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Recent Trends in PCM-Integrated Solar Dryers †

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Abstract: Solar dryers utilize solar thermal energy to dry products by removing the moisture in the product, and the extend the shelf life of the product. Phase change materials (PCMs) are widely used as a storage medium as they offer the benefits of isothermal characteristics and allow for use during non-sunshine hours. Various researchers have indicated the benefits of PCMs in increasing the flexibility of the operation, efficiency, and quality of the dried product. The present paper reviews the recent trends, factors, and performance of PCM-integrated solar dryers. Issues involved in drier operation and recommendations for energy-efficient and cost-effective drying are also discussed.

Keywords: solar drier; phase change material; thermal storage devices

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1. Introduction

Solar dryers are used to dry food products using solar energy. The objective of drying an agricultural product is to reduce its moisture content to an optimum level and prevent the deterioration of the food crops. Drying takes place as a result of the transfer of both heat and mass [1]. Drying a food product under the sun directly leads to many problems like the contamination of food products due to dust, dirt, insects, rain, blowing winds, or infestation; income loss for farmers; a deterioration of the quality of food due to excessive heating. Solar dryers possess so many advantages; for example, they increase the rate of drying and protect crops from dust, insects, and rain. Food product quality is also much better; the food product is more hygienic and nutritious, while transportation is also easy for dried food products [2]. Some major drawbacks of using a solar dryer are that it can only be used during the daytime, so the drying of food crops during nighttime is very difficult and the initial setup cost may be high. This problem can be overcome by using solar dryers integrated with thermal storage devices. Thermal storage devices (TESs) are used to store heat. Thermal energy can be stored in a solar dryer most effectively when a PCM is used as a storage medium.

A phase change material can be used as a storage medium in solar dryers. These materials absorb, store, and release heat energy during a phase transition either from solid to liquid or liquid to solid at a constant temperature. When the PCM is heated, it melts by absorbing the heat energy and it solidifies at specified temperature by releasing the stored heat energy. An LHS system with a PCM as a storage medium possesses a medium level of storage capacity. Agricultural produce dried at a constant temperature produces high-quality products. Therefore, integrating a PCM with a solar dryer and drying the food product gives high-quality products. Using a PCM allows latent heat storage that stores 5–10 times additional heat in contrast to that stored with the use of a sensible heat storage medium.

The present paper addresses the lack of comprehensive analysis of the recent trends, factors, and performance of PCM-integrated solar dryers. Issues involved in drier operation and recommendations for energy-efficient and cost- effective drying are also discussed.

2. Classification of PCM

2.1. Based on Phase Change

Phase change materials can be grouped into three categories based on phase transition. These are solid–solid PCMs, solid–liquid PCMs and liquid–gas PCMs. The most widely used phase change is solid–liquid [3]. PCMs are classified into three groups based on temperature range: low-temperature PCMs (lower than 15 °C), medium-temperature PCMs (within 15–90 °C), and high-temperature PCMs (above 90 °C).

2.2. Based on Material Composition

There are organic PCMs, inorganic PCMs and eutectics of organic and inorganic compounds, as shown in Figure 1.

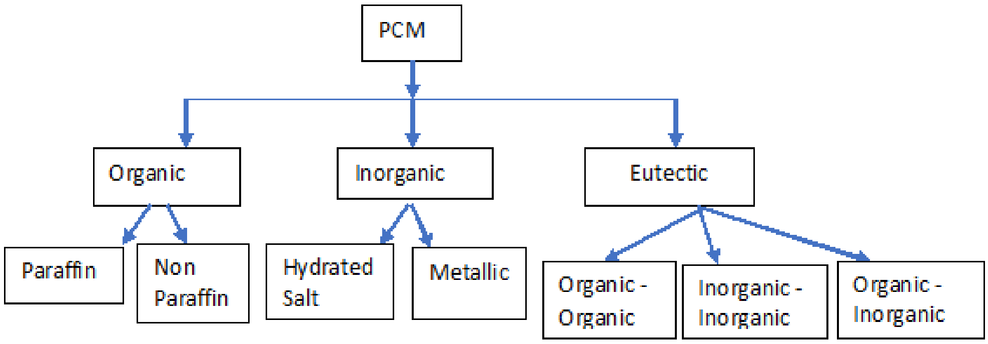

Figure 1. Classification of phase change materials.

