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Article

Study on an indirect solar dryer for drying sliced bitter gourd using PCM

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Abstract: Solar dryers are of significant importance in the food industry since they facilitate the preservation of various edible products, including cereals, vegetables, and fish, by effectively extracting moisture from products. In the current study, an indirect type cabinet solar dryer had been constructed to dry the bitter gourd pieces. To enhance the efficacy of the solar dryer during late evening hours, an inorganic salt, sodium thiosulfate pentahydrate ($Na_2S_2O_3$. $5H_2O$) serving as a phase changing material (PCM), was incorporated into the collecting area of the dryer, which is rarely discussed in the literature. The study examined the process parameters, including the moisture ratio, moisture reduction rate, dryer inlet and outlet temperature, and efficacy of the drying system for the dehydration of sliced bitter gourds in two scenarios: an indirect solar dryer without phase change material (IDSD) and a solar dryer with PCM (IDSD-PCM). The experiments involved maintaining a constant mass flow rate of air at 0.07 kg/s while operating the dryer for a duration of nine hours in an experimental day. The findings obtained were evaluated, and the impact of incorporating such PCM into the indirect solar dryer was examined and reported. The findings of the study indicated that the inclusion of sodium thiosulfate pentahydrate inside the collecting area had a substantial impact on the temperature of the drying chamber, particularly during the late evening hours. Furthermore, the utilization of PCM resulted in a notable increase of 2.8% per day in the proportion of moisture extracted from sliced bitter gourds. The drying system exhibited a 3.6% higher efficacy with the aid of the sodium thiosulfate pentahydrate PCM.

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1. Introduction

Due to the explosive growth of population, the majority of emerging nations are struggling to address their food-related challenges on a global scale. The nutritional equilibrium of a nation is directly impacted by its exponential population growth. Due to insufficient storage mechanisms and substandard methodological approaches, both the quality and post-harvest volume of agricultural goods would be deteriorated [1]. Wastage of crops during harvesting must be controlled in order to preserve the dynamic equilibrium amid availability of agricultural goods and increased population. In rural regions, nevertheless, it is challenging to enhance the farming yield of farming communities. Dehydration through drying of agricultural goods has emerged as a predominant method of food preservation in regions with enough sunlight [2].

Alternative energy resources have been widely implemented for a lot of purposes in modern times. Solar energy had been proven to become the dominant sustainable power source when contrasted to other forms of sources, due to its perpetual existence [3,4]. Solar energy is being utilized in various systems, such as solar-based heaters, solar photovoltaic power plants, solar stills, and other similar applications [5,6]. Sun dryers have been a type of solar-powered equipment that greatly aids food businesses, including food packing and processing of edibles, in conserving food products by removing wetness and preventing the growth of microbes. Solar-based dryers are preferable to direct sunlight drying in several ways. Exposing food products directly to the sunlight during the dehydration process might result in irregular dehydration and additionally excessive drying. In addition, the practice of direct sunlight drying can result in the infestation of bugs and birds and, at times, cause a decline in the nutritional value of the end products as a result of exposure to windblown dust. The abovementioned concerns can be effectively resolved with the assistance of a solar-based dryer [7,8].

The sun dryer can be classified based on its constructional characteristics, namely, direct and indirect types. Furthermore, it may be categorized as inactive dryers and passive types of dryers depending on the method of air circulation [9]. In the direct drying equipment, the food products are enclosed within a glass enclosure and directly subjected to radiation. The drying process can be achieved by directly exposing the substance to sunlight using a glazed concealment. Whereas in the indirect method, the edible items have been placed on shelves in a distinct space, and heated air has been offered to the drying area by means of solar heating arrangements. In the combined method, the drying process could be slightly facilitated by direct irradiation, and the other portion could be achieved by the provision of heated air. Indirect drying units are beneficial for a wide range of agricultural items, including the spices, ginger, chilly, potatoes, seafood, and therapeutic greens [10]. If a very good-grade final result is anticipated, they are greatly desirable. The effectiveness of the drying units is contingent upon the hot air circulation rates and the air temperatures, since they directly affect the drying rates as well as moisture extraction rates. In addition, climatic factors such as humidity values (RH), ambient temperature, air speed, and others are also crucial in the drying cycle [11].

The primary drawback of solar-driven devices is the insufficient accessibility of solar radiation. Sun-powered devices may experience reduced functionality during periods of rainfall, fog cover, and insufficient sun radiation [12]. The latest studies focused on the aforesaid problems and contributed to the improvement of solar-driven equipment through the use of iron insertions, fins-integrated absorbing surfaces [13], and heat-storing substances such as phase change substances (PCMs) [14]. The PCMs are substances that can absorb a significant amount of heat energies in their latent form. They have the ability to absorb and retain solar radiation during periods of high intensity and release it whenever there is a demand for it. Natural PCMs, such as paraffin-based compounds and other forms of PCMs, such as aqueous salts, are used for storing solar radiative heat. The choice of phase change materials (PCMs) depends on the operational temperatures and operational circumstances [15].

Bhardwaj et al. [16] investigated a novel indirect solar dryer with engine oil-based sensible heat storage and paraffin-based PCM. It was reported that the proposed system reduced chilli drying time by 78.12% compared to solar drying without storage and 86% against natural sun drying. It also preserved the quality and nutritional content of the dried chillies. In another study, Bhardwaj et al. [17] examined a solar dryer with sensible storage material along with an organic PCM. They reduced drying time for Valeriana Jatamansi and doubled the drying rate compared to no thermal storage. They also enhanced energy efficiency to 26.10% and improved the quality and bioactive properties of the dried product. One more study proved that a forced convection solar drying system equipped with sensible heat storage and RT-42 as thermal energy storage significantly enhanced drying performance for Valerian rhizomes. The proposed system reduced drying time by 44% and increased energy efficacy to 26.10%. Also, it improved overall system efficiency while minimizing energy consumption to 11.33 kWh/kg of moisture [18].

