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Investigations of A Solar Dryer With Thermal Storage

Rone[1,*]

Abstract

This study presents the design, building, and performance evaluation of a low-cost mixed-mode natural convection solar cabinet dryer in conjunction with a latent heat thermal energy storage system. The work's goal is to reduce post-harvest losses in rural and semi-urban areas by offering an effective and reasonably priced method of preserving agricultural goods. The dryer is made out of a transparent polycarbonate lid to allow for solar heat gain, an insulated cabinet with three perforated trays, and a blackened aluminum absorber plate. To improve drying performance during mixed-mode operation, an additional solar air heater was added. Thermal energy storage was achieved utilizing phase change material (PCM) made of paraffin (n-docosane) combined with kerosene in a 2:1 ratio, selected for its acceptable melting point of roughly 42°C. The PCM was encased in aluminum cans and pipes put beneath the absorber plate to store surplus heat during peak solar hours and discharge it during low-insolation periods. Banana and carrot slices were used as test samples in both full-load and no-load scenarios with and without thermal storage. Performance metrics were assessed, including cabinet temperature, drying efficiency, collector efficiency, and system thermal efficiency. In comparison to traditional sun drying, the results show that the mixed-mode dryer with PCM storage maintained higher drying chamber temperatures for longer periods of time and shortened the total drying time. Latent heat storage may successfully improve sun drying efficiency for agricultural applications, as demonstrated by the incorporation of PCM, which greatly increased heat retention and stabilized temperature variations.

Keywords: Solar Dryer, Thermal Energy Storage, Phase Change Material (PCM), Mixed-Mode Drying, Agricultural Product Preservation, Natural Convection Drying

INTRODUCTION

Solar Energy

Energy from the sun is known as solar energy. One of the main energy sources in India is solar energy. In India, the amount of solar radiation exceeds the country's energy consumption by several thousand times. Every electrical and thermal application, including power production, hot water delivery, building heating, cooling, and lighting, may benefit from sunlight. The supply of solar energy is sporadic and dispersed. As a result, sunlight must be captured and/or transformed for human consumption [1-10].

Solar Energy Conversion

The sun gives to the global terrain in quite a few hours the total energy consumption of the universal population in a year. Despite its potential, the utilisation of solar energy for consumption is considerably low. Even though there are so many ways of using this renewable energy, the simplest and most accepted one is the passive heating. Solar thermal energy has a wide range of applications (Figure 1).

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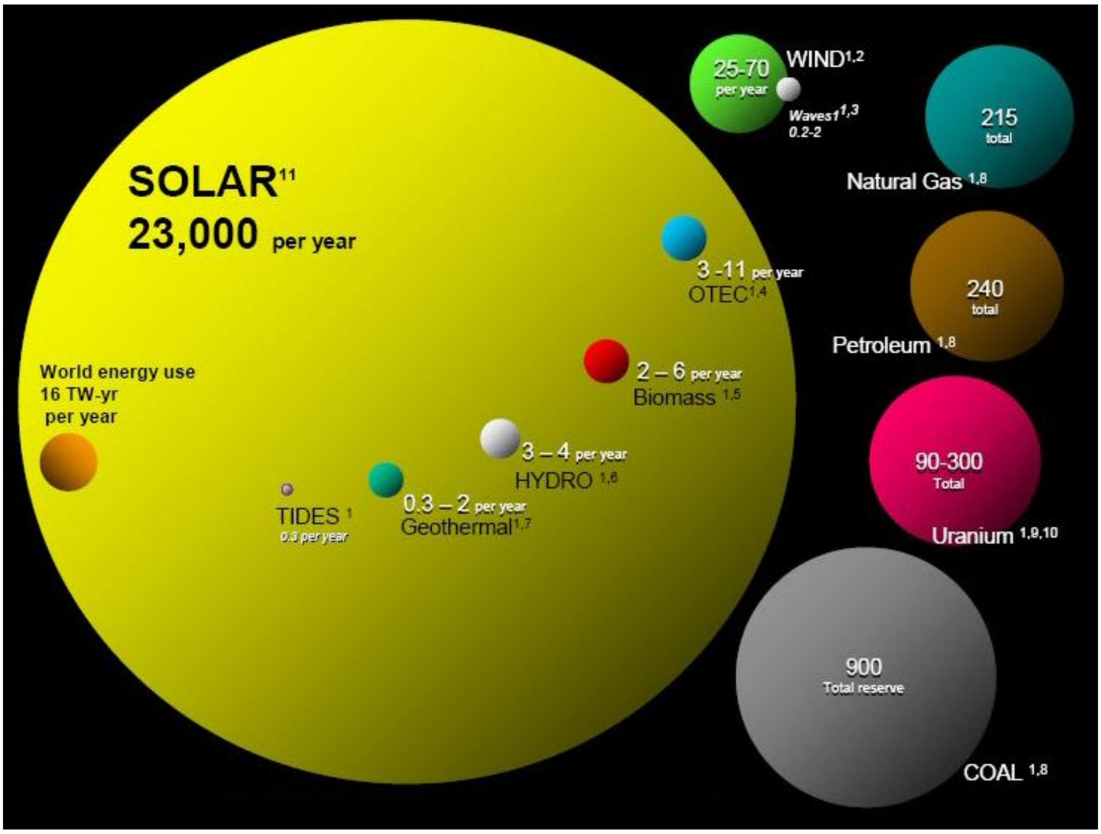

Figure 1. Solar Energy Potential
Source: *Richard Perez* and Marc Perez – A fundamental look at energy reserves for planet*

Solar Energy and Its Availability

If solar energy could be collected from only 1% of the earth's surface, the human population's power supply could be entirely supplied directly by the sun. Solar radiation available on earth's surface is much less than the radiation available outside the earth's atmosphere. Approximately half of the solar radiation outside the earth's atmosphere is lost upon entering it. The greenhouse gases and water vapour absorb and reflect a great deal of the energy radiated to the earth [11].

