removed for tray 1 was found to be 77.74 %. Similarly, tray 2, tray 3, and tray 4 exhibit a decreasing trend in the percentage of moisture removal, with values of 75.15 %, 74.16 %, and 72.28 %, respectively.

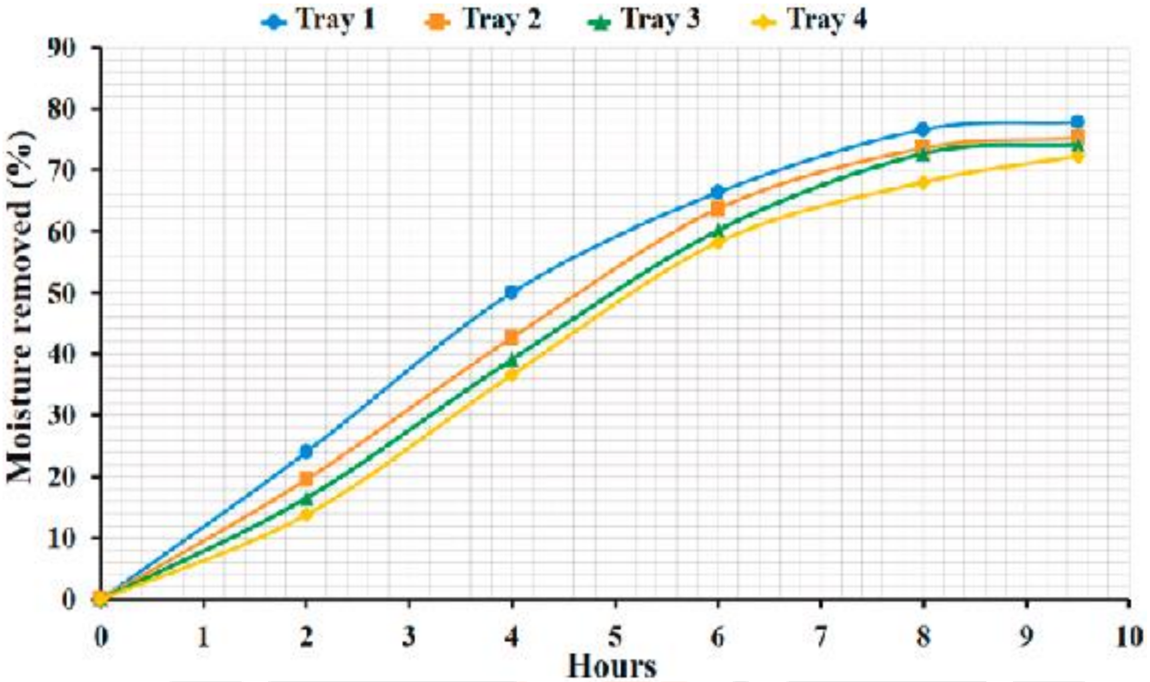


Fig. 10 Moisture removed from banana slices inside drying chamber vs. Time (h)

Fig. 11 illustrates the monitoring of MC in banana slices throughout the day using the ISD. The MC data was recorded for four different trays, labeled as trays 1, 2, 3, and 4. Initially, the banana slices had a MC of 3.5771 kg/kg on a dry basis (db). As the drying process progressed, the MC gradually decreased, resulting in final values of 0.0397 kg/kg db, 0.1292 kg/kg db, 0.1745 kg/kg db, and 0.2597 kg/kg db for trays 1, 2, 3, and 4, respectively. An interesting observation was made regarding tray 1, which exhibited the highest reduction in MC compared to the other trays. This can be attributed to the fact that tray 1 was positioned as the first tray exposed to the heated air in the SAC. At this stage, the air in the SAC is still dry, and its humidity level is relatively low. As a result, tray 1 benefited from the initial exposure to the driest and hottest air, leading to a more significant reduction in MC compared to the subsequent trays. The MC reduction observed in Fig. 11 is a direct result of the efficient moisture removal facilitated by the drying process

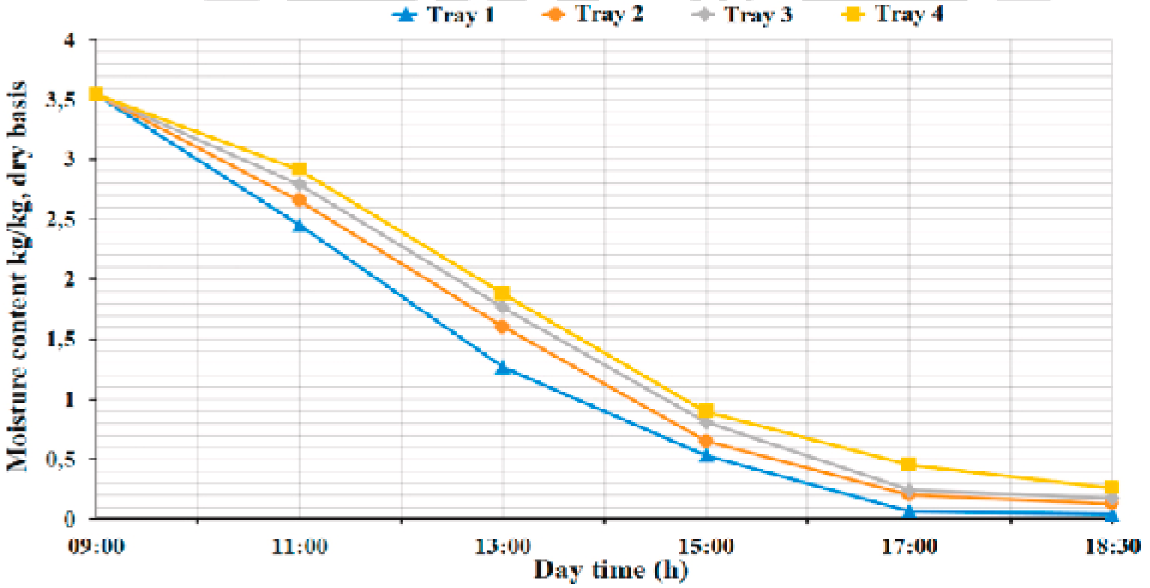


Fig. 11 Variations of moisture content in banana for the four trays during day.