Madhankumar et al. [19] concluded that a solar drying unit with paraffin as PCM has significantly reduced drying time, improved energy performance, and produced high-quality dried bitter gourd slices. Despite a 3.1% higher capital cost, it was recommended as the optimal setup for agricultural product drying in the food industry based on energy and economic analysis. Chaatouf et al. [20] showed that the deployment of a solar dryer with an organic PCM can reduce the drying time by 33% compared to open-sun drying. It can also preserve the quality and nutritional value of orange slices, including higher vitamin C retention (7.77 mg per slice). They have claimed that the solar dryer with PCM outperformed other methods in maintaining color, texture, and overall product quality.

It is observed that the paraffin-based PCMs have been mostly deployed within the dryers for drying the food products, considering their decent thermal properties, ease of capsulation, and economics [21]. Though they are displaying acceptable properties, they are inferior in terms of their low thermal conductivity and large supercooling [22]. On the other hand, inorganic PCMs, such as salt hydrates, are well-known for their broad melting temperatures, high latent heat of fusion, and excellent thermal conductivity, which make them appropriate for a number of applications, such as storage of thermal energy in solar energy systems. Compact energy storage systems are made possible by their increased density, nonflammability, and chemical stability. In contrast to organic paraffin-based PCMs, these materials transport heat effectively and endure several thermal cycles with little deterioration [23].

The comprehensive review on the existing literature reveals that there is a notable knowledge gap on the use of salt-based inorganic phase change materials (PCMs) within the solar thermal collector of an indirect operational solar-driven dryer. In order to address this gap, this study aims to evaluate the performance in terms of moisture removal rate and the efficiency of the indirect sun dryer by utilizing an inorganic salt-based (sodium thiosulfate pentahydrate) PCM while drying chopped bitter gourds. The performance of the system is analyzed after combining it with sodium thiosulfate pentahydrate as PCM, and further, the efficiency of the drying system is measured and compared to the system that is not combined with PCM.

2. Methods and Materials

2.1. Experimental set-up

The solar drying unit was constructed having two components, specifically the drier chamber and the solar collecting unit, which were then linked by a shielded duct. The entire layout was derived from the preceding research [24]. The dryer chamber had been constructed using GI sheets. The artefact had a vertically placed rectangular form with dimensions of 1600 mm in length, 450 mm in width, and 450 mm in depth. A vent had been installed at the uppermost part of the drying chamber to facilitate the discharge of hot air. A frontal doorway was installed on the drying chamber to facilitate entry to the dryer pans located within the cabinet. There were three numbers of drying pans that had been constructed using pierced metal plates to facilitate the even distribution of bitter gourd pieces for the purpose of drying. Every pan was placed into the dryer at an elevation of 450 mm to facilitate an efficient drying process. A flat-plate solar collector had been constructed using a metal sheet. The collecting surface was in rectangle form, with dimensions of 400 mm in width, 200 mm in altitude, and 750 mm long. The solar collector had been shielded with 50 mm thickness of fiberglass on all sides to eliminate thermal losses.

Further, the importance of this research lies in its execution in a geographical location (Tamil Nadu, a southern part of India), where agriculture is a primary occupation for the local population. Therefore, if the drying operation becomes effective, it would enable individuals to enhance the worth of their commodity by implementing drying techniques.

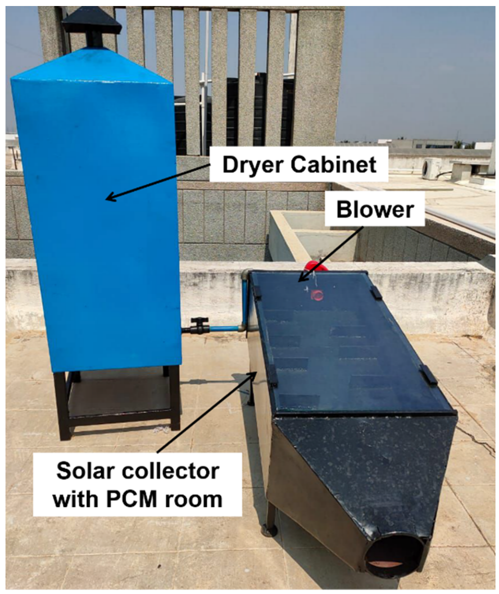

Figure 1. Photograph of dryer.

The absorbing panel consisted of a thick aluminium plate that was coated with black colored enamel to enhance its reception of solar energy. The collector had been equipped with a translucent acrylic plate at its head to allow solar irradiation to reach the absorbing surface. A blower had been used to create an air flow through the solar collector, allowing 0.07 kg/s of air to get heated. There were six chambers affixed underneath the absorbing plate, with all having the capacity to hold 2 kg of PCM. By filling inorganic salt into those spaces, the encasing process has become more effective, resulting in homogeneous heat storage. Figure 1 displays the constructed solar drying unit, comprising a dry chamber with a solar collector. The complete installation was implemented in Coimbatore, a district in Tamil Nadu, South India, where farming is a crucial aspect of the local economy and plays a central role in the lives of the inhabitants. The indirect solar dryer (IDSD) has been fabricated to run the experiments in two scenarios: one without PCM (IDSD) and another on with PCM (IDSD-PCM).