Solar Energy Utilization

The world's most plentiful and sustainable energy source is solar radiation. There are numerous areas where the solar energy is apparently used such as:

- Industrial process heating
- Solar thermal power plant and photovoltaic systems)
- Greenhouses
- Swimming pools
- Domestic water heating
- Space heating and cooling

Availability of Solar Energy in India

Solar Radiation in India

India has an appropriate weather for utilization of solar energy with major parts of the nation experiencing lesser rainfall per year. Having about 320 clear, sunny days annually, the theoretically arrived solar energy incidence on India's terrain is about 4950 trillion kilowatt-hours (kWh) per annum (Figures 2 and 3). The solar energy accessible in a year exceeds the plausible energy yield of all the fossil fuel reserves in India [12-15].

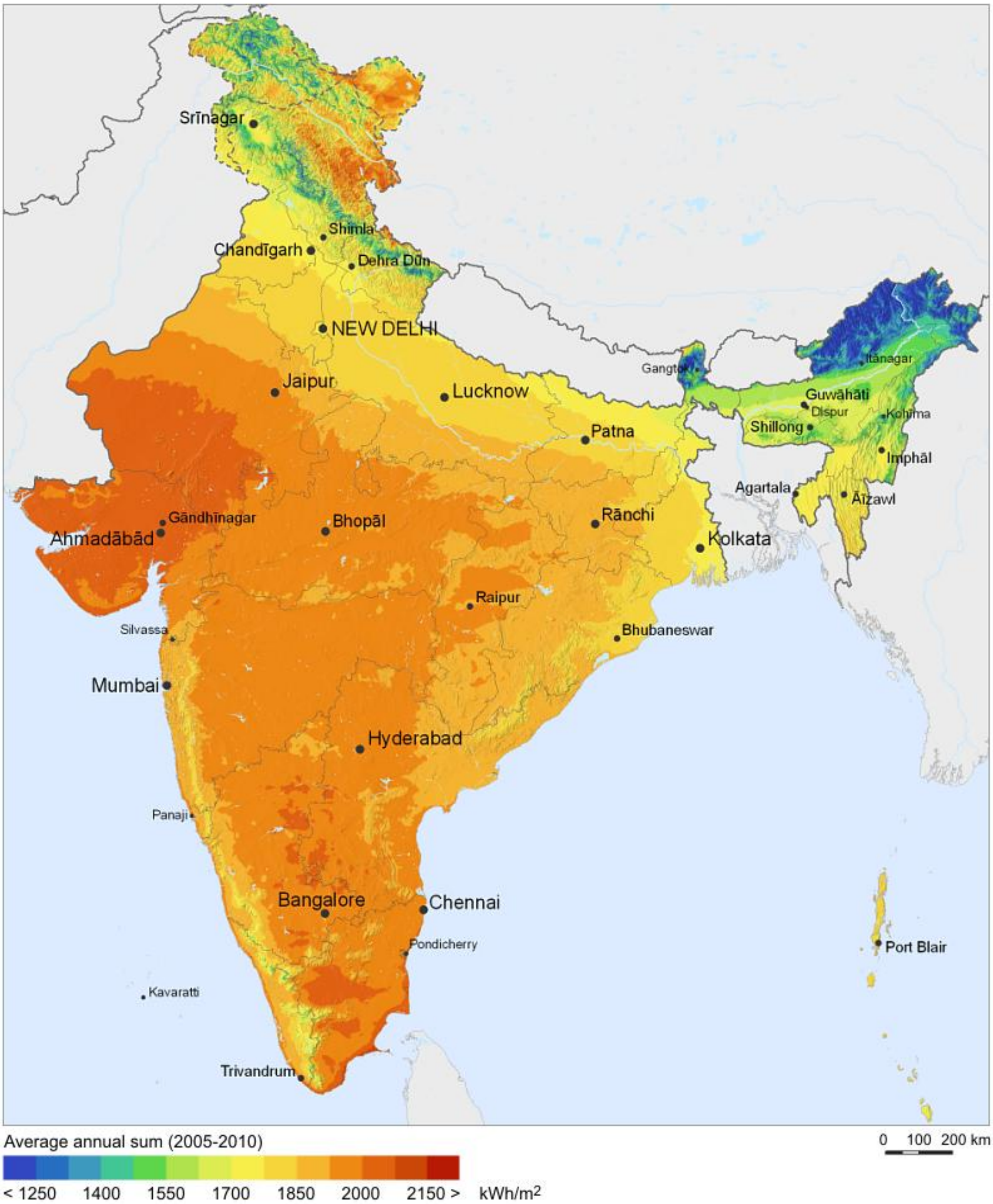

Figure 2. Solar Resource Map of India
Source: *Wiki media commons*

LITERATURE REVIEW

An effective method of using solar energy is solar drying, which may be thought of as an extension of sun drying. One of the most promising ways to lower post-harvest losses appears to be the installation of sun drying systems [15-35]. When compared to open sun-dried items, the solar-dried products are significantly better in terms of colour and texture. Solar dryers are justified by the fact that they dry goods quickly, consistently, and hygienically—qualities that are essential for industrial food drying operations. Nowadays, using solar dryers is more important since they are more efficient than sun drying and have lower running costs than mechanised dryers.