Fig. 12 shows the drying rate (DR) during drying period of banana as it is a wet product inside the ISD. In general, wet products go through three drying phases:

1. The heating-up period: it is often very short and is characterized by an increasing drying rate corresponding to the rise in product temperature to an equilibrium temperature.
2. The period of constant drying rate: it corresponds to the evaporation of free water on the product surface, which is constantly renewed by water coming from the interior of the product, equivalent to the transpiration phenomenon. The product temperature remains constant.
3. The slowing down period of drying: it corresponds to the bound water, after the depletion of free water which migrated from the inner part to the surface of the product. As bound water is more tightly bound to the product, the water evaporates inside the product, constituting an evaporation front that sinks deeper and deeper into the product

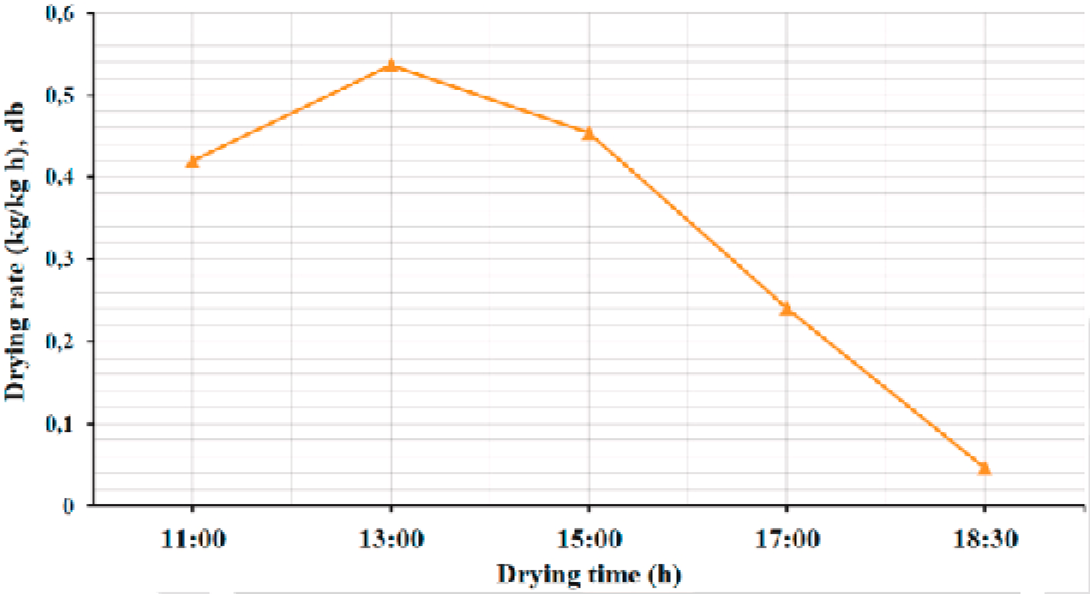


Fig. 12 Variation of drying rate (DR) of banana inside the ISD in function of time

In our case, Fig. 12 shows that drying occurs only during the slowing down period in the absence of the heating-up and constant rate periods. Many experimental studies on agro-food products have shown that the drying kinetics only exhibit the decreasing phase [36], probably due to the structure of these products, but also due to the fact that cell walls disrupt the movement of water from the inner to the outer surface. Furthermore, Fig. 12 demonstrates that the drying of banana slices within the ISD predominantly occurs during the slowing down period, indicating the removal of bound water. The absence of distinct heating-up and constant drying rate periods suggests the specific drying characteristics of the product and the role of cell walls in impeding water migration. These findings contribute to the understanding of the drying kinetics of banana slices and can inform the optimization of drying processes for similar agro-food products

8. CONCLUSION

In conclusion, the current study examined the effectiveness of an ISD in drying banana slices through natural convection. The ISD maintained higher temperatures within the drying chamber, creating favorable conditions for moisture evaporation and leading to noteworthy decrease in the MC of the banana slices. The average solar collector efficiency and dryer efficiency were measured at 23.37 % and 18.8 %, respectively. The drying process led to a reduction in the MC from an initial value of 3.5771 kg/kg (db) to final values ranging from 0.0397 to 0.2597 kg/kg (db), depending on the tray location. The comparison with other studies in the literature also confirmed the improved performance of the ISD. Future research can focus on optimizing the design parameters of the ISD and exploring its application for drying other food products. Additionally, investigating the potential integration of energy storage technologies could enhance the efficiency and versatility of drying processes.

Overall, the study offers valuable insights into the capabilities of the ISD as a sustainable and efficient solution for food preservation. These findings contribute to the continual endeavors in developing environmentally friendly drying technologies.

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