The radiation had been observed using a solar meter. Temperature measurements at several locations were conducted using thermocouples. A combination of 4 thermocouples was employed to measure the solar air collector's intake as well as output temperatures, drier chamber outlet temperatures, and ambient temperatures. These thermocouples had been linked to an electronic indicating unit for recording the measurements. A high-precision digital humidity meter was placed to monitor the ambient RH as well as the RH at the intake and outflow of the dryer chamber. A precision weigh scale had been used to determine the mass of the bitter gourd pieces.

2.2. Processing of bitter gourd pieces and PCM

Bitter gourd is well-known for its medicinal values and its health benefits. It has been majorly consumed in the regular diet of the people who are living in India, South America, East Africa, and some countries in Asia. It is rich in fiber, potassium, essential vitamins, minerals, and so on. Hence, it has several health benefits, such as reducing body cholesterol, purifying blood, cleaning the liver, improving heart functions, reducing the risk of prostate cancer, and so on. However, it can be easily affected by the microbial activities due to the higher moisture content (around 92%). The bitter gourds had been procured from the nearby supermarket. They were thoroughly cleansed using pristine water to eliminate any debris and then cut into uniformly sized slices measuring around 5 mm in depth [24, 25] as shown in Figure 2. The sliced pieces were then placed in a room for two hours to remove the surface-level moisture content.

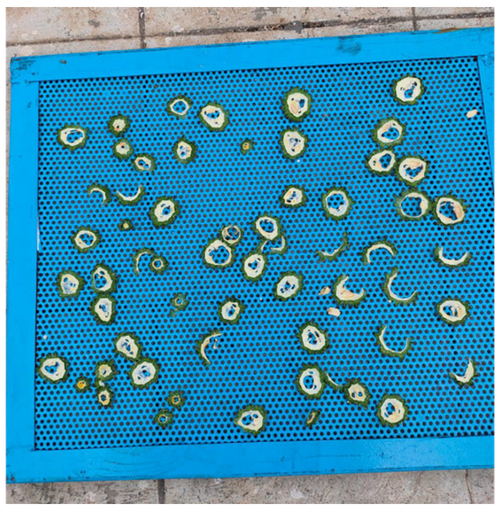

Figure 2. Photograph of sliced bitter gourds on the dryer tray.

The sodium thiosulfate pentahydrate ($Na_2S_2O_3 \cdot 5H_2O$) was acquired at a nearby industrial warehouse, possessing a melting temperature of 49 °C and a latent content of 209 kJ/kg [26]. The research utilized 12 kg of PCM, predicated as per the average radiation of the location. The PCM was meticulously preheated in an oven until they reached their melting temperature, and the molten PCM was then moved to the PCM chambers located underneath the absorbing surface and meticulously enclosed with proper encapsulation. The detailed comparison of $Na_2S_2O_3 \cdot 5H_2O$ properties with other organic PCMs used in similar studies is presented in Table 1. The superior properties of the $Na_2S_2O_3 \cdot 5H_2O$ such as melting point, latent heat value, specific heat, and density, in comparison with the application of other organic PCMs in solar dryers can be vividly comprehended from Table 1.

2.3. Thermodynamic Analysis

The key function of the IDSD is to reduce the water content of the target products to a predetermined or safe level to improve their overall quality. The effectiveness of the dryer in reducing moisture levels in the products can be assessed by determining the water content of the target products at various times during the experiment. Equation (1) can be applied to calculate the hourly moisture reduction rate (WH) of the IDSD. Where 'W_t', 'W_d', and 'W_T' are the weights of the products at the instant, after drying, and at the initial, respectively [19]. The moisture ratio (MR) shows the cumulative rate of reduction of water content in the targeted product [19], which can be assessed using 'W_t' and 'W_T' as presented in Equation (2).

Table 1. Comparison of PCM properties used in solar dryers.

Ref.	PCM used	Melting Temperature $°C$	Latent heat capacity in kJ/kg	Specific heat value in kJ/kgK	Density in kg/m^3
[27]	Paraffin wax	54.0	169	2.17	779
[28]	Lauric acid	43.0	183	–	–
[29]	Paraffin wax	49.0	173	–	790
[30]	Paraffin RT-52	52.0	166	2.10	783
[31]	Stearic acid	58.0	181	–	–
[32]	Paraffin wax	54.2	170	2.165	780
[33]	Paraffin wax RT-42	42.0	165	2.00	880
Present study	Sodium thiosulfate pentahydrate	48.5	209	2.38	1660

$$W_H = \frac{W_t - W_d}{W_T} \times 100 \tag{1}$$

$$M_R = \frac{W_t}{W_T} \tag{2}$$

The efficiency of the drying system, η_{sd}, defines how effectively the incident solar radiation is utilized in drying the targeted products. It can be calculated based on the weight of the product dried (W_d), latent heat of moisture evaporated (h), solar collector area (A_s), and instantaneous radiation (I_s), as given in Equation (3) [16].

$$\eta_{sd} = \frac{W_d\, h}{A_s\, I_s} \times 100 \tag{3}$$

3. Results and Discussion

The examinations had been conducted in March 2023 for 9 hours. The examinations were carried out on the drying unit in two scenarios: one without any phase change material (IDSD), and the other with PCM (IDSD-PCM). In each scenario, the trials had been repeated for five days to ensure consistency. Subsequently, the days with similar meteorological parameters and radiation levels were selected for further evaluation and analysis. The air circulation rate was selected at 0.07 kg/s and consistently sustained throughout the experiments, in accordance with the pressure loss estimations [24]. The data was collected at 60-minute intervals and subsequently evaluated. Figure 3 illustrates the solar intensity during the drying process in two experimental scenarios. It is evident that the sun radiation exhibits a comparable pattern over both dates of the studies. The mean solar radiation was measured as 670 W/m^2. Figure 4 illustrates the fluctuations in atmospheric temperature throughout the dry period. The temperature remained consistently above 33ºC until 17.00 hours and gradually decreased towards the evening. The average temperature had been measured as 33.5ºC on all the experimental days.