Organics: Some organic PCMs are paraffin, fatty acids, esters, etc. Organic PCMs are further subclassified into paraffin and non-paraffin materials. Paraffin wax is the most widely used PCM. These PCMs release a large amount of latent heat. One major disadvantage of paraffin wax is its low thermal conductivity [4]. Non-paraffin wax is huge in amount and has varied properties, for example fatty acids [5]. However, it is not widely used since it costs more than paraffin wax and it is flammable.

Inorganic: There are two types of inorganic PCMs: salt hydrate and metallic alloys. Salt hydrates are crystalline solids formed via the mixture of inorganic water and salt [6]. Metallic alloys are not widely used in PCM technology. They are generally used at high temperatures, when the right type of paraffin wax is not accessible.

Eutectics: Eutectics are a mix of only organic PCMs, only inorganic PCMs or a mixture of organic and inorganic PCM. They are also dormant PCMs that have a high latent thermal storage capability that is higher than that of organic PCMs [7].

3. Advancements in PCMs

Recently, bio-based PCMs that are made up of renewable materials like carbohydrates and proteins are attracting increased attention. In terms of microencapsulated PCMs, as shown in Figure 2, PCMs are encapsulated into small particles within a protective shell or a coating that prevents leakage, enhances the thermal conductivity of the material, and improves its performance [7]., e.g., polymer-encapsulated PCM, in which polymers are used to encapsulate the PCM. Hybrid PCMs are a combination of two or more materials, enhancing their thermal properties. Nanotechnology-based research is being carried out, in which nanoparticles are incorporated into the PCM to increase the thermal properties of PCMs and their stability. Solar collector efficiency can be improved by using nanofluids as PCMs [8]. Graphene-enhanced PCM is an advanced technology in which graphene is used to increase the thermal conductivity and stability of the material [9]. Mehling et al. [10] have discussed the application of PCMs in commercial products including solar dryer.

The choice of several types of PCMs for various applications relies on their physical, chemical and thermal properties and economic characteristics. [11]. Desirable PCM properties are given in Table 1.

Table 1. Desirable characteristics of PCMs [12].

Thermal Properties	Physical Properties	Kinetic Properties	Chemical Properties	Economics Properties
High-level heat transfer rate	Good phase equilibrium	Supercooling should not take place	Chemically stable	Widely available
Greater latent heat of transition	Volume change is small	Sufficient crystallization rate	Non-toxic in nature	Cost-effective
Appropriate phase transition temperature	Vapor pressure is low		Good compatibility with materials	Abundant
			No fire hazard	

