Paraffin Wax: A Versatile Thermal Energy Storage Solution for Enhancing Solar Drying Performance

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Abstract

Using solar energy to dry various materials, such as textiles, industrial components, and agricultural produce, solar dryers are an effective way to dry a variety of materials. Open sun drying (OSD) is a well-established and traditional method of drying agricultural products in the open air. However, OSD has various limitations that can be overcome by employing different types of solar dryers. To enable solar dryers to operate throughout the day, researchers have integrated thermal energy storage (TES) units, leading to a growing field of research. This integration allows solar dryers to function during daylight hours as well. Paraffin wax, which is easily accessible, cost-effective, and possesses a large thermal energy storage (TES) capacity relative to its volume, has been widely utilized as a sensible and latent heat storage material in solar dryers since the 1950s. This work review comprehensively of the applications of paraffin wax in solar dryers integrated with TES units. The article describes thermo-physical characteristics of various types of paraffin wax are discussed in detail. A comparison is made in terms of thermal performance, drying efficiency, and drying time between different types of solar dryers with and without paraffin wax. The review highlights the possibility of incorporating diverse TES units within a dryer. Additionally, the article presents an overview of current technologies thermal conductivity can be enhanced between paraffin wax and drying air, as well as the rate of heat transfer. Furthermore, the challenges and prospects associated with Paraffin wax is discussed in relation to solar drying. Notably, the thermal efficiency of solar dryers can be improved by mixing kerosene and n-docosane with paraffin wax in a 2:1 ratio, resulting in a 50% increase in thermal efficiency.

Keywords: Solar Dryers; PCM; Direct Mode; Indirect mode; Mixed mode; Hybrid Mode

1. Introduction

Given the finite nature of resources and the significant pollution and climate change caused by other energy sources, scientists and researchers worldwide are actively pursuing renewable energy sources. Additionally, the world faces significant challenges due to a growing population and an increase in energy-intensive products. It is possible to make use of solar energy in a number of different ways, including water heating, space heating, drying, solar furnaces, solar power, distillation, and ponds. Drying applications require energy from various sources, including electricity, natural gas, biomass, fossil fuels, and solar energy. The substantial energy consumption associated with drying applications has long been recognized. Specifically, thermal drying accounts for around in developed countries, the amount of industrial energy use varies between 10 and 20 percent [1–4]. Drying agricultural products involves energy-intensive processes that traditionally rely on biomass, solar energy as energy sources, and fossil fuels. In recent years, however, there has been a growing shift towards Solar energy is one of the most sustainable and new sources of energy. This transition is driven by the depletion of the environmental pollution and fossil fuels associated with their usage. Solar energy, in contrast, offers a clean, renewable, and environmentally friendly alternative, free from any harmful emissions. It represents an inexhaustible energy source that holds great potential for sustainable agricultural practices [5]. Drying is a well-established and extensively employed Food preservation method, aimed at reducing Food products' moisture content to prolong their shelf life. This technique is commonly employed in the preservation of agricultural commodities as it not only improves their visual attributes, such as color, taste, and appearance, but also microorganisms are inhibited by it, prevents insect infestations, and reduces the presence of contaminants [6]. Over the past three decades, a diverse range of several types of solar dryers have been developed and brought into commercial use for the purpose of drying food materials. There are different types of solar dryers, including: direct, mixed, and indirect configurations. These advancements in solar drying technology have enabled more efficient and effective drying processes for food materials [7]. Among the different types of dryer models developed and assessed globally, the ISD (Integrated Solar Dryer) Based on both product drying behavior and drying cost, this model has proven to be the most efficient. Three crucial components of an ISD come together in order to facilitate the dehydration of materials in the dryer: solar collectors to generate hot air, a drying chamber to remove moisture from the material, and a blower to circulate air within the dryer. Depending on the method of air circulation, ISDs can be categorized as either natural convection or forced convection units. In recent years, forced convection dryers have gained increasing popularity due to their ability to facilitate more precise drying control and efficient heat extraction [8]. The solar dryer exhibits a drawback in its reliance on solar energy, making it susceptible to the influence of weather conditions, which can significantly impact its efficiency. To overcome this limitation, a viable approach involves the storage of energy during periods of ample solar radiation for utilization during periods when solar energy is unavailable or when the sky is cloudy. Extensive literature offers numerous examples that illustrate this practical solution, highlighting the potential for energy storage to enhance the reliability and effectiveness of solar dryers under varying weather conditions [9]. A study conducted by Abubakar et al. [10] incorporated rock-packed beds as storage units in two mixed-mode solar dryers. Comparing the performance of solar dryers that are equipped with storage materials to those that are not with respect to their performance, the study found that the inclusion of storage material resulted in a notable 13% increase in efficiency.