Figure 5 illustrates the temperatures at the entrance and exit of the dry chamber throughout the dry process. The hot air had been circulated over the solar collector using the blower, allowing it to be heated by close interaction with the absorbing surface. Subsequently, it had been conveyed to the drying chamber via the meticulously positioned ducts.

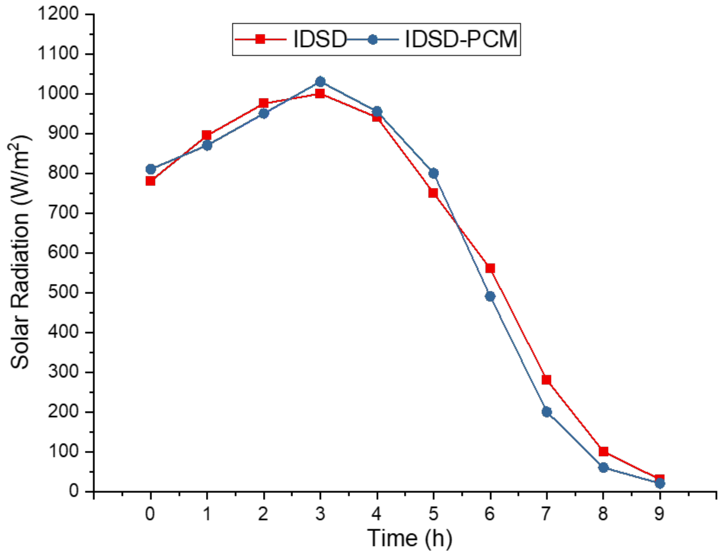

Figure 3. Solar radiation levels.

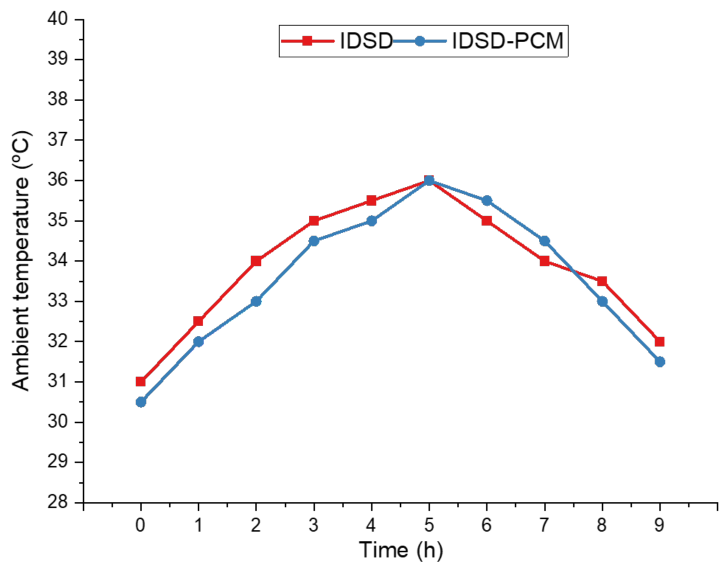

Figure 4. Atmospheric conditions.

The intake temperature remained reasonable throughout the day until 16.00 hours in both the drying conditions (with and without PCM). Nevertheless, the temperature steadily decreased until 19.00 hours. for the indirect dryer without PCM due to the lack of solar intensity. For the IDSD-PCM case, the PCM within the solar absorber is continuously heated at the midday drying process, efficiently collecting thermal energy throughout the noon hours of solar radiation. Therefore, the input temperature of the PCM-filled dryer was measured once more after 16.00 hours by releasing the PCM in the twilight, and it can be seen in Figure 5. The output temperatures of the dryer chamber were regulated to be approximately 4 ºC less than the input temperatures, as a result of the heat exchange occurring between the bitter gourd pieces and the heated air present inside the dryer chamber. The inclusion of PCM improved the operational capacity outside daylight hours and enhanced the overall solar energy absorption of the dryer.

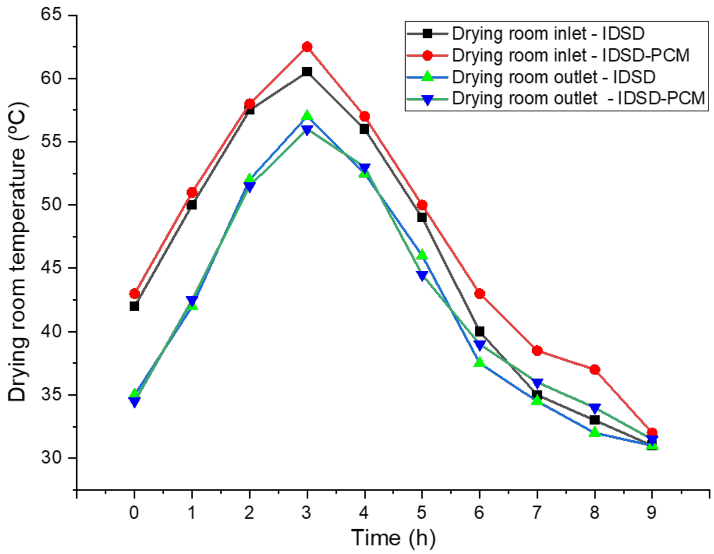

Figure 5. Dryer room air temperature.