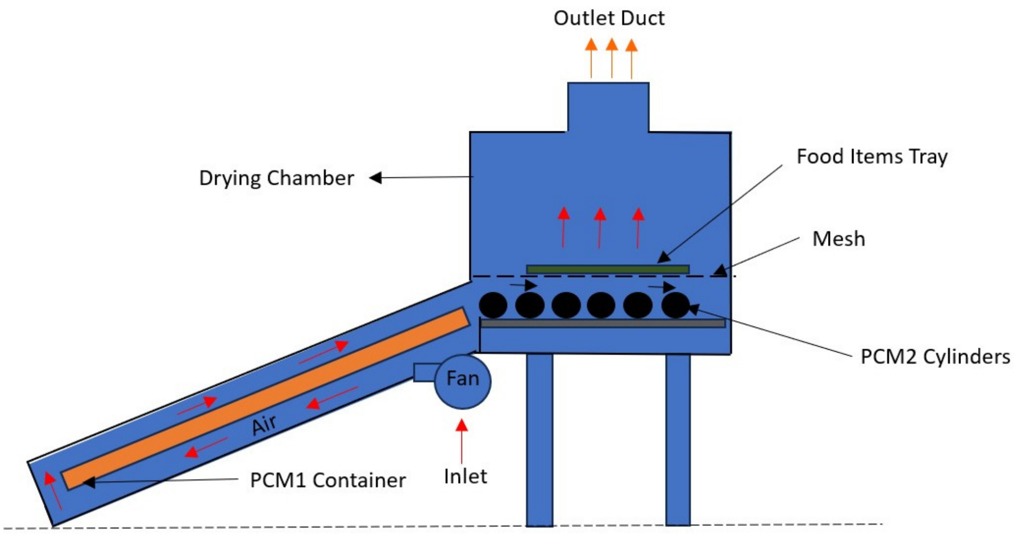

Figure 2. Air double-pass indirect-type solar dryer with two types of PCMs [13].

4. PCMs for Solar Dryer Designs

A solar dryer generally has following parts: a solar collector, a drying chamber, trays, a blower, a temperature and humidity sensor, and a glazing sheet.

An air double-pass indirect-type solar dryer is shown in Figure 2. Ahmed J. Hamad et al. [13] conducted an experiment using two PCMs (PCM1: paraffin wax; PCM2: paraffin RT-42) with different melting points placed on the bottom part of collector and drying chamber. The product used was chili. The drying test was conducted in three cases, one without a PCM using a natural convection process, one without a PCM using forced convection and another with a PCM using forced convection. High performance, a fast drying rate and high drying efficiency are found with PCMs using forced convection. Using multiple PCMs, it was found that the thermal efficiency of the solar collector and the thermal efficiency of the drying chamber were much higher.

Silpa Mandal and Sharma [14] demonstrated an experiment conducted on a hybrid solar dryer containing mint and coriander. Paraffin wax was used as a PCM in this experiment, and 20 kg of PCM was placed inside the collector. It was observed that an increase in bed depth had an effect on drying rate. Even during non-sunshine hours, the products were dried at a continuous and uniform rate. The phenolic content in the mint was retained more in the PCM-integrated dryer compared to that in the dryer without a PCM, providing better-quality products.

Shahin Shoeibi et al. [15] conducted experiments by drying seeded grapes using a PCM-integrated solar dryer. It consisted of the following parts: a solar air collector with an expanded surface, which allowed greater heat transfer and a high turbulence effect, a solar air collector with a PCM integrated to make the drying process work even at nighttime, and a drying chamber with a swirl element in it. The solar dryer dried the products much faster with a lower moisture content in the product.

Pragnan Lad and Rahul Kumar [16] studied the impact on drying temperature of placing a PCM in different configurations, as shown in Figure 3. Three case studies were carried out on a traditional indirect dryer, an altered solar dryer with a PCM inside the collector, and an altered solar dryer with a PCM placed inside the drying chamber. It was found that thermal properties were conserved efficiently in the third case.

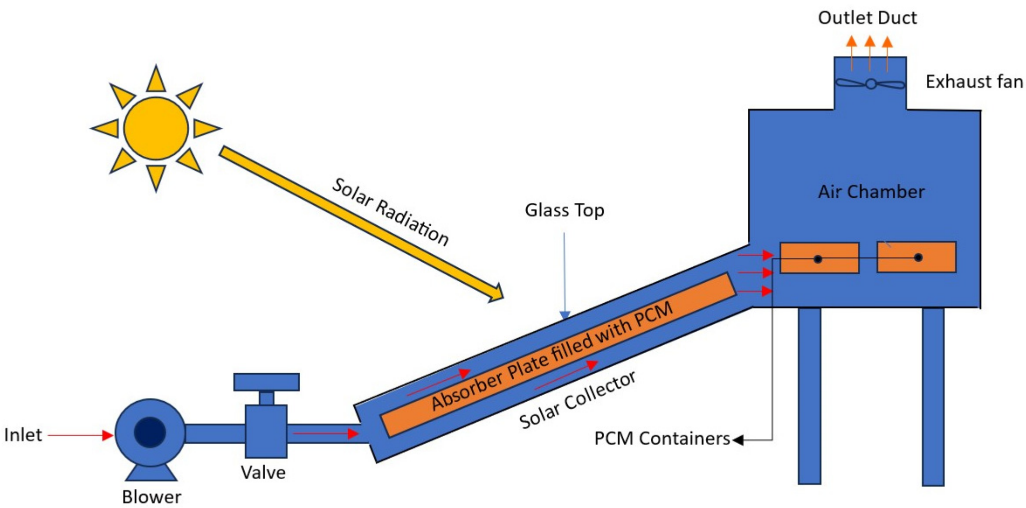

Figure 3. Modified solar dryer with PCM placed inside collector and chamber [16].

