Experimental Study of Solar Dryer with Thermal Energy Storage System for Drying of Agro Products

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Research Article

Keywords: solar dryer, Agro product, Latent heat, Phase Change Material (PCM), Thermal energy storage.

Posted Date: September 3rd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-673328/v1

Abstract

The drying of food products is an essential step in the preservation ofcrops and agricultural by-products that serve as raw materials for numerous end applications. Solar drying with Phase Change Material (PCM) is an efficient low-energy consumption processin the post-reapingstage, reducing food deterioration. A customized solar dryer setup was assembled usingCudappah (black) stones as the baseof the drying chamber to facilitate the absorption of solar energy on its surface. Theorganic paraffin wax, with a melting point of 60℃,was used as PCM in the solar dryer. The novelty of the study is the application of a PCMin asolar dryer to improve the effectiveness of drying and decrease the absolute drying period and the microbial content in the dried food products. The study compared the drying characteristics between open sun drying, solar dryingwithout and with PCM (100 and 200 grams). The fabricated setup was utilised for drying coconut using a PCM-based solar drying method.The coconut was dried from an initial moisture content of 55.5% to a final moisture content of about 9%. The prototype dryer modelminimized the use ofthe workforce,avoided improper drying,and decreased the absolute drying time. A Total Plate Count (TPC) test was conducted to characterize the microbial content in the dried coconut.The microbial count decreased with the use of 200 g PCM as the use of PCM retained the heat for a longer time in the chamber. The drying time of the coconut was decreased by about 28 and 52 hours by installing of about 100 and 200g of PCM respectively. The drying time of the coconut decreased with an increase in the amount of PCM in the solar dryer. The sensory characteristics like colour, taste, flavour, quality, and texture of the solar-dried coconut sample were superiorto the sun-dried coconut sample.

1. Introduction

The drying of vegetables and crops is one of the crucial processes that improve the usability ofthe products. Since drying is a method requiring high energy, different drying methodswere exploredto decrease energy utilization and increase drying efficiency(Atalay 2020).The sun is an indispensable source of obtainable energy (i.e., solar energy) for Earth. With the increasing energy demand, the environmental effect of fossil fuel consumption, and mounting concerns of higher fuel costs, solar-powered energy poses an affordable option that does not significantly contribute to CO_2 and CO discharges and other contaminants(Vasquez et al. 2019).There are several solar drying systems: cabinet solar drying, solar greenhouse drying, direct solar drying, direct sun drying, indirect type solar drying,and mixed-mode solar drying(Singh et al 2020).Among all the available drying systems, sun drying is the conventional and the most adopted technique to dry and preserve farming products like grains, fruits, and vegetables in most countries. However, the drying methods adopted in the preservation process raise serious concerns about the lossesin the quality and quantity of the driedproducts(Pangavhane et al 2002).For example, in open sun drying, the exposure to the sun is inconsistent from the period before noon to sunset, and when directly exposed to sunlight, the essential oil compounds are not completely reduced while the exposure damages the required colour, texture, and fragrance of the food products(Bhardwaj et al 2019). Besides, the open environment may expose the products to dust particles, insects, flies, wind, humidification at night,affecting the quality of the dried productsand may subsequently affect the market value of the raw materials andfinal product(Ali mohammudi et al 2020).

The drying process requires a large amount of thermal energy as high latentheat is desired for water evaporation. Currently, convective dryingandfreeze-drying are the two broadly utilized methods of drying around the world. It requires both mechanical and electrical energy input(Ananno 2020).Compared to other drying methods, the solar dryer saves a large amount of energy and obtains a better-quality food product. Nevertheless, the intermittent impact of weather and climatic conditions has been significant obstructions to the successful utilization of sunlight for solar dryers. As a result, different solar drying systems are incorporated with thermalstorage materials to remove the reabsorbedmoisture content from the products (Komalafe et al 2018). In order to ensure a consistent pattern of drying, phase change materials (PCMs) are used in the drying system. In the daytime, the solar energy is stored and released in the evening by the PCM, wherein the PCM uses the stored thermal energy as sensible and latent heat energy (Azaizia et al 2020). Therefore, the material temperature remains higher than the ambient condition in the sensible heat storage system (Kumar et al 2017). The most commonly used PCMs are fatty acids, paraffin wax, Glauber's salt, calcium chloride hexahydrate, sodium thiosulfate pentahydrate, and sodium carbonate decahydrate (Esakkimuthu et al 2013). The high specific heat, latent heat of fusion, high density, thermal conductivity, chemical inertness, and non-toxic nature are some of the properties considered while selecting PCM for drying applications (Shalaby et al 2014). In the daytime, the PCM is charged using solar energy for about 8 hours (based on effective sunlight exposure) and discharges the stored energy in the remaining period of the day(Arfaoui et al 2017). Paraffin wax can be used as a PCM in latent heat storage systems. It is a non-corrosive, low-cost material, and chemically stable below 500℃ with a minimal volume difference during melting (Baniasadi et al 2017). The solar dryers have been comparatively examined with and without different PCMs.Studies have revealed that after 2:00p.m. the drying air temperature in the solar dryer with PCM increased about 3.5 to 6.5℃which was more than the other casesi.e., systems without PCM (El khadraoui et al 2017).

The quality of the food product is a very significant characteristic to be evaluated after drying, and the visual appearance of the food product also changes during drying irrespective of the method of drying; some of the changes that occur in the product isbrowning, loss of nutrient, hardening, etc (Mohana et al 2020). However, the moisture content in the crop needs to decrease after the drying process. The extent of bacterial degradation can be significantly decreased by removing the moisture content.Therefore, it is feasible to accumulate adried-outfood product for an extended period(Bahari et al 2020). The methodology of solar drying is typically intended to meet specific drying attributes of farming products with an improved approach to energy utilisation. The payback time of the developed drying system can be shortened based because the driercan serve inthe winter as well as summer seasons. Consequently, the actual price of the dryer is cheap(Swami et al 2021).

