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Integrated Thermal Energy Storage for Enhanced Performance in Indirect Solar Drying Systems

S.Hari Krishnan[1*], S.Dhanushkodi[1], K.Sudhakar[2]
[1]PRIST University, Vallam, Thanjavur – 613403, Tamilnadu, India
[2] Energy Centre, National Institute of Technology, Bhopal, M. P., 462003 India
*harikrishnan.cudd@gmail.com

Abstract
An indirect, active-type, low-cost solar drier with latent heat thermal energy storage was built utilising affordable, locally accessible materials to dry agricultural products.
The dryer is made up of a drying chamber, a solar flat plate collector with thermal energy storage material, and a blower to create the necessary air flow in the system. The crop selected for the experiment is ginger since it has a high yield and significant losses in India. Dried ginger is also a necessary part of a diet because of its high nutritional and medicinal value. In this studies multiple PCM with different melting temperature was filled in the baffles of solar collector so that it can be easily melt in day time and release heat in off sun shine hours. In these experiments, the final moisture content is obtained in seven hours in an indirect solar dryer with thermal energy storage, eight hours in a direct solar dryer, and eleven hours in an open sun dryer. The average efficiency of collector was found to be 85 %, whereas the efficiency of dryer was found to be 47 %. The dryer runs effectively for the next three to four hours after sunset, maintaining a temperature inside the drying chamber that is eight degrees celsius greater than the atmospheric air. The dryer's effectiveness is further enhanced by placing a liquid or solid sensible heat-storage material in the drying chamber's bottom.
Keywords: *Thermal storage, Multiple PCM, PCM container.*

INTRODUCTION

The perennial herbaceous plant known as ginger (Zingiber officinale) is a member of the Zingiberaceae family. It is one of the oldest oriental spices and a significant revenue crop worldwide. In addition to raw, dried, powdered, and bleached dry ginger, it can also be found in a number of other forms, such as ginger oleoresin, brined ginger, ginger oil, and many more. There are many uses for ginger and its products in the meat product, bread, and perfume industries in addition to culinary preparation. In addition to being used to make food more palatable, ginger is frequently utilized as medicine in Ayurveda [1].Due to a lack of post-harvesting, agricultural yield deprivation is high in emerging economies, affecting roughly 25–35% of fruits and vegetables and 8–15% of food grains [2].Reducing the moisture content to a safe storage level allows things to be stored longer without deteriorating. This is the basic goal of drying. Additionally, it lowers the products' mass and volume, which lowers the cost of packaging, storing, and shipping [3]. Electrical and steam drying are the methods used by the majority of processing industries to accomplish this procedure [4]. In India, there are more than 275 days with adequate sunshine each year and an average daily solar radiation of 5-7 KW/m^2 [1].A solar dryer can be used to dry the product in drying air temperatures that range from 45 to 60 degrees Celsius, which is a more ideal range for many agricultural products [5]. Still, there are issues with the solar dryer due to its unpredictability of solar radiation supply. These worries have an impact on the solar dryer's dependability, which restricts its use. These researches have investigated a number of methods. In general cases, the solar dryer is comprised of three primary parts: a drying chamber, an LHS unit with one or more PCM containers, and a solar air heater (SAH). Save the excess solar energy available during day time and utilize during off sun shine hours. One of the effective methods for effectively trapping the discontinuity of solar energy is the use of phase change material (PCM) to store thermal energy [6-7]. There are three types of PCM: eutectic, inorganic, and organic. Every variety has unique benefits and drawbacks. Lauric acid was found to have an average air temperature of 53^0C on the fluid in the drying chamber, while paraffin wax and palmitic acid had average air temperatures of 51.2^0C and 56.3^0C, respectively [8]. An indirect forced convection solar dryer using PCM in the drying chamber and sensible heat storage material in the collector was used to experimentally dry a medicinal herb. They saw that the rate of drying was twice as quick as it would have been without thermal energy storage. Furthermore, the quality of the dried medium in terms of essential oil biomedical components is improved by the use of PCM and sensible heat storage [9]. Paraffin was frequently utilised as a TES material in FISD due to its exceptional thermo-physical properties [29–31]. Latent heat storage systems using phase transition materials provide a greater thermal storage capacity than sensible heat storage technologies [10]. Many studies have been conducted on the usage of PCM materials in solar dryers. The experiment findings show that the dryer maintains a temperature within the chamber that is six degrees Celsius higher than the ambient air for the next five to six hours after sunset [11-12]. Khadraoui et al. [13] carried out a comparative study on SAHs employing phase change material. He conducted an experimental study using a hollow filled with paraffin wax (PW) and an aluminium array acting as a latent storage unit. He discovered that the PCM cavity increased the exit air temperature by 4 to 7 °C over night compared to SAH without PCM. Two hours after sundown, the sensible heat storage units' drying air temperature remains constant. Nonetheless, the paraffin wax drier was able to maintain the temperature for an additional three hours [14]. Through studies, the drying of 500 g of Cavendish bananas was investigated. trustworthy results showing a significant drop in the moisture content of the original sample from 74.4% to 9.6%. With thermal energy storage, this reduction took 270 minutes, while without it, it took 360 minutes. At 23.23%, the drying efficiency with thermal energy storage reached its highest [33]. After adding paraffin wax for TES, the dryer ran independently for 3.5 hours without exposure to sunlight [34]. When using PCMs on the lower tray of the cabinet dryer, the components dried more quickly than when using other methods.