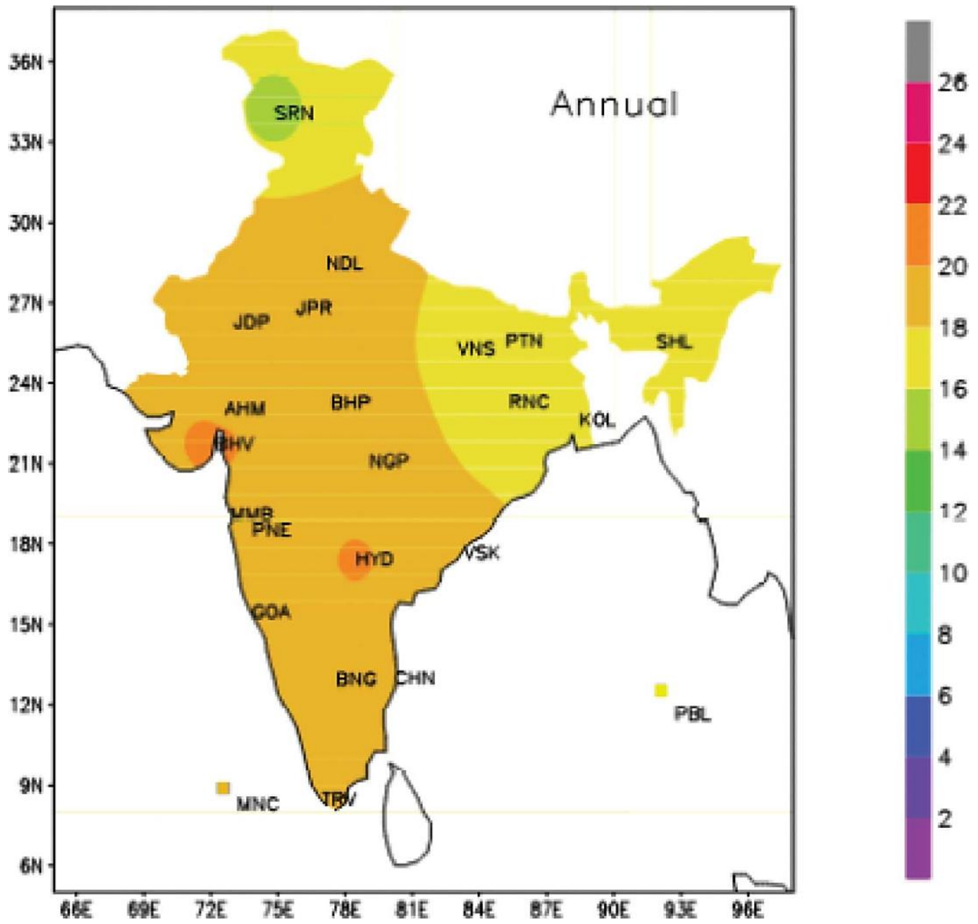

Figure 3. Global solar radiation exposure of India over an year
Source: *Solar Radiation Hand Book, Solar Energy Centre, Ministry of New and Renewable Energy, Government of India*

Ekechukwa and Norton (1998) [31] and Farkas (2004) [35]have studied various sun dryer types for drying biological materials . Air temperature, relative humidity, air velocity, and material size all have an impact on drying kinetics . Forced convection solar dryers offer better control over drying air for commercial agricultural product manufacturing, but they need more energy to operate [36-40]. Therefore, while drying food goods, especially in thin layers, natural convection sun dryers are highly recommended .

25 Fudholi *et al.* **(2010)** found that thermal storage material employed absorbs some of the heat from the solar collector. When the solar collector can no longer absorb energy from the sun, the thermal storage material releases heat back into the dryer, continuing the drying process. Thus it becomes clear that natural conversion solar dryer with latent heat thermal storage can sustain the drying cabinet temperature for a longer time [39].

Comparison Between Sun Drying and Solar Drying

According to Hii et al. (2012), sun drying, or placing crops in direct sunlight, is cost-effective, but the resultant product is of inferior quality because of contamination from rain, dust, insects, birds, and dogs [41-50]. In addition, it takes a long time to dry and has unsatisfactory colour changes and vitamin and mineral loss from direct UV exposure [49].

Solar dryers have been reported to produce higher-quality dried products while reducing drying time by approximately 20% compared to traditional open-air drying methods.

Comparative studies between solar drying and conventional sun drying indicate that solar dryers achieve higher drying temperatures, maintain lower relative humidity levels, reduce final product moisture content, and minimize spoilage during the drying process..

Solar Dryer with Natural Convection

A solar-based dryer/heater system was designed, fabricated, and experimentally evaluated for the dehydration of fruits and vegetables. Ten to fifteen kg of fruit or vegetables might be dehydrated in three to five days, according to experiments.

The design and functionality of a solar-powered drying system that consists of a drying chamber and a solar air heater were examined. They investigated the drying section's and the solar air heater's thermal efficiency. Solar-dried sultana grapes, green beans, sweet peppers, and chillies had drying durations that were 1.8, 2.2, 1.9, and 2.0 times lower than those of the natural sun-dried items (drying period: 6-10 days), according to the data.

Ekechukwu and Norton (1997) discovered that while natural-convection solar dryers are made to decrease capital and operating expenses, controlling the drying process poses a significant challenge [29]. Special control measures are thus not necessary. The ideal strategy is to use chimneys, which control how long the drying air stays in the drying chamber. They created a solar chimney for natural-convection solar dryers using this method. According to their findings, if solar chimneys are constructed correctly, they may sustain chimney air temperatures above the surrounding air temperature, which will improve the drying rate and the intended buoyancy-induced air flow through the chimney.

A solar cabinet dryer was utilized to dry thin layers of pumpkin, green pepper, stuffed pepper, green beans, and onions, and the drying performance was subsequently compared with that of the conventional natural sun-drying method. The results revealed that drying air temperature could increase up to 46°C and the drying air velocity had an impact on the drying process. They reported that the drying time was reduced (30.29-90.43 h) in solar drying as compared to open sun drying (48.59 and 121.81 h) for different vegetables.