Coconuts are one of the most popular farm products, wherein the popularity of the fruit is ascribed to its culinary use and several health benefits. Besides its surface processed for natural fibres, coconuts can also be treatedto obtain coconut milk, copra, and oil. In the cooking process, thewhole fruit is known to havecountless benefits (Sumarni 2021). Conventional drying methodsare used to reduce the moisture and dry the coconut for future use. However, the methods may induce undesirable characteristics to the dried product like shrinkage, toughening of thesurface, and colour changes, which have been reported to influence consumer acceptance(Jariyawaranugoon 2018).The idea of using the solar dryer has proved to be comparatively inexpensive and effective for the drying process. In a study on the solar drying of coconuts, the moisture content in the wet base (w. b.) decreased from about 52% to 8% in 62 hours. The moisture content of copra reduced using solar dryers is higher that of open sun drying (Padmanaban et al 2017). Recent research studies have highlighted an effective drying system using a solar dryer to decrease the absolute drying period and increase the drying effectiveness of agricultural products. Using PCMs can improve the drying characteristics and decrease the drying period of coconuts.The key objective of the research is to decrease the microbial content in the dried food product, reduce human intervention and avoid improper drying during winter. Naturally, solar drying can preserve the food crops by retaining the colour, taste, fragrance, and quality (Ayyappan 2018). The current studyattempts to determine the role of paraffin wax as an effective phase change material (PCM) in drying coconutsusing a solar dryer. The improvement in the quality and value of the dried-out products with and without PCM has also been investigated.

2. Materials And Methods

2.1. Construction of Solar Dryer:

A normal convection solar dryer (700 × 300 × 300 mm) was manufactured and mounted at Kalasalingam Academy of Research and Education, Tamilnadu (India). It consists of a UV-coated double-layered polycarbonate sheet bent in parabolic shape to receive solar energy more efficiently. It was used to absorb the solar radiation inside the drying chamber. The polycarbonate sheet is durable and offers 60 % better thermal insulation than glass. The UV coating is essential to protect the underlying material from harmful radiation. The parabolic polycarbonate sheet is attached to aluminium supports. The base of the polycarbonate sheet is a Cudappah Black Stone slab (700 × 300 mm). It was used to resist the flow of heat energy from PCM through the bottom of the stand. Rails were provided along the longitudinal length of the stand for the movement of the chamber base. A stand made of iron acts as the skeleton of the arrangement holding the drying chamber supported and positioned by four nylon wheels. The solar panel (PV Panel) is attached near the dehumidifier and was used to provide electrical energy to run the exhaust fan. An exhaust fan was used to evacuate the saturated air from the drying chamber and fill the chamber with fresh air from the atmosphere. It was operated automatically using sensor data, and it consumes power from the solar panel. The paraffin wax (PCM) was placed on the base of the stand and shielded with stainless steel. The humidity and temperature measurement device were placed within the dryer to record the temperature and humidity values. The nylon wheels on the bottom of the base helped in easier loading and unloading.

2.2. Experimental procedure:

The solar dryer works by absorbing solar energy and changing it into heat energy for the drying process. The mode of energy transfer is primarily conduction and radiation. While only a small amount of heat transfer accounts for radiation, conduction is the dominant mode of heat transfer in this process. The solar energy passes through the UV-coated double-layered polycarbonate sheet. The polycarbonate sheet allows solar energy to pass through but does not allow the energy to leave the chamber. The iron stand held the Black Cudappah stone, which was the chamber's basement, and the chamber corners and edges were well packed. The PCM, i.e., paraffin wax, was placed in a container inside the chamber.

In the experiment, coconut was the agricultural product investigated in the fabricated heat storage and drying system. The experiments were conducted in March when the effective period of solar energy exposure was between 9 a.m. and 5 p.m. Both charging and discharging phases of the PCM occurred simultaneously during the drying process. The temperature inside the energy storage system, ambient air temperature, was measured every 30 mins and recorded by the data logger. In addition, the mass of the dried products and the energy density of solar radiation were also recorded every 30 min. The experiments were conducted in the chamber with and without PCM (0,100, 200 g of paraffin wax). The experiment was evaluated based on the drying efficiency, total plate count (TPC), and sensory attributes of the dried product.

Table 1
Properties of PCM- Organic paraffin wax

PCM	**Melting Temperature (°C)**	**Density (kg/m^3)**		**Specific heat (J/kg K)**		**Thermal conductivity (W/m K)**		**Latent Heat of fusion (kJ/kg)**
		Solid	**Liquid**	**Solid**	**Liquid**	**Solid**	**Liquid**	
Paraffin Wax	60	874	786	2400	2200	0.24	0.21	190

2.3. Calculation of Moisture Content and Total Plate Count (TPC):

The effect of using PCM on the drying process is evaluated by determining the moisture ratio. The drying efficiency is defined as the maximum energy gained by the PCM and the useful energy supplied to dry the sample in the chamber. The energy supplied for drying must heat the sample and remove the moisture content from the sample (Akhijahani et al 2017). The coconut was broken into two halves for effective drying, exposing the inner part of the coconut. The samples were weighed before drying, and then the loss of moisture was evaluated by weighing the sample every 30 minutes until the end of the experimental duration. The samples were weighed using a weighing balance of 0.1g accuracy. The moisture content of the dried sample was calculated by the below Eq. (1):

$$MC = \frac{m_i - m_d}{m_i} \times 100 \qquad (1)$$

where MC is the moisture content, m_i is the initial mass of the product before drying, m_d is the mass of the dried product (Lingayat et al 2020).