Additionally, the overall thermal efficiency of the cabinet dryer ranged from 35.23 to 38.92% [35]. No one can fill the baffles used in the solar collector with more than one paraffin wax with a different melting temperature, according to the data above. The purpose of this study project is to close the gap that the researcher left. This work's primary goal is to: 1. Create a solar dryer using thermal energy storage materials 2. To use latent heat PCM with varying melting temperatures to trap the solar radiation that is available during the day and use the trapped heat at night. 3. To research ginger's drying properties, including drying rate, moisture content, drying efficiency, and dried product quality.

MATERIALS AND METHOD

2.1 Solar collector

The complete collector system is made out of a rectangular box-shaped mild steel frame covered in a 1 mm thick layer of galvanised iron. To absorb incident solar energy, a black-painted, 2 mm thick aluminium plate is utilised as an absorber. The air heating system took up two square meters. Air passes through the gap between the absorber plate and the rear plate while it is operating. To alter the direction of air flow, certain areas within the collector are baffled.

2.2 Solar collector without thermal energy storage

There are 13baffles are used. Out of 13 baffles first five not filled PCM since in this region available temperature is not meet the melting temperature of PCM.In this region baffles only change the direction of air flow.

2.3 Solar collector with thermal Energy storage unit

Baffles from 6th – 13^{th} act as a PCM container. PCM container filled with paraffin wax as Phase changing material, Wax filled in the PCM container is based on the melting temperature of wax and available temperature in the solar collector. Each PCM container holds 2kg of paraffin wax so that 16kg of wax is used in the system. From 6-9 PCM container wax filled in the granular form, From 10-12 PCM container filled with paraffin wax with melting temperature65°C-80°Cwax in the Bar shape, for uniform distribution of wax the bar was melted and filled in the PCM container. The13^{th} PCM container is filled with powder formed paraffin wax with melting temperature is 80°C-100°C so that PCM melt accordingly during the sunshine hours and come back to solid form during the off-sunshine hours. The front end of the collector (which measures 0.07 x 0.08 meters) has collector inlet connectors. The blower is connected to the collector's inlet to operate the system in force convection mode. With the system operating in free convection mode, the blower is taken out and the inlet end is left exposed to the atmosphere. The drying chamber and collector outflow end are directly connected (figure 1).