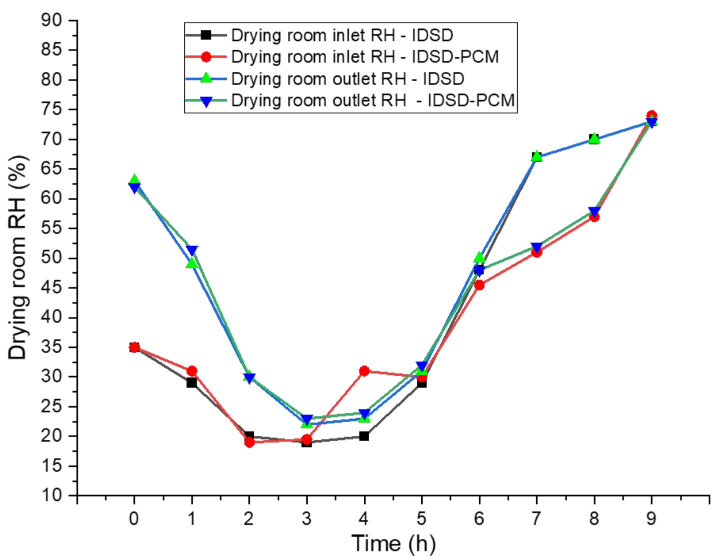

Figure 6. RH levels during drying process.

Figure 6 displays the RH value of the dry chamber at the entrance and outflow for both IDSD and IDSDS-PCM experimental scenarios. The RH of the inflow air refers to the level of humidity contained in the ambient air as it enters the dryer chamber. Similarly, the RH of the outflow air signifies the level of humidity present in the heated air that exits the dryer chamber. The relative humidity of the output air was higher than that of the entrance air owing to the water added by the chopped bitter gourd pieces. Moreover, there was a significant disparity in the relative humidity (RH) amounts between the entry as well as the exit. This discrepancy can be attributed to the substantial evaporation of the water present at the start of drying. As the humidity levels inside the bitter gourd decreased, the variations in RH values decreased for both the dryer conditions (with and without PCM). However, the process of removing moisture was almost nonexistent beyond, which was due to the minimal change in humidity levels between the air entering and leaving the air. In contrast, the PCM Dryer significantly assisted to moisture extraction beyond 16.00 hours by sustaining a high rate of water extraction. This can be attributed to the difference in relative humidity between the intake and exit of the heated air.

Figure 7 illustrates the moisture ratio of bitter gourd pieces throughout the course of the dry process. The water extraction rates were accelerated during the first half of the day for both dryer scenarios due to the high amount of moisture levels on the surface of the bitter gourd pieces. However, the rate of extraction was impeded when the proportion was decreased substantially, as the evaporation of water content from the surface of the slices was achieved completely within the first half of the day. It was observed that the moisture extraction was minimal following 16.00 hours for the IDSD unit and resulted in a final moisture level of 7.6% at the completion of the evening. However, the IDSD-PCM unit demonstrated remarkable performance after 16.00 hours as a result of the accumulated heat from the PCM. It effectively decreased the moisture content of the bitter gourd pieces further to 4.8%, which was 2.8% greater than that achieved by the simple IDSD.

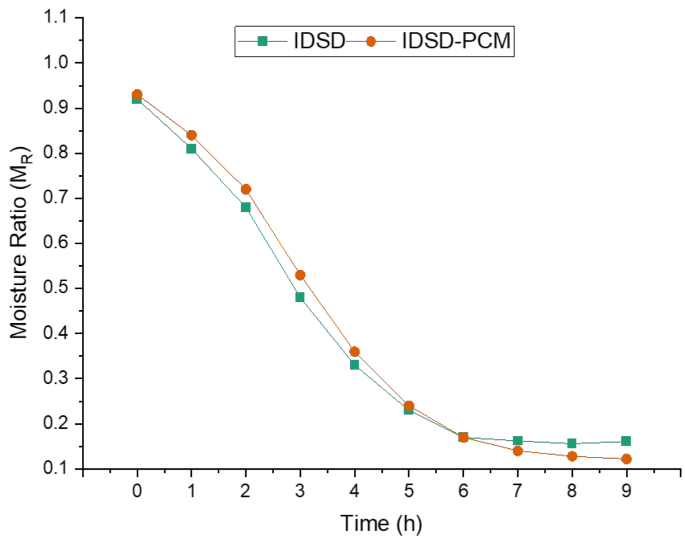

Figure 7. Moisture Ratio during process.