Helwa & Abdel Rehim [11] An analysis of the efficiency of a solar dryer has been conducted in this study with the objective of finding out system that incorporated a pebble bed storage system alongside solar energy. According to the results of the study, the solar dryer has proved to be a successful method of drying with pebble bed storage effectively raised the inlet air temperature during nighttime without causing a decrease in the daytime inlet air temperature, and vice versa.

Natarajan et al [12] A tunnel-type dryer was investigated by utilizing a variety of heat storage materials in order to assess the thermal performance of the dryer such as a sand bed, a rock bed, and aluminum fillings. The study compared the thermal efficiencies of different dryer configurations, including a dryer without heat storage, a dryer with a sand bed, a dryer with a rock bed, and a dryer with aluminum fillings, which yielded thermal efficiencies of 9.9%, 15.46%, 14.75%, and 13.7%, respectively. The findings suggest that tunnel dryers exhibit superior material storage capabilities when utilizing sand beds. According to this study was carried out by Koçak et al. [13] the utilization of thermal energy storage mediums a dryer's performance can be enhanced by this. The inclusion of a thermal storage medium, as identified in this study, leads to a reduction in energy losses from the drying chamber.

The present study provides a comprehensive examination of TES systems utilizing paraffin wax integrated with various solar dryers. It explores different solar drying methods, including Hybrid, indirect, and direct approaches, along with the types of dryers and specific applications of the TES system and the types of PCM used for drying. The performance of paraffin wax-based dryers is analyzed in comparison to non-paraffin wax-based dryers based on collector efficiency, drying efficiency, and drying time. There is an extensive discussion of the thermophysical properties of different paraffin waxes, discussing their advantages, disadvantages, merits, and demerits. Additionally, methods and technologies for enhancing TES systems based on paraffin are discussed in regards to their conductivity and the rate at which heat is transferred. The study presents the results in tabular form, summarizing various types of operating conditions, and TES setups. Various factors influencing the drying process, such as temperature range, drying time, protecting the food items from dust, and the types of materials (e.g., fruits, vegetables, medicinal, seafood or herbal leaves), are considered. The article presents novel insights into the field is possible to manufacture solar dryers using paraffin wax, offering valuable details for further research and development.

2. Various Types and Classifications of Solar Dryers

Typically, there are two basic types of solar dryers: natural convection models and forced convection models. These two classifications are based on the underlying principles of air circulation within the dryer system as shown in Figure 1.

Solar dryers employing natural convection utilize buoyancy-driven mechanisms to generate airflow, whereas solar dryers powered by electricity or solar panels employ blowers to generate airflow.