A mathematical model for the natural convection solar drying of maize grain was introduced . According to the data, there were two drying fronts that were going in opposing directions—one at the top of the bed and the other at the bottom—because the temperatures at the top and bottom of the bed were higher than the center. A good agreement between theoretical and actual values was found when the results were validated against experimental data from a prototype natural convection maize sun drier.

A natural convection sun drier was created to dry cashew nut shells (CNS). In addition to producing a high-quality standard product, the dryer could raise the temperature of the dry air to 78°C. A flat-plate solar air heater coupled to a drying chamber is the basis of the natural convection solar dryer created by El-Sebaii et al. (2002) [32]. When compared to the open sun drying method, they found that the dried goods had higher quality. They dried tomatoes, grapes, figs, green peas, and onions.

A solar air heater with two absorber systems in a single flat-plate collector was created. A drying chamber for dehydrating food was incorporated with the heater. The solar dryer's thermal properties may be manually adjusted with flexibility thanks to its collector design. Fresh samples of mango slices were dried in order to assess the dryer's functionality. Around midday, the air heater increased the drying air's temperature from around 31.7 to 40.1oC while converting up to 21.3% of solar energy into thermal power.

Thin-layer convective sun drying of prickly pear peel was experimentally investigated to evaluate its drying characteristics and performance. During the drying process, they measured the following parameters: relative humidity (23 to 34%), drying air temperature (50 to 60oC), ambient air temperature (32 to 36oC), drying air flow rate (0.0277 to 0.0833 m3/s), and daily sun radiation (200 to

950 W/m2). They came to the conclusion that the drying air temperature was the primary element influencing the drying rate and that the experimental drying curves only displayed a declining drying rate phase. A solar tray dryer capable of operating in both direct and indirect drying modes was designed and fabricated for versatile drying applications. The maximum temperature attained was 65ºC in direct conditions and 60ºC in indirect condition. It was reported that the Lewis single-exponential model effectively describes the thin-layer drying behavior of cassava, banana, and mango slices dried using a natural convection solar dryer.

DEVELOPMENTAND DESIGN

After performing a thorough literature research of solar dryers were design requirements determined and taken into consideration for implementation. This solar dryer's overall design was regarded as a natural-convection solar dryer, as previously mentioned in the literature review.

A set of engineering simulations for natural-convection solar dryers were used to provide specific design specifications. This modified model considers a number of variables, such as the environmental circumstances and physical characteristics. These characteristics established a preliminary benchmark that the real design was expected to reach or surpass in terms of efficiency, and they were used as input for the suggested model. The mathematical computations were then used to identify specific features of the solar dryer, and schematics were created using this data.The solar dryer was then manufactured using the schematics as a guide. Low-cost building materials that could be found in underdeveloped areas were taken into consideration. Naturally, depending on material availability, other materials are anticipated to replace the existing design. The performance of the solar dryer was then assessed through experiments. The purpose of these evaluations was to gauge the dryer's effectiveness and performance. Although the literature contains a long list of solar dryers, this system was created with straightforward and reasonably priced production techniques in mind. Attempts were made to prevent this design from becoming unduly complex because trained workers and building supplies are sometimes scarce in developing nations.

Basic Design

The fundamental layout consists of a rectangular, insulated box with fibre glass covering. The whole experimental setup, including the auxillary collector and thermal storage, is shown in Figure 4. Both the upper and lower halves of the box include vents to let in fresh air and expel damp air, respectively. To absorb solar radiation, dull black paint was applied to the collection plate and the interior of the cabinet. The absorber plate warms the air as it travels through the collector and into the drying cabinet. Warm air from the collector rises through the food and exits through the top of perforated trays within the cabinet to dry the food (Figure 4).

Fabrication of The Solar Cabinet Dryer

Construction of the Frame

The horizontal beams of the frame were made using 1m long mild steel square tubes. Then the upright columns of the frame were made using mild steel square tubes of 0.5 m length. The two upright columns were placed on a level surface.

A beam between the two upright pieces was welded in place. Similarly, another beam was welded. Thus the front panel was complete. Likewise, back panel was made using 1m long beams and columns of 0.75 m. On a level surface, the rear panel was maintained vertically. Next, the 0.5-meter-long bottom side pieces—one on each side—were welded against the rear panel. These side parts were maintained in a vertical position above the front panel. Appropriate clamps were used to keep the bottom side pieces and vertical panels erect. Appropriate square tubes were used to join the tops of the front and rear panels. The top side parts were welded to meet the necessary inclination angle of 21º because the front is shorter than the back. The upper side parts were now welded utilising four clamped joints while remaining between the front and rear panels.A horizontal beam of 0.5 m length was inserted into the bottom panel, about 4" up from the front panel to make the bottom vent. Thus the dryer frame was complete.