The Total Plate Count (TPC) for coconut samples was determined by a direct plate count method after serial dilution procedures by spread plate technique and a nutrient agar medium. In the present case, the TPC is the number of aerobic consuming, mesophilic organic entity that grows in an aerobic environment in a modest temperature range of 20–45°C. The TPC evaluation consolidates all microorganisms and non-microbes in the sample and helps determine the hygiene grade of dried food.

2.4. Sensory characteristics:

Sensory attributes such as colour, flavour, surface texture, and the other visual attributes of dried coconut samples were examined. The colour of the dried product is examined using naked eye observation. The changes in the size, shape, deformation in the fruit body were also considered. The odour of the dried product, a qualitative factor, is evaluated by smell. The surface texture is the property of food which is related to the feeling experienced by the finger during touch or the mouth by chewing. A textural property is best demonstrated by the sensation brought about by contact with hard and delicate pieces of the samples in the mouth (Ahmad et al 2005).

3. Results And Discussion

The solar dryer was set up at Kalasalingam Academy of Research and Education, Tamilnadu (India), in March 2021. The drying experiments were conducted for four different conditions: open sun drying, solar drying without PCM, the solar drying with 100 grams and 200 grams of PCM. Organic paraffin wax, with a melting temperature of 60℃, was used as PCM in the solar dryer. The drying performance and characteristics were analysed for different drying methods based on the moisture removed, drying time, and sensory attributes of the samples. In addition, comparative evaluation of drying time, peak temperature, and the average temperature in the drying chamber for coconut in the proposed solar dryers' system were conducted.

The outcome of PCM in the solar dryer on the drying experience can be assessed based on the ability of the setup to maintain a uniformly high temperature in the chamber. Naturally, the temperature in the chamber reaches a maximum level, i.e., peak temperature, during the time of severe solar exposure. i.e., solar noon. Although the period is relatively short, the high temperature during that period favours a higher drying rate. However, the benefit of using PCM in the solar dryer is that the total drying time is reduced by maintaining the required temperature in the chamber. A food product is claimed to be maximumly dried if the weight remains constant consecutively for at least 3–5 measurements. Table 2 presents the average temperature maintained in the drying chamber and the peak temperature reached in the chamber for different drying conditions with and without PCM. Paraffin wax begins to melt above 45–50℃, and during the peak temperature (above 60℃), it entirely melts. However, the wax tends to solidify when the outside temperature decreases (below ~ 45℃). So, the phase transition occurs within a smaller range of temperature, wherein the effect of PCM is observed.

From Table 2, the average temperature sustained in the chamber in the presence of PCM is higher; nevertheless, the temperature is over the solidification temperature of paraffin wax. During winters, the temperature may drop off considerably more, so the phase transition temperature range may be more extended, so the heat storage and liberating limit of paraffin wax are required to be significantly higher. In the summer, the average temperature of the chamber is adequately high to allow moisture removal with direct drying of the food crops. PCMs have improved the moisture removal rate in food crops in a minimum period than food crops dried without PCM.

Table 2
Average and peak temperature in the drying chamber; drying duration (Errors in temperature: ±1°C)

S. No	Drying method	Average Temperature (°C)	Peak Temperature (°C)	Drying duration (hrs)
1.	Open sun drying	29	40	128
2.	Solar dryer without PCM	44	63	120
3.	Solar dryer with 100 grams of PCM	47	68	100
4.	Solar dryer with 200 grams of PCM	49	69	76

3.1. Weight and temperature analysis of coconut during drying:

Figures 2 and 3 show the trend of weight changes over the total duration of drying of coconut for different drying conditions. It can be observed that open sun drying of coconuts resulted in an inconsistent loss of weight throughout the drying duration. On the other hand, drying the coconuts using solar dryers (with and without PCM) resulted in a step-by-step loss of weight. A two-step process characterized the trend of weight loss for the dryer with 200 g of PCM, while the weight loss of the coconuts with 100g and without PCM was noticed to have more than two steps, which were essentially observed in the peak solar exposure time of drying. The role of PCM in improving the drying rate was very evident from Fig. 2.

In all the drying processes, the first 10 hours of drying witnessed a steep fall in the weight of the coconut. After the 10th hour, the curves exhibited distinct variations depending upon the nature of drying. As a result of the sharp falls at specific periods of drying, the gravimetric observations of coconut samples tend to remain unchanged, i.e., maximum removal of moisture occurs at certain stages of drying, and the weight of the samples reach a state of stagnation earlier than the samples dried in the open sun and using solar dryers without PCM. This stagnation can only be noticed when there is no further removal content of water in the samples. Another notable aspect of solar drying with PCM is that there is no increase in the weight during the night hours, i.e., no reabsorption of moisture from the surrounding atmosphere. This is because the PCM activity tends to compensate for the drop in outside temperature during the night; as a result, the temperature inside the chamber still tends to remain high enough, avoiding possible moisturizing of the drying sample. From Fig. 4, it can be seen that the samples dried with PCM (100 and 200g) exhibited the highest peaks, which correspond to specific time periods, such as solar noons. The lowest magnitude of weight change occurred during the night, which was also very negligible in the case of samples subjected to PCM-based drying. On the contrary, the samples undergoing drying through the open sun drying method and solar drying without PCM had moisture being absorbed into them.

The drying time of the samples in different drying systems was distinct and reasonable based on the hypothesis of the study. The coconut samples had taken about 128 hours for complete drying, while solar drying took only about 120 hours. Up to 50 % of drying time was reduced using PCMs in the solar dryers, wherein 100g and 200 g of PCM incorporated in the solar dryer set up decreased the absolute drying time to 100 and 76 hours, respectively.