Fig 1. Photograph of the indirect solar dryer with thermal storage and PCM container

2.4 Drying chamber

The mild steel frame of the drying chamber is coated with a transferring polycarbonate sheet that is 5 mm thick and is 0.6 x 0.55 m in length and width, respectively. They are positioned equally, 0.05 meters apart. Galvanised iron sheets encased the entire unit, and glass wool was placed between the outer and inner shells for insulation. In order to load and unload the product in the drying chamber, a door with a locking mechanism was supplied. Sponge rubber is used to seal the door airtight. To control air flow and remove wet air from the drying chamber, a round pipe with a 0.1 m diameter and 0.5 m length is installed on top of the chamber. Table 1 lists the specific design parameters for the solar dryer with the latent heat thermal energy storage material.

Table 1. Latent heat storage material

S.no	Paraffin wax	Melting temperature	No of PCM container	Location of PCM	Quantity used
1	 Granulated form	$45^{\circ}C$-$60^{\circ}C$	4	Collector baffles 6-9	8
2	 Solid form	60°C-$70^{\circ}C$	3	Collector baffles 10-12	6
3	 Powder form	$80^{\circ}C$-$100^{\circ}C$	1	Collector baffles 13	2

2.5 Direct solar dryer

Fig. 2 depicts the experimental setup for direct solar crop drying. and the details listed in Table 2. The glass cover reflects some of the incident solar radiation back into space, while the remainder enters the cabin drier. Additionally, some of the radiation that is transmitted is reflected back from the crop's surface. The crop's surface absorbs the remaining portion. The crop's temperature rises as a result of solar radiation absorption, and it begins to release long-wavelength radiation that, unlike open sun drying, cannot escape to the atmosphere because of the glass cover. As a result, the temperature inside the chamber above the crop rises. Another benefit of the glass cover is that it lowers direct convective losses to the surrounding air, which helps to raise the temperature of the crop and the chamber, respectively. The black metal absorber heats the air that enters the solar dryer from the bottom. Through the vents at the top, the warm air escapes after rising above the food. These dryers operate at temperatures between 50°C and 65°C, which is a useful range for drying the majority of food products.

Fig 2. Photograph of the direct solar dryer

3. Experimental Procedure

Experiments were carried out in forced convection mode with 1000g of ginger loaded under ideal airflow conditions of 0.0312 kg/s following sample preparation. The PCM temperature in the collector at the halfway, three-quarter, and final points are recorded every hour using a thermocouple, and the temperature of the atmosphere is recorded every hour using an infrared thermometer. Using a solar power meter, the solar intensity was monitored every hour. Additionally, experiments with open sun drying and direct solar dryers were carried out. Open sun drying was contrasted with the experimental outcomes from the direct solar dryer mode and the indirect forced convection solar dryer mode. The numerous Performance parameter and their definition and equation of solar dryer are given in the table 3[15].

Table 2. Performance parameter of solar dryer

S.no	Design Parameter	Description	Equation	Unit
1	Moisture content	The moisture content of product is calculated every hour by using initial and final mass of the product. It refers to water content present in a certain object.	$Mc = \frac{Mi - Md}{Mi} \text{X } 100$	%
2	Drying rate	Evaporation of moisture from the drying product. It depends on heat supply to the product.	$Rd = \frac{Mi - Md}{t}$	Kg/s
3	Collector Efficiency	The ratio of useful heat gain over any time period to the incident solar radiation over same period.	$\eta c = \frac{QU}{IAC}$	%

4	Moisture ratio	Moisture ratio is the ratio of the moisture content at any time 't' to that of the initial moisture content of the sample.	$MR = \frac{Mt}{Mo}$	-
5	Moisture evaporated	The Quantity of moisture evaporated from the product	$m_w = \frac{m_i(M_i - M_f)}{(1 - M_f)}$	Kg/hr

3.1 Sample preparation

Fresh raw ginger was purchased from local market and washed and cleaned in water thoroughly to remove surface dust and extraneous matter. The clean ginger was hand peeled by knife and cut into suitable size and shape. The slices were kept in the tray and loading in to the solar dryer with thermal energy storage for drying (Figure 3)

(a) Raw ginger (b) Peeling (c)After loading

Figure 3 Sample materials

3.2 Instrumentation

A solar power meter was used to measure solar radiation. To measure the temperature of the drying air, three calibrated thermocouples with an accuracy of ± 0.05°C. The blower's energy usage was measured using an energy meter with an accuracy of ±0.1Kwh. Anemometer was used to measure the air velocity at the collector's inlet (accuracy ±0.01 m/s). With an accuracy of 0.01g, the mass of the ginger was measured using an electronic balance (Table 3).