Zhang and Zhu [17] reviewed the different types of solar air collectors (a flat-plate, evacuated-tube, and concentrated collector). They concluded that integrating circular turbulators with a flat-plate collector offers high thermal efficiency and high performance compared to those of other types of collectors. Mugi et al. [18] conducted an experiment including an exergy analysis of a natural convection indirect solar dryer and forced convection indirect solar dryer. Muskmelon slices were made to dry. They suggested using the forced convection mode as it gives high exergy efficiency in the collector and drying cabinet and reduces the waste exergy ratio. Getahun et al. [19] conducted CFD analysis on a solar dryer with a PCM and using a traditional method, but in terms of hydrodynamic and thermal transport phenomena, research was not carried out. CFD analysis gives details on airflow, the characteristics of heat and mass transfer, and moisture distribution but not on the quality aspect of food products.

5. Heat Storage Aspects

Phase change materials in a latent heat storage system have a larger storage density compared to that when they are under sensible heat storage [20]. Latent heat storage improves the quality of dried product as the heat is supplied at a constant temperature [21]. A solar dryer incorporated with a PCM reduces the heat losses in the drying system [22]. A PCM stores 5–15 times additional heat in contrast to that stored in sensible heat storage materials like water, masonry, and rock [23]. The thermal behavior of PCMs can also be affected due to their design and configuration of the dryer system, for example the location at which a PCM is placed inside the solar dryer, the PCM container's size and shape, and the solar collector's orientation inside the system; these affect the heat transfer and storage properties of the PCM [24].

6. Recommendations

Compact effective storage capacity using thermal conductivity enhancers in PCM can be attached to the drying unit. A solar dryer integrated with PV panels will have a lower environmental impact [25]. A solar drier integrated with auxiliaries such as biomass heating with a PCM results in reliable operation [26]. CFD-based evaluation of performance aids in the design and optimization of the system and will give improved results [27]. A cascaded storage system leads to the effective utilization of solar energy and provides high efficiency compared to that under the heat sink mode [28]. Energy and exergy analysis promotes better design with minimal heat loss. To obtain the maximum performance of solar dryers, numerical optimization studies can be carried out further [29]. Real-time monitoring systems and remote control can be incorporated in the solar dryer system to control and monitor drying parameters easily, thereby improving the efficiency and effectiveness of the drying process [30]. There are many performance enhancement techniques like using auxiliary heater inputs, multiple PCMs, PV panels, an IOT-based real-time monitoring system, etc. Incorporating all those in a single solar dryer unit will yield a high benefit while keeping the total cost at the minimum [31]. Cost-effective, larger PCMs being available with sustainable solar drier design and operation will lead to good commercialization in the market.

7. Conclusions

This paper reviewed the recent trends, factors, and performance of PCM-integrated solar dryers. Paraffin wax is the most preferred PCM due to its self-nucleating properties and much higher latent heat of fusion. The performance and versatility of PCMs can be improved via microencapsulation, making it a promising approach. A PCM is the most efficient, effective and a low-cost thermal energy storage device. Nano PCMs result in higher efficiency; as the surface area increases, there will also be an increase in the heat transfer rate. Placing PCMs in the bottom part of the drying chamber gives more efficient thermal performance than when placed on a collector. PV panel-integrated solar dryers will help in reducing energy consumption. Solar dryers integrated with various performance enhancement techniques along with a PCM will result in higher benefits while keeping costs at the minimum. Thus, a solar dryer with a PCM enhances the thermal efficiency of the dryer, leads to a faster drying rate and better-quality food products and improves the reliability of the system.