Figure 4 shows the temperature variations during the drying of coconut for different conditions. When the coconuts were subjected to open sun drying, the temperature in the chamber was maintained above 30°C for more than 15 hours of solar exposure and above 40°C for about 2 hours. The temperature maintained in the chamber during the night remained the lowest in the case of open sun drying. During the night, the temperature tended to decrease, favoring the drying samples to reabsorb some moisture. In the solar dryer without PCM, the temperature was maintained above 40°C for more than 6 hours of solar exposure and above 50°C for about 12 hours and exhibited a steady drop towards the evening. However, the temperature did not lower further than that of open sun drying, which could be due to the enclosed space used for drying. In the presence of PCM (100 g and 200 g of paraffin wax), the temperature remained higher than 50°C for a longer time. When the temperature is higher, the PCMs effectively absorb the energy and store them, and when the outside temperature is lowered, the PCM underwent phase transition and released the energy in the form of heat into the chamber. This is the reason the average chamber temperature remained higher with the use of PCMs compared to the other drying conditions. Thus, the PCM had influenced the temperature to remain slightly higher throughout the drying process. The smooth logarithmic decrease of the weight of the coconut can be attributed to the effect of PCM. The paraffin wax has limited the weight gain during the night by ensuring consistently higher temperature in the chamber, so no visible crests were seen. However, in the absence of PCM, the food crops had been subjected to temperature and humidity effects towards the evening and during night.

3.2. Total Plate Count (TPC) analysis

The Total Plate Count of coconut samples was determined and is presented in Fig. 6. For every TPC test conducted, 1 gram of dried coconut sample was used. The bacterial population constantly improved in refrigeration storage and reached a value beyond 10^7 per gram (Ahmad et al 2005). From the count analysis, it was inferred that the storage temperature of the food product was higher, the bacterial population growth would be lower (Manea et al 2017). The higher temperature inside the solar dryer inhibits the survival of bacterial population, so there is a lower count of bacteria in solar dryers (with and without PCM) than in open sun-dried coconut samples. Figure 6 shows the image of the plates with bacterial population for samples of coconut obtained from different drying conditions.

3.3. Sensory characteristics

Figures 7 (a-h) show the images of the coconut samples before and after drying using different methods. In the open sun-dried condition (Fig. 7a-b), the slices of coconut showed notable changes in appearance in terms of the surface colour. They appear light brownish colour due to direct exposure to the sun's rays. The shrinkage in the volume of the coconut was also mildly evident. The sun-dried samples will have more microbial attraction as they are dried in an open environment. The images of coconut samples dried using a solar dryer without PCM reveal relatively lesser shrinkage and discoloration. Figures 7 (c) and (d) show that the extent of shrinkage of the coconut after drying was slightly greater than that of the sun-dried sample. It has to be noted that shrinkage is one of the critical characteristics of moisture loss, so the shrinkage needs to be high to indicate a higher removal of moisture content. Figures 7 (e-h) present the images of dried coconut samples using 100g and 200g of PCM. There is significant shrinkage in the volume of the coconut samples, whereas the colour changes were not noteworthy compared to that of the drying without PCM. On examining the coconut after dried in the solar dryer with 200g of PCM (Fig. 7(h)), the colour of the inner fleshy part turned pale white after drying, and the shell had become hard and brittle. The microbial attraction will be lower in the solar dryer and solar dryer using PCM compared with open sun-dried samples.

Table 3
Summary of the previous studies and present study based on solar dryer.

S. No.	Author name	Experimental work done	Product	Moisture content	Drying time
1.	Atalay [1]	Pebble Stone Thermal Energy Storage	Lemon slices	94.8 to 10%	6.23 hr
2.	Pangavhane et al. [4]	Natural convection solar dryer	Grapes	34.95 to 17%	4 days
3.	Bhardwaj et al. [5]	Forced convection solar dryer with PCM	Valeriana Jatamansi	89 to 9%	120 hrs
4.	Komolafe et al [8]	forced convection solar dryer integrated with heat storage material	Cocoa beans	0.6 to 0.034 g water/g w.b	58 hours
5.	Azaizia et al. [9]	mixed mode solar greenhouse dryer with PCM	Red pepper	95% reduction	30 hrs
6.	Bahari et al. [17]	α-AL2O3-PW nanocomposites for thermal energy storage in the solar dryer	Kiwi fruit	99.8 to 0.56%	14 hrs
7.	Padmanaban et al. [21]	desiccant assisted packed bed passive solar dryer	Coconut	52 to 8%	62 hrs
8.	Ayyappan [22]	solar greenhouse dryer	Coconut	53 to 7%	74 hrs
9.	Present study	Natural convection solar dryer with 100 and 200 grams of PCM	Coconut	55.5 to 9%.	100 and 76 hrs

From Table 3, it was concluded that in the previous studies were conducted in various types of solar dryer with thermal energy storage for drying different food products. The organic and inorganic PCM are used in the previous studies. But in the present study the natural convection solar dryer with organic paraffin wax PCM is used. The PCM is nontoxic and environmentally friendly. The solar dryer is work without electricity or any external aid, due to this the construction cost and operation cost is very low.

4. Conclusion

In this study, the performance of solar dryers with PCM for drying agricultural crops was assessed. Paraffin wax was utilized as the PCM in the solar drying method for coconut samples. The results revealed that when the amount of PCM was increased in the conventional solar dryers, the drying time decreased. About 8 hours of drying time was saved on drying the samples using conventional solar dryers rather than open sun drying. The drying time was decreased by about 50 % with the use of PCMs in solar dryers. Although the PCM-based solar dryer was constructed to handle 60 kg PCM loading, the experiments were conducted on a minimal scale for this study. The PCM-packed conventional solar dryer successfully decreased the absolute drying period and increased the drying effectiveness, and also reduced the microbial content in the dried food products. The nutritional degradation of the dried coconut was very low in the solar dryer using PCM. It was established that the colour, taste, flavour, quality, and texture of the solar-dried coconut sample were superior to the sun-dried coconut sample.