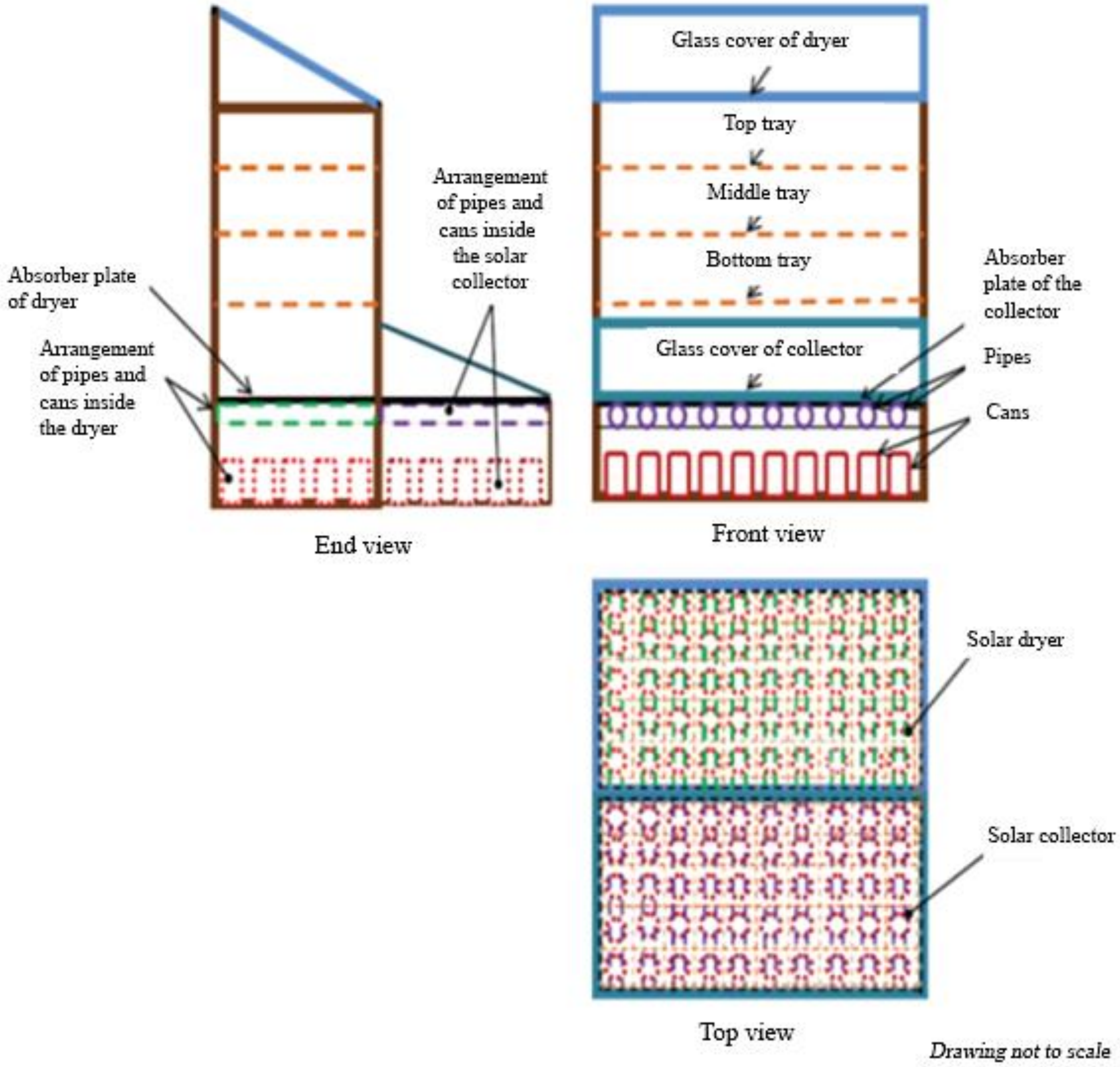

Figure 4. Illustration of the Dryer in Mixed Mode with Thermal Storage Unit

Making the Door

To verify for size, two 0.5-meter door uprights and one-meter-long beams were positioned above the front (door panel) opening. It was made sure that the door panel overlaps the frame on all sides. Now the door frame was welded together. A piece of plywood having a suitable size to cover the door frame was cut and attached using the drill and sheet metal screws. Thus the door was finished. It was attached to the frame only after everything else was completed.

Addition of Tray Supports and the Heat Absorber

Before covering the frame, the tray supports were installed. Using suitable ties the plywood boards were fixed in to the dryer frame. A piece of aluminum sheet of size 1m x 0.5 m was cut suitably and fixed to form the heat absorber as shown in Figure 5 A gap was left between the absorber and back panel to ensure smooth air movement.

Covering the Frame

To provide enough coverage of the frame, a polycarbonate sheet was appropriately cut and fastened to the exterior of the welded frame, one on top and one on the front panel. Because polycarbonate is prone to breaking under extreme force, the clamps were smoothly tightened. To fasten the polycarbonate to the metal frame, metal screws were inserted into pre-drilled holes around the

Figure 5. Absorber Plate fixed in the Drying Cabinet

Figure 6. Tray Frame

polycarbonate's perimeter. The sides were covered with cut pieces of plywood. Metal screws were used to secure the boards to the frame.Two plywood pieces of even size were used to cover the bottom with provision of thermal storage space through which the incoming air enters. A 2" gap at the top provides the exhaust vent.

Sealing the Gaps, Insulation and Painting

Silicone caulk was used to seal all of the sheet metal and polycarbonate panels' edges and joints. The inner surface of the cabinet was covered using 25 mm thermocole sheet to minimize heat loss, thus acting as a thermal insulator. The surface of the thermal collector made of aluminium sheet was painted black to ensure maximum heat absorption.

Making the Drying Trays

The tray frames as shown in Figure 6 were made keeping enough clearance for easy loading and unloading without damage to the side frames. The rectangular shapes exactness was ensured to avoid improper formation of the tray corners. A piece of aluminium mesh was folded and tightened around the edges of each frame and stapled well, pulling it tight. Two screws attached at the bottom forms the guides. Sliding the tray in and out of the dryer is made simpler by these aids.

Figure 7. Door for Loading and Unloading the Trays

Figure 8. Complete Setup of the Cabinet Dryer

Attaching the door

The door was attached using hinges and a latch as shown in Figure 7. Similar procedure was followed to construct the components of the auxiliary collector unit. Before using, the dryer was kept in the sun for a few days to allow any fumes from the paint and silicone to escape (Figure 8).