Table 3. The tools utilised for the experiment

S.No	Instruments	Parameters	Accuracy
1	Thermocouple	Temperature	0.05°C
2	Electronic Balance	Mass	0.01g
3	Solar Power Meter	Solar radiation	± 0.5w/m^2
4	Anemometer	Air velocity	±1.5%
5	Energy Meter	Blower energy ccconsumption	±0.1Kwh

RESULT AND DISCUSSION

4.1 Collector temperature

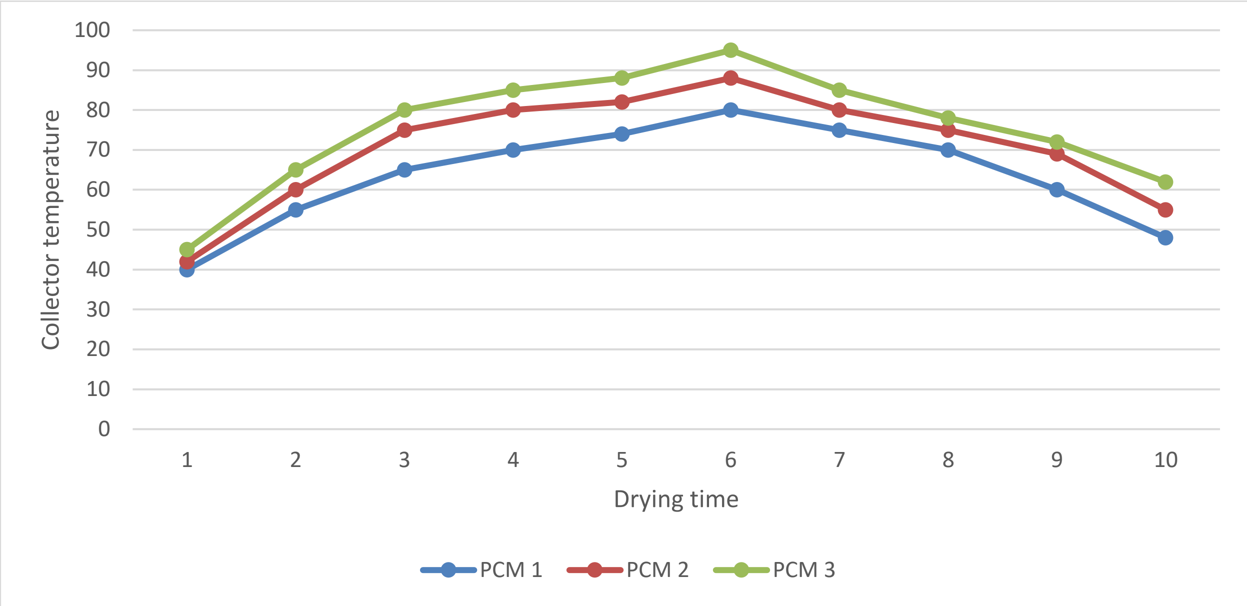

Figure 4. collector temperature Vs drying time

The figure 4 illustrates how the collector temperature changes with drying time. Phase change material was poured into the collector baffles according to the temperature in the collecting zone. In the collector, PCM1 is filled in the middle, PCM2 is filled roughly three-quarters of the way, and PCM3 is filled at the very end. As a result, the maximum temperature of PCM1 is approximately 80°C, while the minimum temperature is approximately 40°C. PCM1 melts easily throughout the day since its melting point is between 45 and 60 degrees Celsius. Similarly, PCM2 can reach temperatures of up to 88°C and as low as 55°C. PCM2 melts easily throughout the day since its melting point is between 60 and 70 degrees Celsius. Furthermore, PCM3 may reach temperatures as high as 95°C and as low as 63°C. as PCM3 melts at temperatures between 80°C and 100°C.