The farmers will be the beneficiaries of this cost-effective solution for drying food products like fruits and vegetables. This innovative drying system can significantly reduce the risk of spoilage and wastage of food items. Moreover, the natural taste can be retained, and the goodness of the product will not be altered when drying the food products. The product is also protected against flies, pests, dust, and rain.

5. Abbreviations

PCM Phase Change Material

TPC Total Plate Count

TES Thermal Energy Storage

MC Moisture Content

M_i Initial mass of the product before drying

M_d Mass of the dried product

PV Photo voltaic

6. Declarations

Acknowledgement

The authors would like to thank the principal and management of Kalasalingam Academy of Research and Education for their assistance in completing this research project.

Declaration of competing Interest

The authors declare that there is no competing interest.

Availability of data and materials

All data are given in the manuscript

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Authors Contribution,

Gopinath Radhakrishnan Govindan- Investigation, Writing original draft

Muthuvel Sattanathan-Project administration, review & editing

Muthukannan Muthiah- review & editing

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Figures

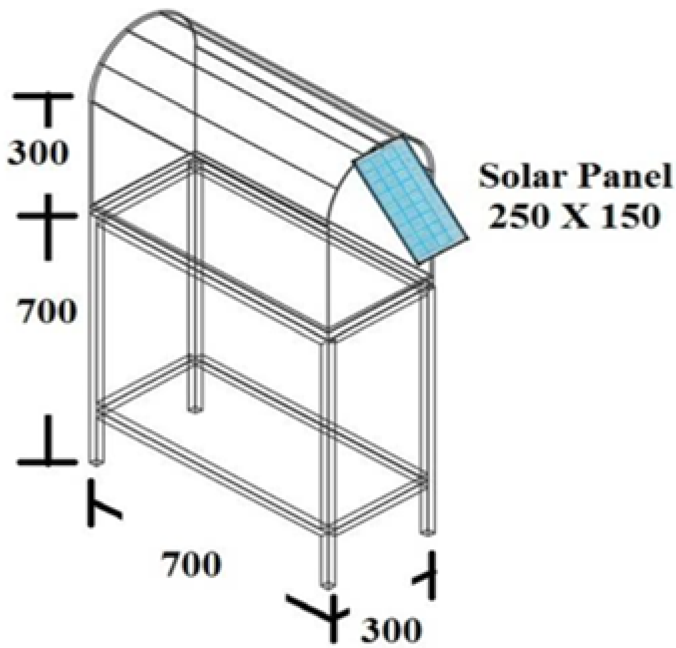

Figure 1

Schematic representation of the solar dryer (3D view) (dimensions are in mm)