EXPERIMENTAL ANALYSIS

Dryer Optimisation

A complete factorial design was used to examine the dryer's performance. The factors of the design were: 1) two levels of product density load per tray, 2) dryer with and without auxiliary collector, and 3) dryer with and without thermal storage. The two variables for product loading per tray were high (60% of the tray covered with slices) and low (40% of the tray covered with slices). Thermal storage was done in cans and pipes having phase change material. The variables in thermal storage were thermal storage only with pipes, thermal storage only with cans, and thermal storage with both cans and pipes. Also experiments were done on the effect of adding thermal conductivity enhancers, and variation of PCM quantity. In addition, the slice thickness suitable for drying using this cabinet dryer was also investigated.

Performance Tests without Thermal Storage

No Load Test

The first performance analysis done on the experimental setup was the no load tests, in which the temperature in the dryer was observed without food materials in the dryer under direct mode as shown in Figure 9. The temperature changes at the collector, drying chamber, fiber glass cover and ambient

Figure 9. No Load Setup.

temperature values were recorded at uniform time interval. The no load tests helped to identify the maximum potential of temperature rise in the drying chamber as compared to the corresponding changes in solar intensity, ambient temperature, and air velocity variations. Parameters such as temperatures at different zones and intensity of solar radiation were recorded during these tests to determine the collector efficiency.

Experiments were conducted on consecutive days in the month of April 2025. The dryer was tested under direct mode for few days. Then an auxiliary collector was added and the same dryer was tested under mixed mode on the following days. These tests were carried out before sunset from 10:00 a.m. to 4 p.m., the time period when solar radiation intensity was considerable.

Determination of Slice Thickness

Food product preservation is a challenging procedure with several problems. Although there are many fruits and vegetables in nature, they spoil quickly. Despite the abundance of preservation techniques, the majority of them alter the product's colour and texture (Figure 10). Customers like high-quality goods with extended shelf lives. Using a sun dryer to reduce moisture is a cost-effective way to preserve perishable food items. This study examined how temperature and moisture content affect the texture and colour of dried goods. Because of its high moisture content and significant loss in India, bananas were selected for the experiment. Three banana slice thicknesses were taken into consideration for this study. This paper included detailed information about the impact of slice thickness on the quality of dried goods, an element that is rarely taken into account. After three days of drying, the proportion of acceptable slices was calculated. For the experiments, three sizes—2 mm, 4 mm, and 6 mm—were employed. At 4 mm thickness, a high proportion of satisfactory slices were.

Without overlapping, the slices were placed on the trays. Slices were weighed both before and after drying, and each tray was filled with a certain size. Slices that were sticky and shrivelled were taken out. The colour and scent of the slices were examined. The discoloured brownish bits were separated. Slices that were chewy, had a decent texture, and had a pleasant scent were separated. After the dried samples were kept at room temperature, the percentage of mouldy slices—slices that are decaying—was discovered. Slices were sliced to see whether there was extra moisture in the core, and a few pieces were squeezed out to check for moisture. As a result, elements that were too light, too dark, or too starchy were eliminated. Based on the experimental output it was clear that 4 mm thick slices were suitable for drying using this experimental dryer and so further experimentation consisting of partial load tests, full load tests without thermal storage, and full load tests with thermal storage were continued using the specified size slices.