4.2 Drying chamber temperature

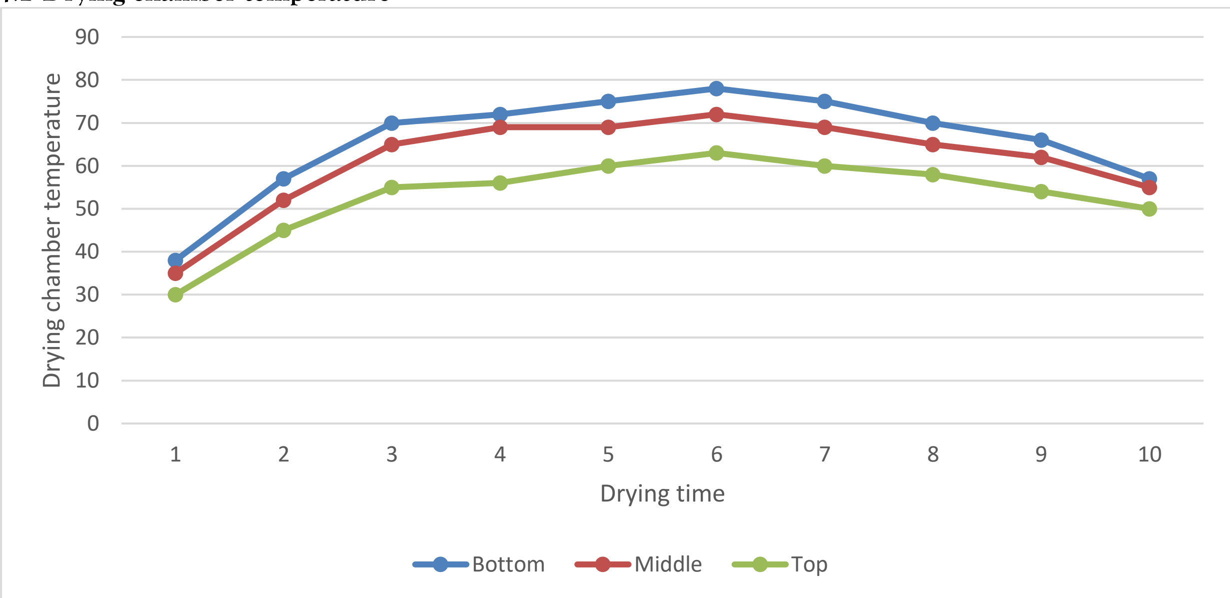

Figure 5. drying chamber temperature Vs drying time

The figure 5 illustrates how the drying chamber temperature changes as drying time does. The bottom, middle, and maximum temperatures of the drying chamber are shown on the graph. This means that for seven hours, the average temperature in the drying chamber was maintained at 66°C. This temperature is ideal for drying ginger.