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References

1. Kalogirou, S.A. *Solar Energy Engineering*; Introduction-Chapter 1; Elsevier: Amsterdam, The Netherlands, 2014; ISBN 9780123972705.
2. Udomkun, P.; Romuli, S.; Schock, S.; Mahayothee, B.; Sartas, M.; Wossen, T.; Njukwe, E.; Vanlauwe, B.; Müller, J. Review of solar dryers for agricultural products in Asia and Africa: An innovation landscape approach. *J. Environ. Manag.* **2020**, *268*, 110730. [CrossRef]
3. Harmen, Y.; Chhiti, Y.; Alaoui, F.E.M.; Bentiss, F.; El Khouakhi, M.; Jama, C.; Duquesne, S.; Bensitel, M.; Deshayes, L. Thermal and energetic behaviour of solid-solid-liquid phase change materials storage unit: Experimental and numerical comparative study of the top, bottom and horizontal configurations. *J. Energy Storage* **2021**, *33*, 102025. [CrossRef]
4. Agrawal, A.; Sarviya, R.M. A review of research and development work on solar dryers with heat storage. *Int. J. Sustain. Energy* **2014**, *35*, 583–605. [CrossRef]
5. Kumar, N.; Banerjee, D. Phase Change Materials. In *Handbook of Thermal Science and Engineering*; Springer International Publishing: Cham, Switzerland, 2018; ISSN 978-3-319-26695-4.
6. Madad, A.; Mouhib, T.; Mouhsen, A. Phase Change Materials for Building Applications: A Thorough Review and New Perspectives. *Buildings* **2018**, *8*, 63. [CrossRef]