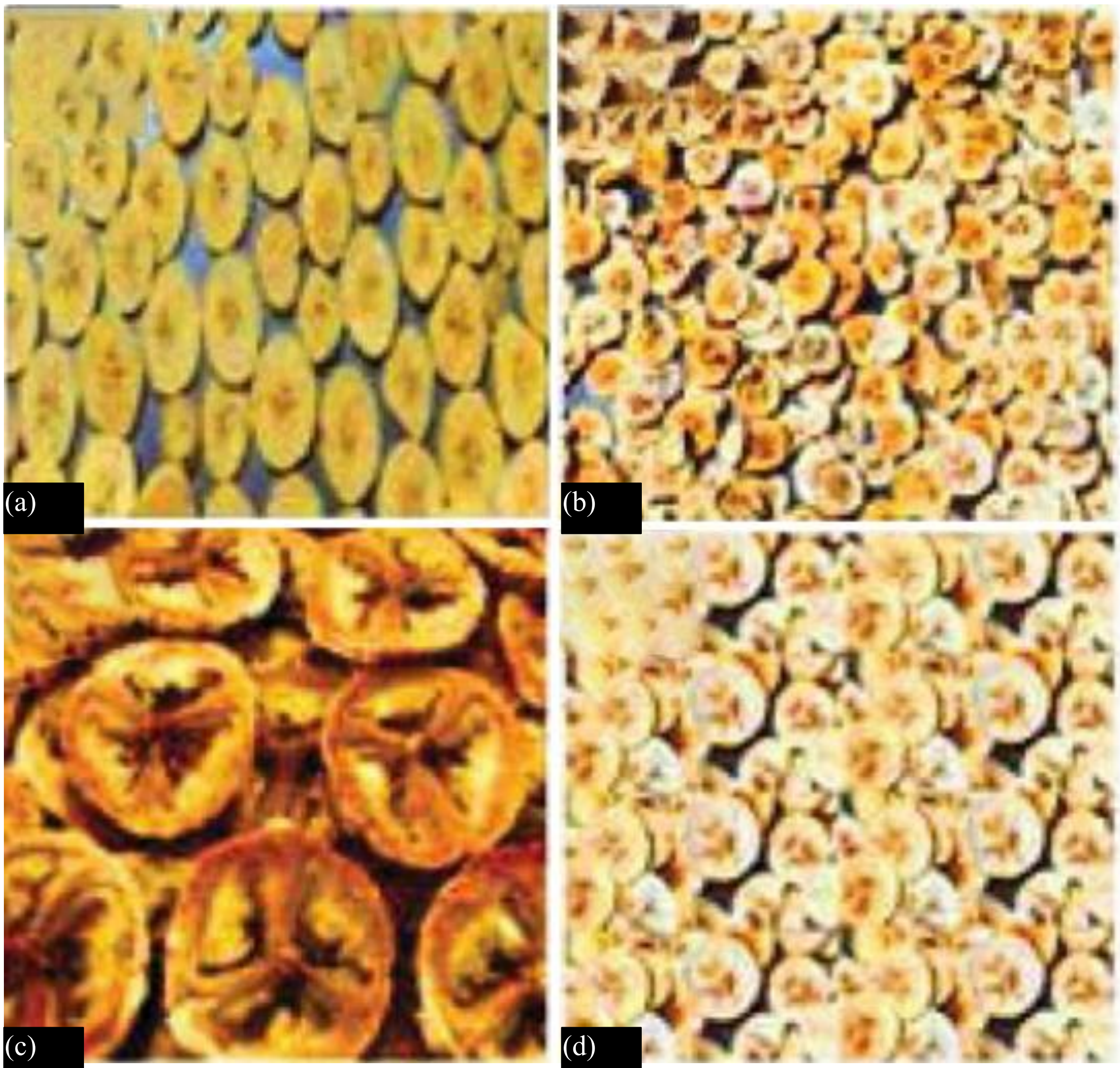

Figure 10. Colour and Textural Changes of the Slices

Load Test

The dryer performance was evaluated using banana as it contains considerable moisture. Collector efficiency, system thermal efficiency, and drying efficiency based on product load density were the performance metrics utilised for evaluation of the various experiments that were conducted. Within two days, the banana's moisture content was lowered to the acceptable level (less than 20%) for storage.

Hygiene and cleanliness were highly valued. The agro-products were fully developed. Mold-contaminated materials were eliminated. Rotten, broken, or sick ones were thrown away. Since the drying rate depends on the homogeneity of the slices, slices of nearly equal diameters and uniform thickness were employed. To prevent contamination, trays were cleaned and rinsed. To prevent pieces from adhering, loading was done right away after slicing. Without overlapping, the slices were placed on the trays. To guarantee complete drying, the trays were moved about on a regular basis. Each tray was covered with a single layer of slices. This ensured even drying and prevented overlapping (Figure 11).

Partial Load Test

During this test, the only heat source used for drying was sun radiation. At consistent intervals, the temperature of the dryer, the ambient temperature and humidity, and the collector output temperature

Figure 11. Dryer with Partial Loading of Banana Slices

were recorded. The items' original moisture content was ascertained by oven drying. Until no more weight loss was noted, drying was carried out. The moisture loss of the produce during the drying process was determined by using these beginning moisture content values and weighing the fruit at regular intervals. Drying efficiency was used to assess the dryer's performance. The various load tests that were conducted were compared using these numbers. At 40% and 60%, the product loading density on the trays was measured.

Full Load Experiments on the Dryer without Thermal Storage

The experiments were conducted for few consecutive days without PCM cans and pipes. Ambient temperature and humidity, dryer temperature and collector output temperature were recorded at uniform time interval. Observations were made until sunset to bring out the actual performance in the absence of thermal storage. Performance calculations were made based on the observations.

RESULTS AND DISCUSSION

This research endeavour on a solar cabinet dryer with thermal storage has been undertaken with the intention to improve the effectiveness of locally cultivated products. The major objective of this research work is to facilitate marginalized and underprivileged farmers with an equipment to conserve their agricultural produce thus eradicating food spoilage due to lack of amenities in the region. Therefore, the goal of the current project is to design and test a compact solar cabinet drier that has a built-in heat storage system for drying fruits and vegetables.

A complete factorial design was used to examine the dryer's performance.The factors of the design were: 1) two levels of product density load per tray, 2) dryer with and without auxiliary collector, and 3) dryer with and without thermal storage. The two variables for product loading per tray were high (60% of the tray covered with slices) and low (40% of the tray covered with slices). Thermal storage was done in cans and pipes having phase change material. The variables in thermal storage were thermal storage only with pipes, thermal storage only with cans, and thermal storage with both cans and pipes. Also experiments were done on the effect of adding thermal conductivity enhancers, and variation of PCM quantity. In addition, the slice thickness suitable for drying in this cabinet dryer was also investigated.

No Load Tests on the Solar Dryer Without Thermal Storage

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The temperature changes at the collector, drying chamber, fiber glass cover and ambient temperature values were recorded at uniform time interval.

The no load tests helped to identify the maximum potential of temperature rise in the drying chamber as compared to the corresponding changes in solar intensity, ambient temperature, and air velocity variations. Parameters such as temperatures at different zones and intensity of solar radiation were recorded during these tests to determine the collector efficiency.

Performance Analysis

Figures 12 and 13 shows the typical results of no load test under direct and mixed modes respectively. Experiments were conducted for 6 consecutive days in the month of April 2025. The dryer was tested under direct mode for 3 days. Then an auxiliary collector was added and the same dryer was tested under mixed mode on the following 3 days. These tests were carried out during peak sunshine hours from 10:00 a.m. to 4 p.m., the time period when solar radiation intensity was considerable.