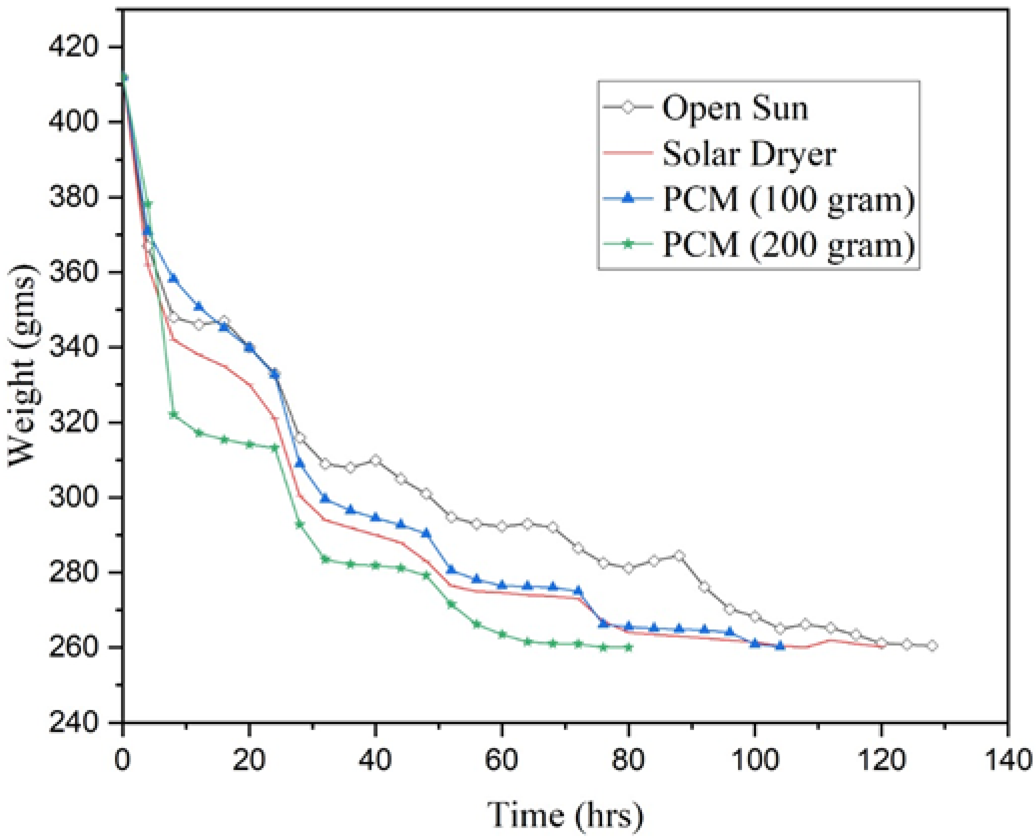

Figure 2

Weight of coconut for different drying conditions

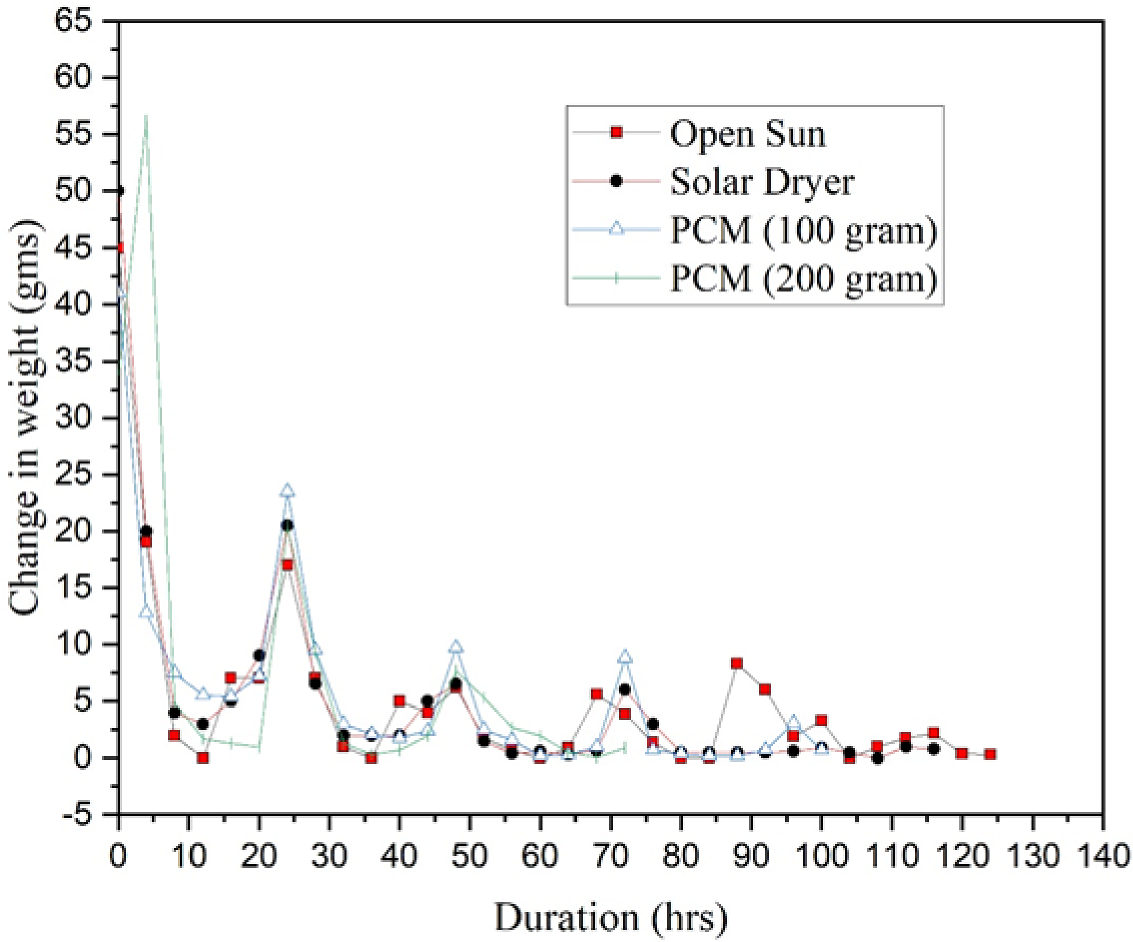

Figure 3

Weight changes in coconut in different drying conditions