7. Al Shannaq, R.; Farid, M. Microencapsulation of phase change materials (PCMs) for thermal energy storage systems. In *Advances in Thermal Energy Storage Systems*; Elsevier: Amsterdam, The Netherlands, 2015; ISBN 9781782420880.
8. Subramaniam, B.S.K.; Sugumaran, A.K.; Athikesavan, M.M. Performance Analysis of a Solar Dryer Integrated with Thermal Energy Storage Using PCM- Al2O3 Nanofluids. *Environ. Sci. Pollut. Res.* **2022**, *29*, 50617–50631. [CrossRef]
9. Nazir, H.; Batool, M.; Osorio, F.J.B.; Isaza-Ruiz, M.; Xu, X.; Vignarooban, K.; Phelan, P.; Inamuddin; Kannan, A.M. Recent developments in phase change materials for energy storage applications: A review. *Int. J. Heat Mass Transf.* **2019**, *129*, 491–523. [CrossRef]
10. Mehling, H.; Brütting, M.; Haussmann, T. PCM products and their fields of application—An overview of the state in 2020/2021. *J. Energy Storage* **2022**, *51*, 104354. [CrossRef]
11. Ali, S.; Deshmukh, S. An overview: Applications of thermal energy storage using phase change materials. *Mater. Today Proc.* **2020**, *26*, 1231–1237. [CrossRef]
12. Bal, L.M.; Satya, S.; Naik, S.N.; Meda, V. Review of solar dryers with latent heat storage systems for agricultural products. *Renew. Sustain. Energy Rev.* **2011**, *15*, 876–880. [CrossRef]
13. Hamad, A.J.; Hussien, F.M.; Faraj, J.J. Multiple Phase Change Materials for Performance Enhancement of a Solar Dryer with Double Pass Collector. *J. Energy Eng.* **2021**, *118*, 1483–1497. [CrossRef]
14. Mandal, S.; Sharma, P.K.; Mani, I.; Kushwaha, H.L.; TV, A.K.; Sarkar, S.K. Design and development of Phase Change Material based hybrid solar dryer for herbs and spices. *Indian J. Agric. Sci.* **2020**, *90*, 2217–2224. [CrossRef]
15. Çakmak, G.; Yıldız, C. The drying kinetics of seeded grape in solar dryer. with PCM-based solar integrated collector. *Food Bioprod. Process.* **2011**, *89*, 103–108. [CrossRef]
16. Lad, P.; Kumar, R.; Saxena, R.; Patel, J. Numerical Investigation of Phase Change Material Assisted Indirect Solar Dryer for Food Quality Preservation. *Int. J. Thermofluids* **2023**, *18*, 100305. [CrossRef]
17. Zhang, J.; Zhu, T. Systematic review of solar air collector technologies: Performance evaluation, structure design and application analysis. *Sustain. Energy Technol. Assess.* **2022**, *54*, 102885. [CrossRef]
18. Mugi, V.R.; Gilago, M.C.; Chandramohan, V. Energy and exergy investigation of indirect solar dryer under natural and forced convection while drying muskmelon slices. *Energy Nexus* **2022**, *8*, 100153. [CrossRef]
19. Getahun, E.; Delele, M.A.; Gabbiye, N.; Fanta, S.W.; Demissie, P.; Vanierschot, M. Importance of integrated CFD and product quality modeling of solar dryers for fruits and vegetables: A review. *Sol. Energy* **2021**, *220*, 88–110. [CrossRef]
20. Farid, M.M.; Khudhair, A.M.; Razack, S.A.K.; Al-Hallaj, S. A review on phase change energy storage: Materials and applications. *Energy Convers. Manag.* **2004**, *45*, 1597–1615. [CrossRef]
21. Jouhara, H.; Żabnieńska-Góra, A.; Khordehgah, N.; Ahmad, D.; Lipinski, T. Latent thermal energy storage technologies and applications: A review. *Int. J. Thermofluids* **2020**, *5–6*, 100039. [CrossRef]
22. Shalaby, S.; Bek, M.; El-Sebaii, A. Solar dryers with PCM as energy storage medium: A review. *Renew. Sustain. Energy Rev.* **2014**, *33*, 110–116. [CrossRef]
23. Bal, L.M.; Satya, S.; Naik, S. Solar dryer with thermal energy storage systems for drying agricultural food products: A review. *Renew. Sustain. Energy Rev.* **2010**, *14*, 2298–2314. [CrossRef]
24. Mourad, A.; Aissa, A.; Said, Z.; Younis, O.; Iqbal, M.; Alazzam, A. Recent advances on the applications of phase change materials for solar collectors, practical limitations, and challenges: A critical review. *J. Energy Storage* **2022**, *49*, 104186. [CrossRef]
25. Divyangkumar, N.; Jain, S.; Panwar, N.L. Influences of latent heat storage heat sink integrated with solar dryer to enhance drying period. *Energy Nexus* **2022**, *8*, 100160. [CrossRef]
26. Madhlopa, A.; Ngwalo, G. Solar dryer with thermal storage and biomass-backup heater. *Sol. Energy* **2007**, *81*, 449–462. [CrossRef]
27. Iranmanesh, M.; Akhijahani, H.S.; Jahromi, M.S.B. CFD modeling and evaluation the performance of a solar cabinet dryer equipped with evacuated tube solar collector and thermal storage system. *Renew. Energy* **2019**, *145*, 1192–1213. [CrossRef]
28. Wang, Z.; Yang, L.; Hu, J.; Gu, Z. Analysis on Cascade Heat Utilization of Solar Energy in Building Heating Based on Phase Change Thermal Storage. *Procedia Eng.* **2017**, *205*, 2266–2272. [CrossRef]
29. Gilago, M.C.; Mugi, V.R.; Chandramohan, V.P. Performance assessment of passive indirect solar dryer comparing without and with heat storage unit by investigating the drying kinetics of carrot. *Energy Nexus* **2023**, *9*, 100178. [CrossRef]
30. Choosumrong, S.; Hataitara, R.; Panumonwatee, G.; Raghavan, V.; Nualsri, C.; Phasinam, T.; Phasinam, K. Development of IOT based smart monitor and control System using MQTT protocol and Node- RED for parabolic greenhouse solar drying. *Int. J. Inf. Technol.* **2023**, *15*, 2089–2098. [CrossRef]
31. Bade, V.S.; Yegireddi, S.; Teegala, S.K.; Gaurav, D.; Ali Torabi, H.; Epari, R.P. Natural energy materials and storage systems for solar dryers: State of the art. *Sol. Energy Mater. Sol. Cells* **2023**, *255*, 112276.