The function of the drying system can be more clearly comprehended with the aid of Figure 8. It demonstrates the moisture reduction rate of the drying system in an hour-wise picture. The reduction rate was substantially high at the beginning of the process due to high surface moisture along with the increase in solar intensity. However, the rate of removal suppressed subsequently after the noon hours owing to the decrease in solar insolation and reduced surface moisture level. It can be visibly seen that the removal of moisture in IDSD is slightly high at the morning hours compared to the IDSD-PCM. It can be accredited that a part of energy from the sun was absorbed by the PCM during the initial time period of operation, and by the way, the PCM would get charged simultaneously, and it resulted in a reduced rate of moisture removal in the IDSD-PCM system [11]. During the noon, the removal of the moisture from both IDSD and IDSD-PCM seems to be similar owing to the saturated charging position of the PCM in IDSD-PCM. However, the rate of removal was substantially high in the IDSD-PCM system compared to IDSD after the noon hours, and the operation of IDSD-PCM was substantially improved in the early evening owing to the discharge of PCM [11]. The outcome suggests that including sodium thiosulfate pentahydrate into the indirect solar dryer will improve its efficiency by effectively harnessing more energy throughout daylight hours and allowing the dryer to operate beyond sunset. Table 2 demonstrates the comparative performance of the IDSD-PCM with the reported literature. The comparison illustrates the moisture ratio of the studied IDSD-PCM for the similar IDSDs with similar products [24, 34] as well as other varieties of agriculture products. In any way, the present study proved to be superior in terms of its acclaimed moisture ratio and capability in water content removal from the products compared to similar dryers presented in the literature. It can be recognized that the proposed IDSD-PCM system can also be effectively utilized for other agricultural products and medicinal herbs to achieve dried products with high quality through the application of green energy.

Table 2. Comparison of solar dryer performance with other studies.

Ref.	Product used in dryer	Moisture at the beginning (%)	Moisture at the end (%)
[17]	Valeriana	89	9
[24]	Bitter gourd	92	9
[34]	Bitter gourd	92	6.3
[35]	Mango	77	20
[36]	Watermelon	91.5	7.78
[36]	Apple	86	12.03
[37]	Grapes	80	18
Present study (With PCM)	Bitter gourd	92	4.8

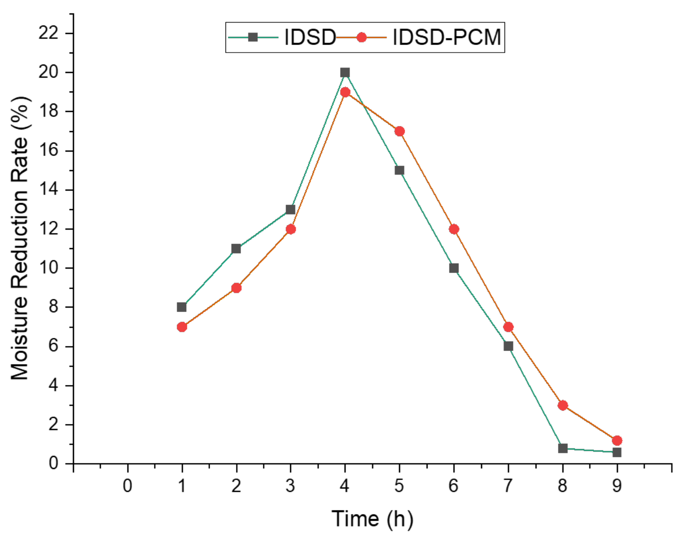

Figure 8. Moisture Reduction Rate during process.

The system efficiency of the drying unit at two scenarios IDSD and IDSD-PCM is illustrated in Figure 9. It shows the capability of the system to utilize the absorbed solar thermal radiation in drying the bitter gourd pieces with the minimum possible losses. The recorded daily efficacies are 20.8% and 24.4%, respectively, for IDSD and IDSD-PCM systems. It is observed that IDSD-PCM has publicized 3.6% higher efficacy than IDSD (without PCM), which is significantly higher for such an IDSD system. The PCM within the IDSD-PCM has been supported to back additional energy during the peak solar hours through their latent storage, and the same has been liberated out during the late evening hours for further enhancement of the solar dryer operation. It is clearly understood from the obtained results that sodium thiosulfate pentahydrate has been a good choice for improving the performance of the drying unit. It helps the farmers to improve the value of their products and reduce waste without compromising their quality. These experimental results would be a supportive document for the policymakers in making decisions to make use of the solar thermal energy in an efficient manner for enhancing the livelihood of the farmers and reducing food waste.

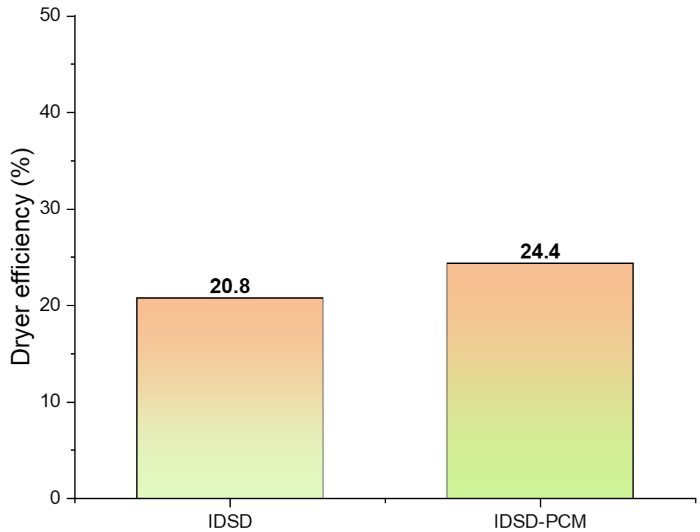

Figure 9. Daily efficiency of drying system.