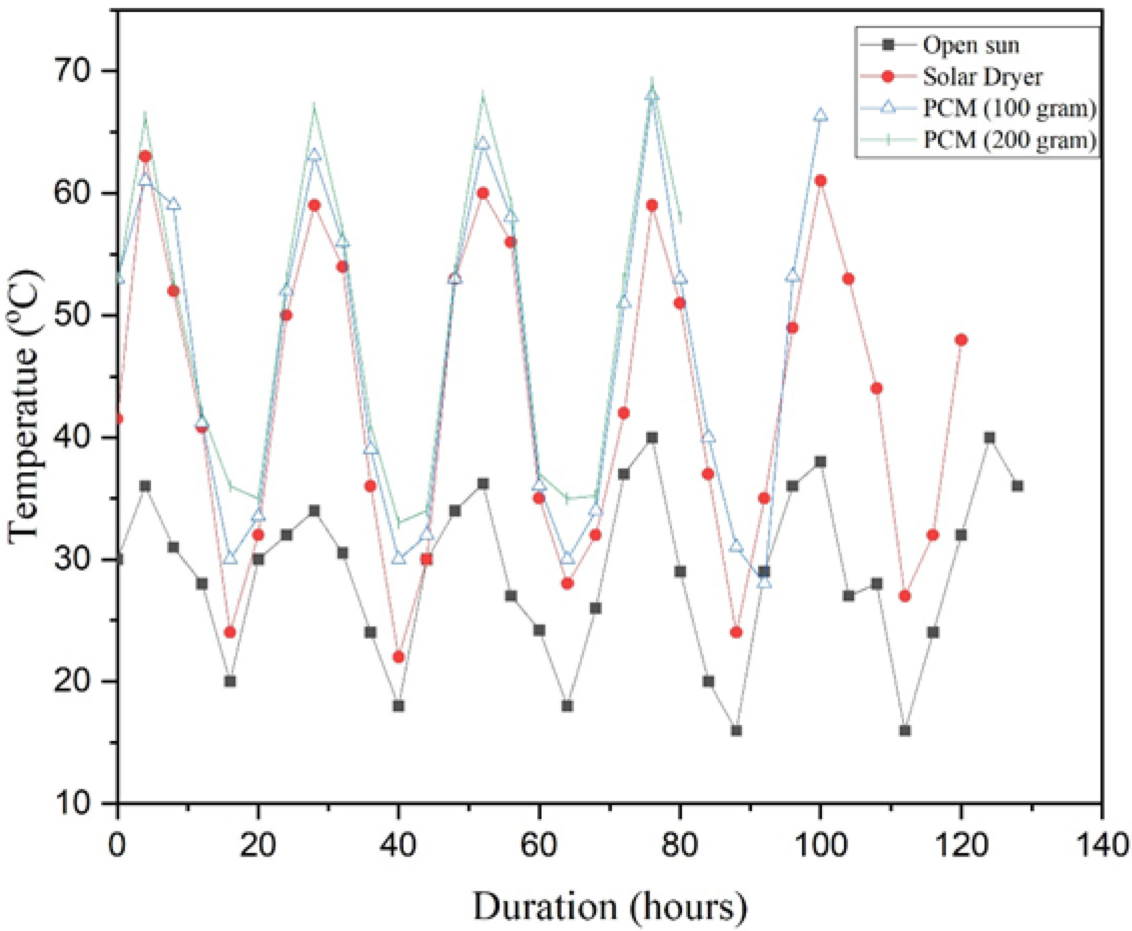

Figure 4

Temperature variations during drying for all methods

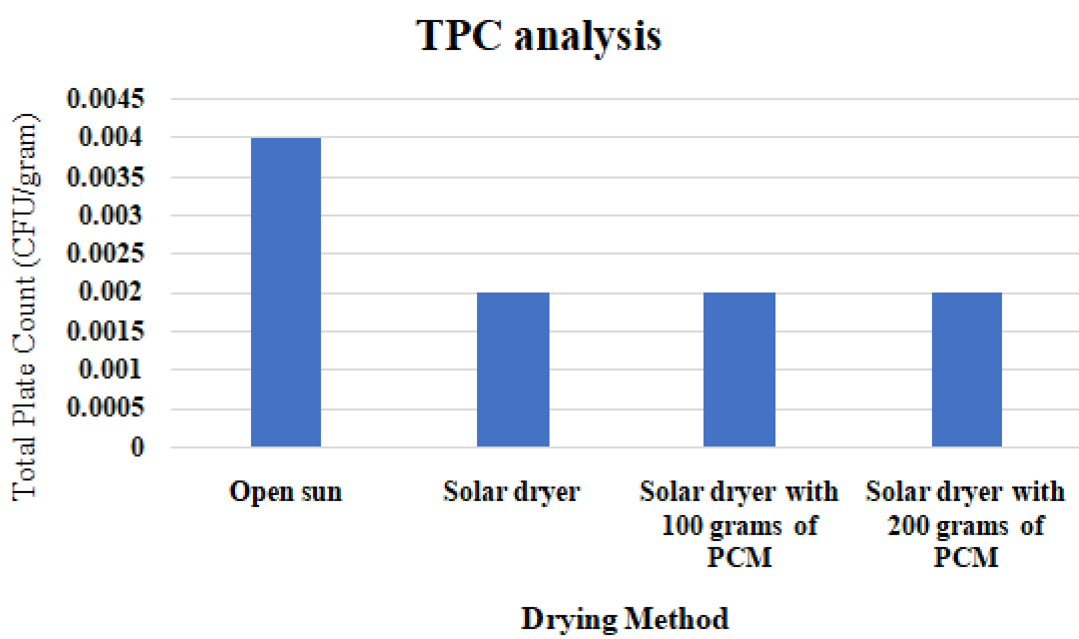

Figure 5

Total Plate count obtained for dried coconut samples obtained from different drying methods