The highest solar insolation recorded was 1018 W/m^2 on the 3rd day of experimentation under direct mode. Likewise the highest average solar insolation recorded was 1054 W/m^2 on the first day of

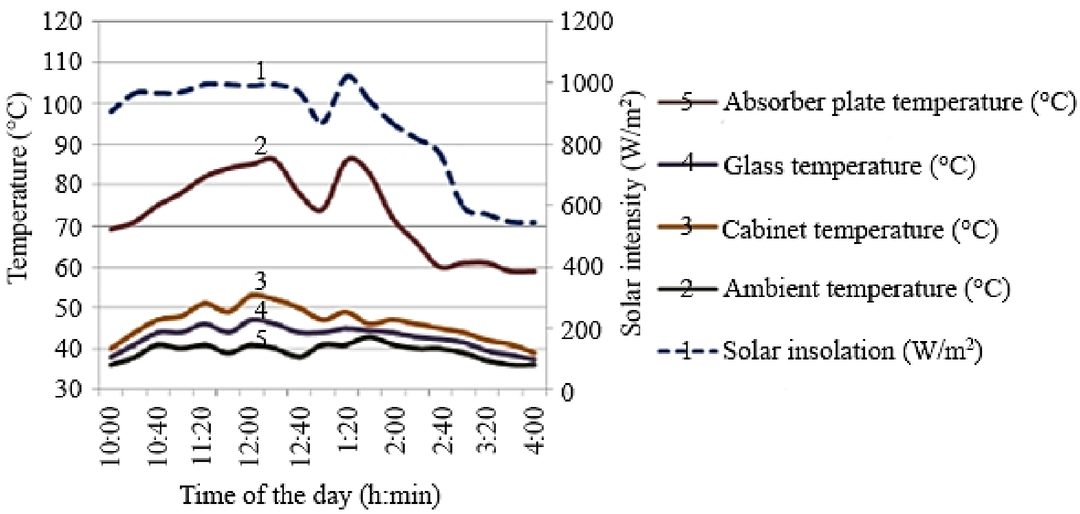

Figure 12. Typical Results under No Load without Thermal Storage – Direct Mode

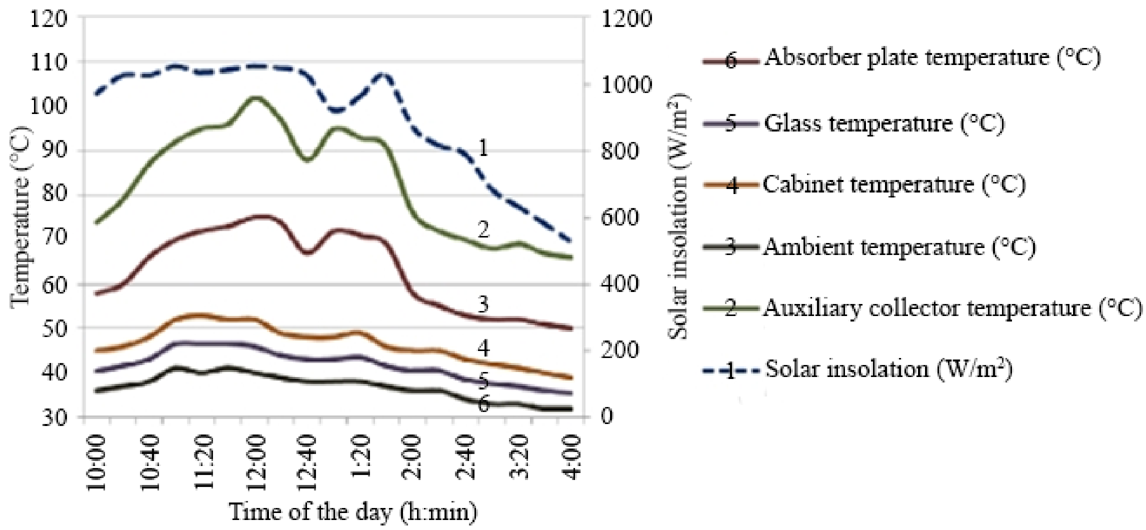

Figure 13. Typical Results under No Load without Thermal Storage– Mixed Mode

experimentation under mixed mode. The highest ambient temperature recorded was 42°C on the 2nd, 3rd & 6th days of experimentation likewise the lowest ambient temperature of 32°C was recorded on the 4th day of investigation.

CONCLUSION

The performance evaluation of a mixed-mode solar dryer for food preservation is presented in this paper. Every individual living in this area may afford the dryer that was built after consulting numerous research journals, and it can be created using materials that are readily available in the area. Due to a lack of facilities in the area, the dryer was built to prevent unplanned and undesirable food spoiling.In addition to passing hot air from a separate solar collector through the dryer, the drying cabinet also directly collects solar energy via its transparent roof. As previously said, one of the main objectives of this design was to keep the dryer's cost down. Because they were readily available or reasonably priced, the materials utilised in this design were selected. The findings from the test period showed that, for the most of the day, the temperatures within the dryer and solar collector were significantly higher than the outside temperature. For almost three hours right after midday, the drying cabinet's inside temperature rose noticeably.

- The average temperature found within the drying chamber is significantly greater than the average temperature of the atmosphere, which presents a favourable chance to build a low-cost solar cabinet drier. According to the research, the drying chamber's peak temperature of about 60°C happens in the middle of the day on a fully sunny day.
- Waste heat in the solar dryer may be recovered and reused with success using a latent heat storage (LHS) system with PCM.
- It has been shown that while the heat retained is significant during the first charging time, it eventually drops.
- The decrease in heat stored during the PCM phase shift period is less severe and nearly constant. This is a significant benefit of the LHTES system, which will be helpful for real-world applications as it allows for a consistent pace of charging and discharging for an extended amount of time.
- In a solar cabinet dryer, paraffin n-docosane may be stored thermally.
- The PCM mixes in the vicinity of the can and pipe walls harden earlier than the mixture in the can's center. This is because the PCM provides heat resistance. Heat transmission happens in the reverse direction, inward via the previously solidified section, whereas the solidification front moves toward the outer surface throughout the solidification process. As a result, wax becomes more resistant to heat. The 2:1 composite PCM mix ratio worked well for the application since it melts at a temperature that is ideal for solar dryer use in this region.
- The bottom side heat loss is decreased by the PCM cans placed at the base, which hold the heat that is transferred from the absorber to the bottom side.

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