4.3 Moisture content

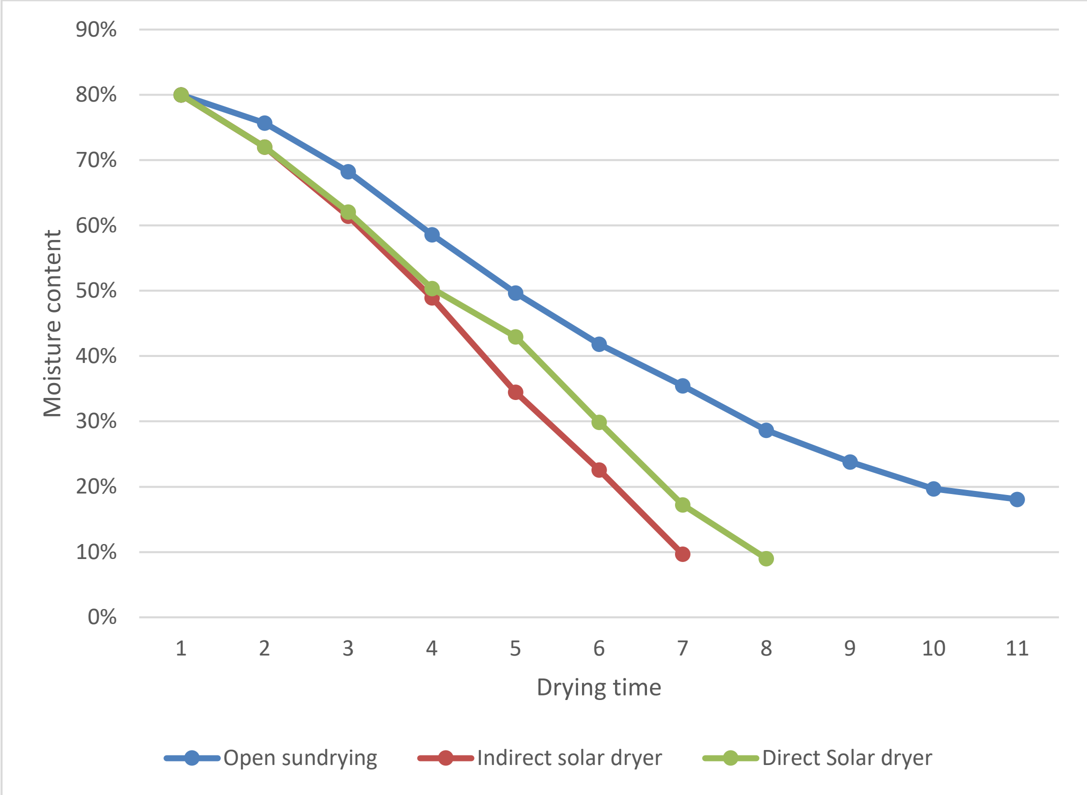

Figure 6 : Variation of moisture content with drying time

The figure 6. illustrates how the moisture content varies with drying time. In just seven hours in an indirect solar dryer with thermal energy storage, eight hours in a direct solar dryer, and eleven hours in an open sun dryer, the final moisture content is obtained after the drying process. The dryer runs effectively for the next three to four hours eight degrees Celsius greater than the atmospheric air.

4.4 Collector and Dryer efficiency

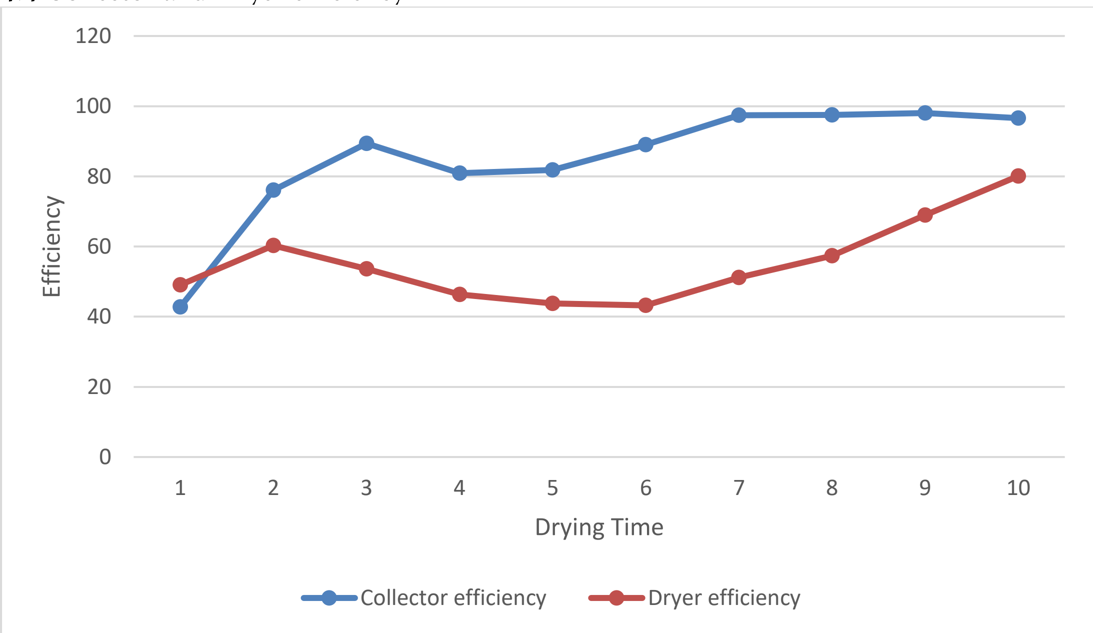

Figure 7 : Variation of Efficiency with drying time

The graph displays (figure 7) how efficiency changes as drying time increases. It reveals that the typical dryer efficiency is about 47% and the typical collector efficiency is about 85%.