4. Conclusions

An indirect-type solar-driven drying unit was constructed specifically for the purpose of dehydrating bitter gourd pieces. The salt-based phase change material (PCM) made out of sodium thiosulfate pentahydrate had been included within the solar collecting surface of the drying unit. The trials had been conducted for a duration of nine hours as a part of the inquiry. Two scenarios were considered: a drying unit without phase change material (IDSD) and a drying unit with PCM (IDSD-PCM). The incorporation of sodium thiosulfate pentahydrate PCM into the solar collecting surface resulted in a considerable increase in the input temperatures of the drying chamber for an additional one more hour following the duration of daylight.

The water level of bitter gourd pieces was reduced from 92% to 7.6% with IDSD. Whereas, the incorporation of sodium thiosulfate pentahydrate further reduced the moisture content to 4.8% owing to the extended operation of the drying unit with the aid of the PCM. In addition, the drying system efficiency has been augmented from 20.8% to 24.4% through the enhanced storage of the system with PCM.

However, the system needs to be tested at different climatic conditions to assess its suitability for a year-round operation. In the future, investigations on exergy and enviro-economic studies of the IDSD-PCM system may be performed to value its reliability for prolonged operation.

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References

[1] Azwin Kamarulzaman, M. Hasanuzzaman, and N.A. Rahim. Global advancement of solar drying technologies and its future prospects: A review. *Solar Energy*, 221:559–582, June 2021.

[2] Hany S. EL-Mesery, Ahmed I. EL-Seesy, Zicheng Hu, and Yang Li. Recent developments in solar drying technology of food and agricultural products: A review. *Renewable and Sustainable Energy Reviews*, 157:112070, April 2022.

[3] P. Manoj Kumar, K. Mylsamy, Karthick Alagar, and K. Sudhakar. Investigations on an evacuated tube solar water heater using hybrid-nano based organic phase change material. *International Journal of Green Energy*, 17(13):872–883, August 2020.

[4] Sashank Thapa, Raj Kumar, and Daeho Lee. Energetic and exergetic analysis of jet impingement solar thermal collector featuring discrete multi-arc shaped ribs absorber surface. *Energy*, 306:132392, October 2024.

[5] K. Ravi Kumar, N.V.V. Krishna Chaitanya, and Natarajan Sendhil Kumar. Solar thermal energy technologies and its applications for process heating and power generation – a review. *Journal of Cleaner Production*, 282:125296, February 2021.

[6] Saurabh P. Tembhare, Divya P. Barai, and Bharat A. Bhanvase. Performance evaluation of nanofluids in solar thermal and solar photovoltaic systems: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 153:111738, January 2022.

[7] G. Srinivasan and P. Muthukumar. A review on solar greenhouse dryer: Design, thermal modelling, energy, economic and environmental aspects. *Solar Energy*, 229:3–21, November 2021.

[8] Patchimaporn Udomkun, Sebastian Romuli, Steffen Schock, Busarakorn Mahayothee, Murat Sartas, Tesfamicheal Wossen, Emmanuel Njukwe, Bernard Vanlauwe, and Joachim Müller. Review of solar dryers for agricultural products in asia and africa: An innovation landscape approach. *Journal of Environmental Management*, 268:110730, August 2020.

[9] Anand Chavan, Vivek Vitankar, Arun Mujumdar, and Bhaskar Thorat. Natural convection and direct type (ncdt) solar dryers: a review. *Drying Technology*, 39(13):1969–1990, April 2020.

[10] Vishnuvardhan Reddy Mugi, Pritam Das, Ramakrishna Balijepalli, and Chandramohan VP. A review of natural energy storage materials used in solar dryers for food drying applications. *Journal of Energy Storage*, 49:104198, May 2022.

[11] N. Vigneshkumar, M. Venkatasudhahar, P. Manoj Kumar, A. Ramesh, Ram Subbiah, P. Michael Joseph Stalin, V. Suresh, M. Naresh Kumar, S. Monith, R. Manoj kumar, and M. Kriuthikeswaran. Investigation on indirect solar dryer for drying sliced potatoes using phase change materials (pcm). *Materials Today: Proceedings*, 47:5233–5238, 2021.

[12] P. Manoj Kumar and K. Mylsamy. A comprehensive study on thermal storage characteristics of nano-ceo2 embedded phase change material and its influence on the performance of evacuated tube solar water heater. *Renewable Energy*, 162:662–676, December 2020.

[13] Subhash Chand, Prabha Chand, and Harish Kumar Ghritlahre. Thermal performance enhancement of solar air heater using louvered fins collector. *Solar Energy*, 239:10–24, June 2022.

[14] P. Manoj Kumar, K. Mylsamy, and P.T. Saravanakumar. Experimental investigations on thermal properties of nano-sio2/paraffin phase change material (pcm) for solar thermal energy storage applications. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 42(19):2420–2433, April 2019.

[15] Mohammad Alhuyi Nazari, Akbar Maleki, Mamdouh El Haj Assad, Marc A. Rosen, Arman Haghighi, Hassan Sharabaty, and Lingen Chen. A review of nanomaterial incorporated phase change materials for solar thermal energy storage. *Solar Energy*, 228:725–743, November 2021.

[16] A.K. Bhardwaj, Raj Kumar, Ranchan Chauhan, and Sushil Kumar. Experimental investigation and performance evaluation of a novel solar dryer integrated with a combination of shs and pcm for drying chilli in the himalayan region. *Thermal Science and Engineering Progress*, 20:100713, December 2020.