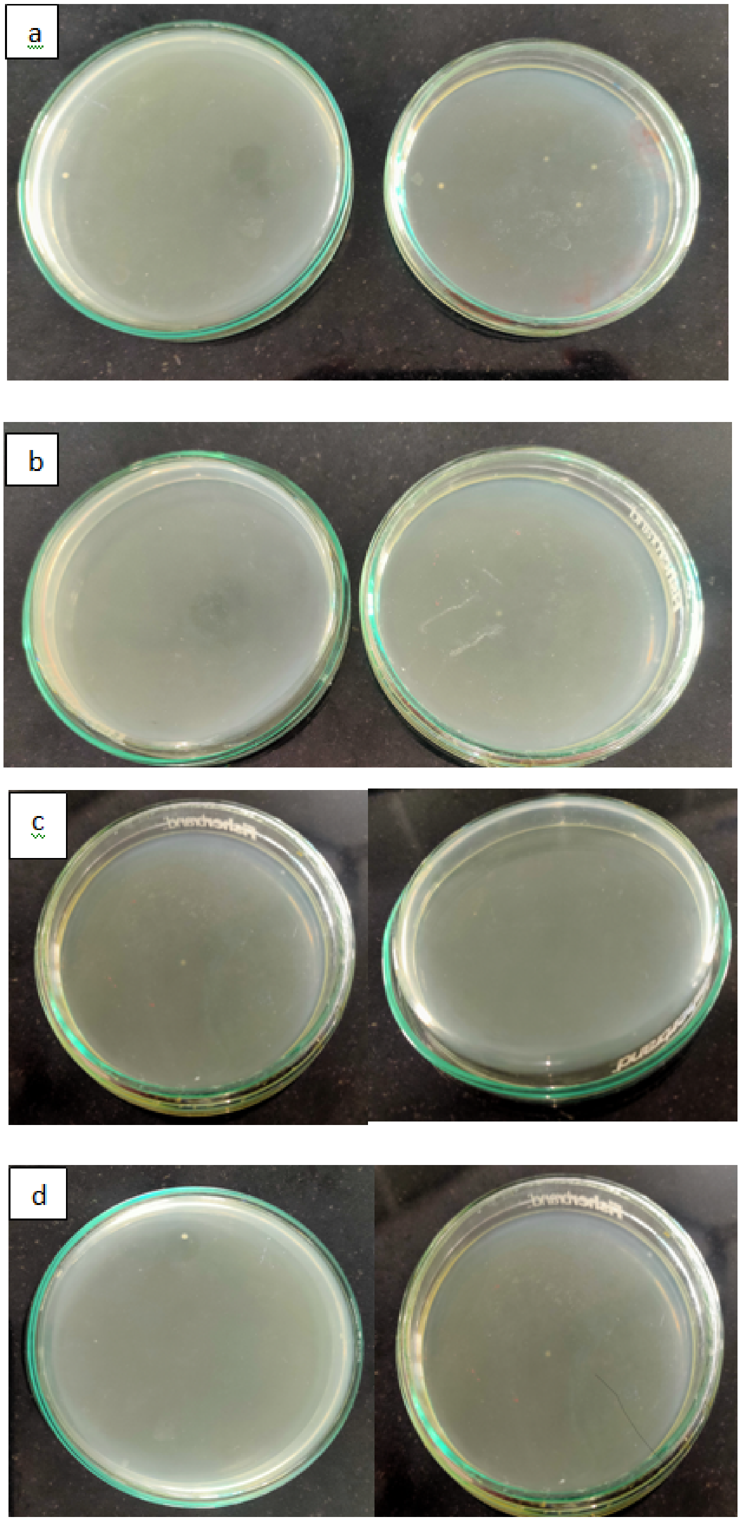

Figure 6

Total plate count analysis of samples obtained from different drying methods (a) open sun drying (b) solar drying (c) solar drying with 100 g of paraffin wax (d) solar drying with 200g of paraffin wax.

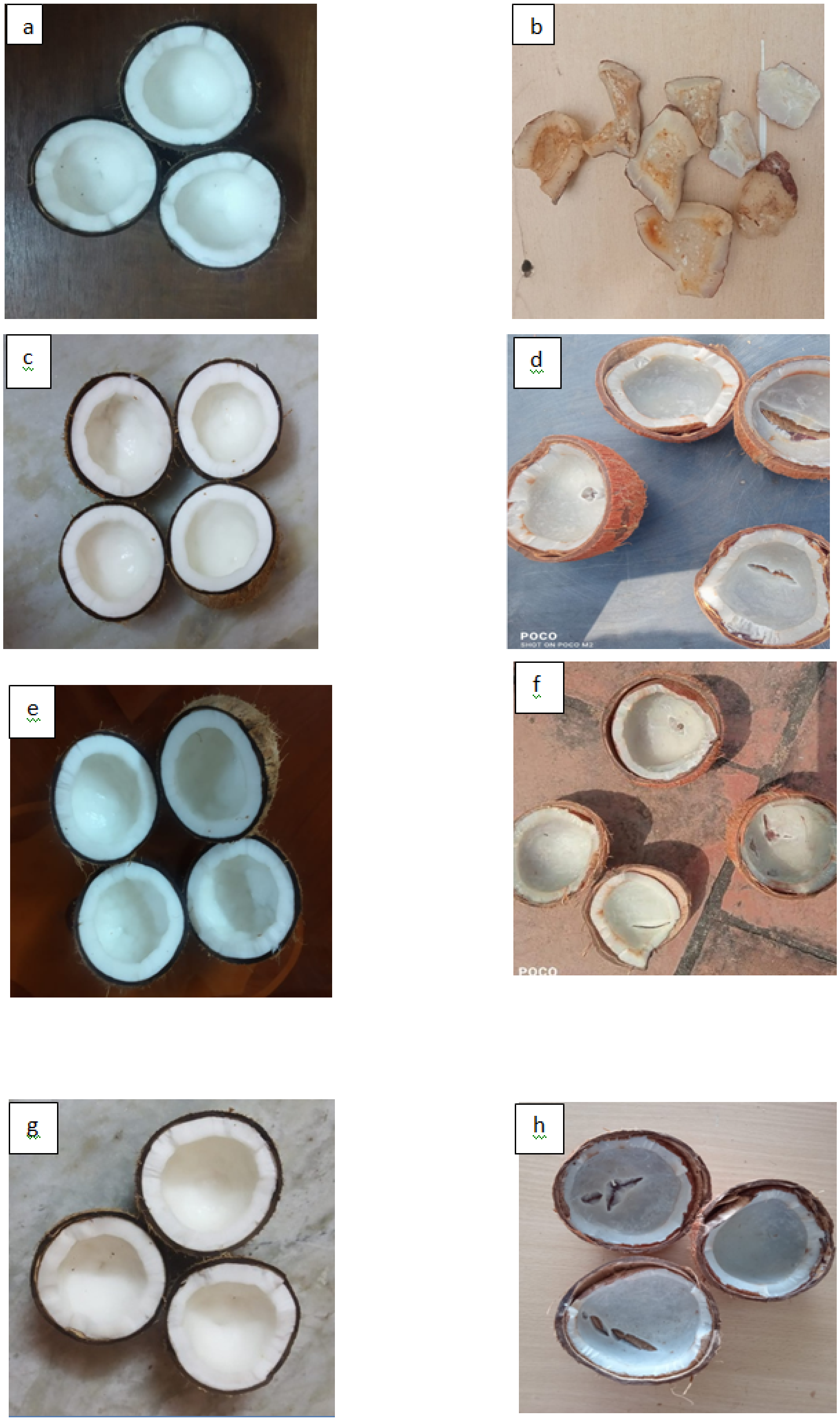

Figure 7

Naked eye observation of coconut samples before and after drying using different methods; (a-b) open sun drying, (c-d) solar drying, (e-f) solar drying with 100g of paraffin wax, (g-h) solar drying with 200 g of paraffin wax. Images on the left and right are before and after drying, respectively.