4.5 Drying rate

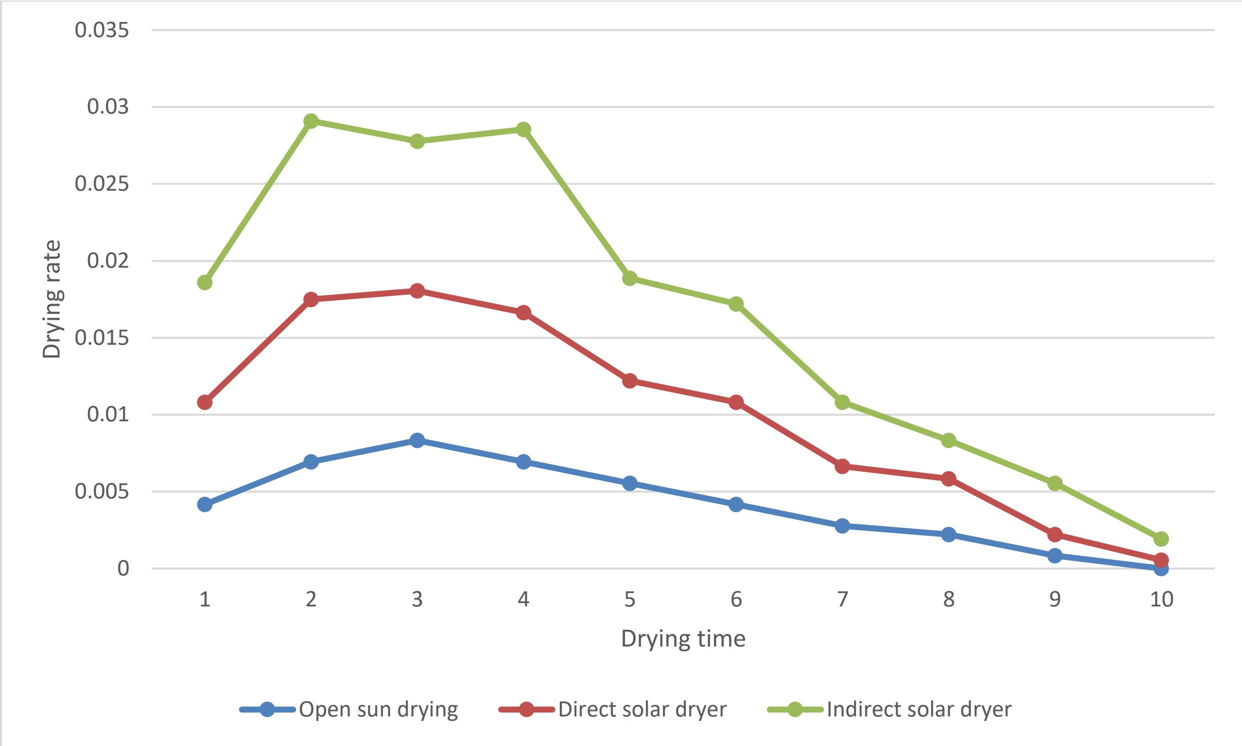

Figure 8 : Variation of Efficiency with drying time

For open sun drying, direct solar drying, and indirect solar drying with thermal energy storage, Fig. 8 shows the drying rate variation with drying time. Indirect solar drying with thermal energy storage, direct solar drying, and open sun drying all have average drying rates of 0.00655 kg/sec, 0.004606 kg/sec, and 0.005937 kg/sec, respectively.