[17] A.K. Bhardwaj, Raj Kumar, and Ranchan Chauhan. Experimental investigation of the performance of a novel solar dryer for drying medicinal plants in western himalayan region. *Solar Energy*, 177:395–407, January 2019.

[18] A.K. Bhardwaj, Raj Kumar, Sushil Kumar, Bhasker Goel, and Ranchan Chauhan. Energy and exergy analyses of drying medicinal herb in a novel forced convection solar dryer integrated with shsm and pcm. *Sustainable Energy Technologies and Assessments*, 45:101119, June 2021.

[19] S. Madhankumar, Karthickeyan Viswanathan, Wei Wu, and Muhammad Ikhsan Taipabu. Analysis of indirect solar dryer with pcm energy storage material: Energy, economic, drying and optimization. *Solar Energy*, 249:667–683, January 2023.

[20] Dounia Chaatouf, Benyounes Raillani, Mourad Salhi, Samir Amraqui, and Ahmed Mezrhab. Experimental and numerical study of a natural convection indirect solar dryer with pcm tubes: Dynamic, thermal and nutritional quality analysis. *Solar Energy*, 264:111975, November 2023.

[21] Mohammad Saleh Barghi Jahromi, Vali Kalantar, Hadi Samimi Akhijahani, and Hadi Kargarsharifabad. Recent progress on solar cabinet dryers for agricultural products equipped with energy storage using phase change materials. *Journal of Energy Storage*, 51:104434, July 2022.

[22] Abuelnuor A.A. Abueluor, Majdi T. Amin, Mohamed Ali Abuelnour, and Obai Younis. A comprehensive review of solar dryers incorporated with phase change materials for enhanced drying efficiency. *Journal of Energy Storage*, 72:108425, November 2023.

[23] V.V. Tyagi, K. Chopra, R.K. Sharma, A.K. Pandey, S.K. Tyagi, Muhammad Shakeel Ahmad, Ahmet Sarı, and Richa Kothari. A comprehensive review on phase change materials for heat storage applications: Development, characterization, thermal and chemical stability. *Solar Energy Materials and Solar Cells*, 234:111392, January 2022.

[24] S. Vijayan, T.V. Arjunan, and Anil Kumar. Mathematical modeling and performance analysis of thin layer drying of bitter gourd in sensible storage based indirect solar dryer. *Innovative Food Science amp; Emerging Technologies*, 36:59–67, August 2016.

[25] S. Vijayan, T.V. Arjunan, and Anil Kumar. Exergo-environmental analysis of an indirect forced convection solar dryer for drying bitter gourd slices. *Renewable Energy*, 146:2210–2223, February 2020.

[26] Maria Telkes. Thermal energy storage in salt hydrates. *Solar Energy Materials*, 2(4):381–393, July 1980.

[27] Zakaria Alimohammadi, Hadi Samimi Akhijahani, and Payman Salami. Thermal analysis of a solar dryer equipped with ptsc and pcm using experimental and numerical methods. *Solar Energy*, 201:157–177, May 2020.

[28] A.K. Srivastava, S.K. Shukla, and Sandeep Mishra. Evaluation of solar dryer/air heater performance and the accuracy of the result. *Energy Procedia*, 57:2360–2369, 2014.

[29] S.M. Shalaby and M.A. Bek. Experimental investigation of a novel indirect solar dryer implementing pcm as energy storage medium. *Energy Conversion and Management*, 83:1–8, July 2014.

[30] Masoud Iranmanesh, Hadi Samimi Akhijahani, and Mohammad Saleh Barghi Jahromi. Cfd modeling and evaluation the performance of a solar cabinet dryer equipped with evacuated tube solar collector and thermal storage system. *Renewable Energy*, 145:1192–1213, January 2020.

[31] Anand Jain, Anil Kumar, A. Shukla, and Atul Sharma. *Development of Phase Change Materials (PCMs) for Solar Drying Systems*, page 619–633. Springer Singapore, 2017.

[32] Hana Ebrahimi, Hadi Samimi Akhijahani, and Payman Salami. Improving the thermal efficiency of a solar dryer using phase change materials at different position in the collector. *Solar Energy*, 220:535–551, May 2021.

[33] A.K. Bhardwaj, Ranchan Chauhan, Raj Kumar, Muneesh Sethi, and Adit Rana. Experimental investigation of an indirect solar dryer integrated with phase change material for drying valeriana jatamansi (medicinal herb). *Case Studies in Thermal Engineering*, 10:302–314, September 2017.

[34] AR. Umayal Sundari, P. Neelamegam, and C. V. Subramanian. An experimental study and analysis on solar drying of bitter gourd using an evacuated tube air collector in thanjavur, tamil nadu, india. *Conference Papers in Energy*, 2013:1–4, May 2013.

[35] Wei Wang, Ming Li, Reda Hassanien Emam Hassanien, Yunfeng Wang, and Luwei Yang. Thermal performance of indirect forced convection solar dryer and kinetics analysis of mango. *Applied Thermal Engineering*, 134:310–321, April 2018.

[36] Abhay Lingayat, V.P. Chandramohan, V.R.K. Raju, and Anil Kumar. Development of indirect type solar dryer and experiments for estimation of drying parameters of apple and watermelon. *Thermal Science and Engineering Progress*, 16:100477, May 2020.

[37] Khalil E.J. Al-Juamily, Abdul Jabbar N. Khalifa, and Tadahmun A. Yassen. Testing of the performance of a fruit and vegetable solar drying system in iraq. *Desalination*, 209(1–3):163–170, April 2007.