4.6 Effectiveness factor

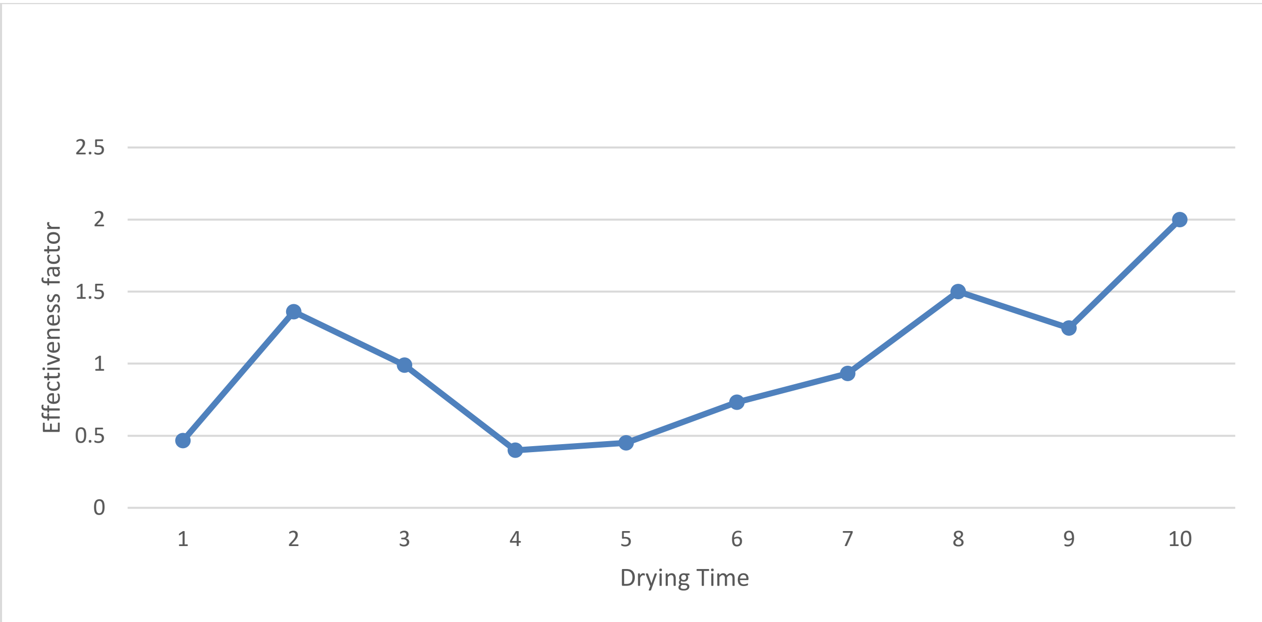

Figure 9 Variation of effectiveness factor with time

Figure 9 illustrates the drying time variation in relation to the effectiveness factor. The average effectiveness factor is found to be almost one. When compared to open sun drying, the indirect solar drier with thermal energy storage is more beneficial, as indicated by its high effectiveness factor of 2.

4.7 Ginger after Drying

The sun dried ginger is brown in colour with irregular wrinkled surface where as direct and indirect dried ginger is light brown with regular wrinkled surface (Figure 10).

(a) Indirect drying (b) direct drying (c) open sun drying

Figure 10. Ginger after Drying

CONCLUSION

In order to dry 36 kg of ginger every batch, a solar dryer with latent heat storage thermal energy material was constructed. The system's average collector and dryer efficiency is 85% and 47%, respectively. Depending on the weather, the drying chamber can reach temperatures ranging from 50 to 71 degrees Celsius. This is a practical method that may be applied not just to ginger but also to other agricultural goods.When compared to open sun drying, this method might cut drying time in half, allowing the created dryer to dry two batches of ginger every day while still producing high-quality dry ginger. By increasing the air flow rate and adding a different liquid or solid sensible heat-storage medium to the bottom of the drying chamber, the dryer's effectiveness can be further enhanced. It is clear that farmers in rural areas of emerging nations would benefit more from the developed dryer.

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