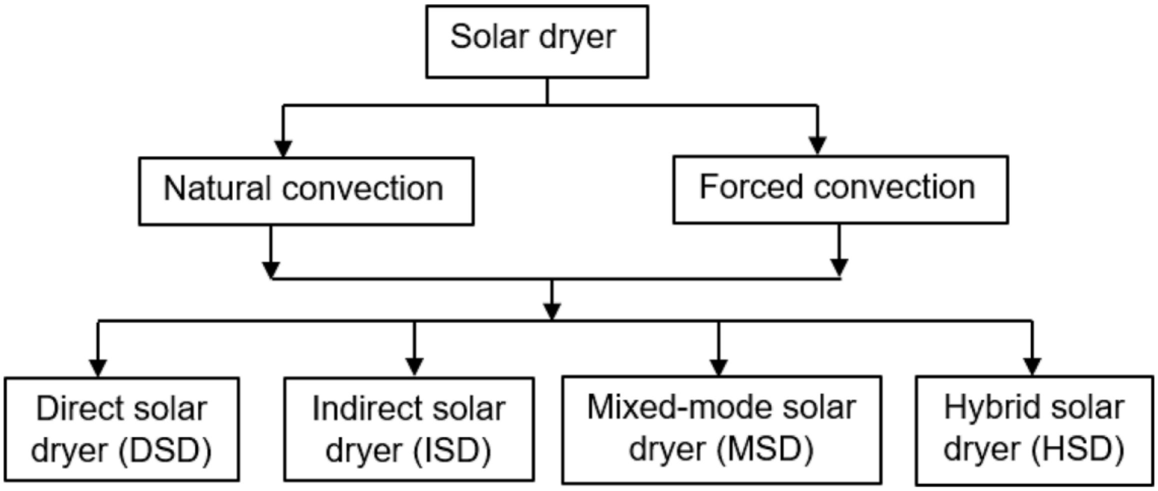

Figure 1: Dryers are categorized based on their operational effectiveness

There are four distinct types of solar dryers, which fall under either natural or forced convection: hybrid, mixed-mode, indirect, and direct solar dryers [14,15].

2.1. Direct Solar Dryers (DSDs)

solar drying systems consisting of a box or greenhouse structure with trays where products are positioned on a transparent cover. The transparent glass allows for the direct transmission of solar energy to the products [16], illustrate in Figure 2.

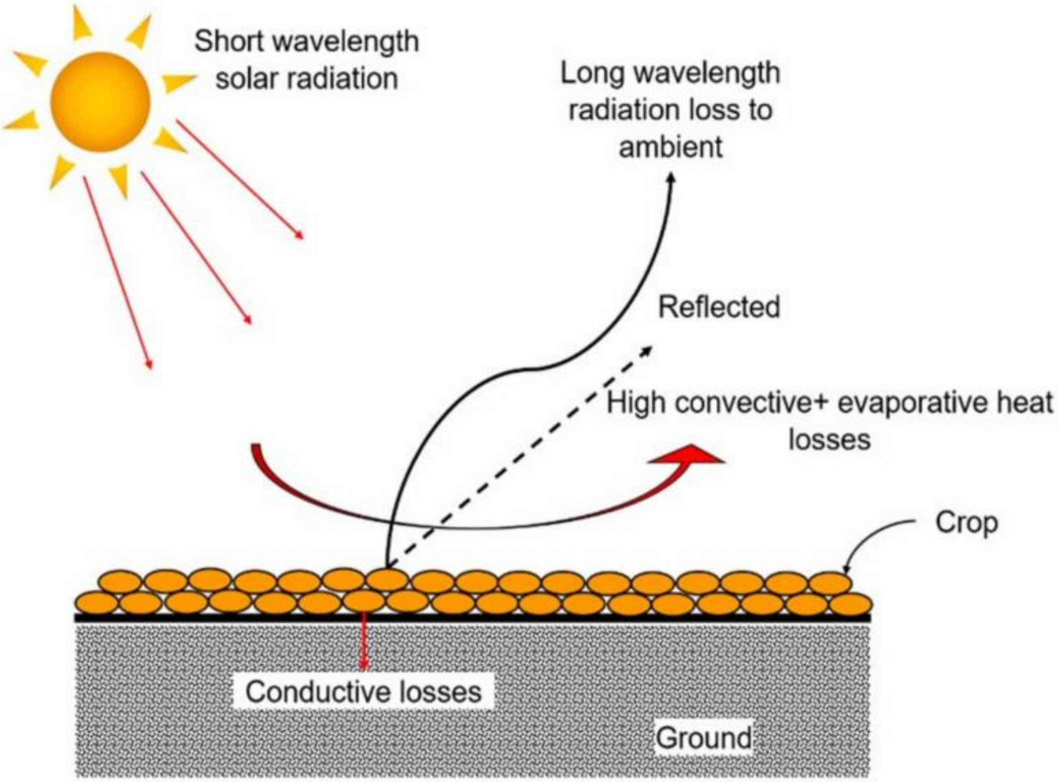

Figure 2: Direct solar dryer [17]

2.2. Indirect Solar Dryers (ISDs)

Figure 3 illustrate solar air collectors (SACs) are utilized air is heated to make it comfortable then directed into a drying cabinet. In this cabinet, trays are arranged to hold the products undergoing drying. Moisture from the products is subsequently expelled through a chimney located at the top of the system [18].

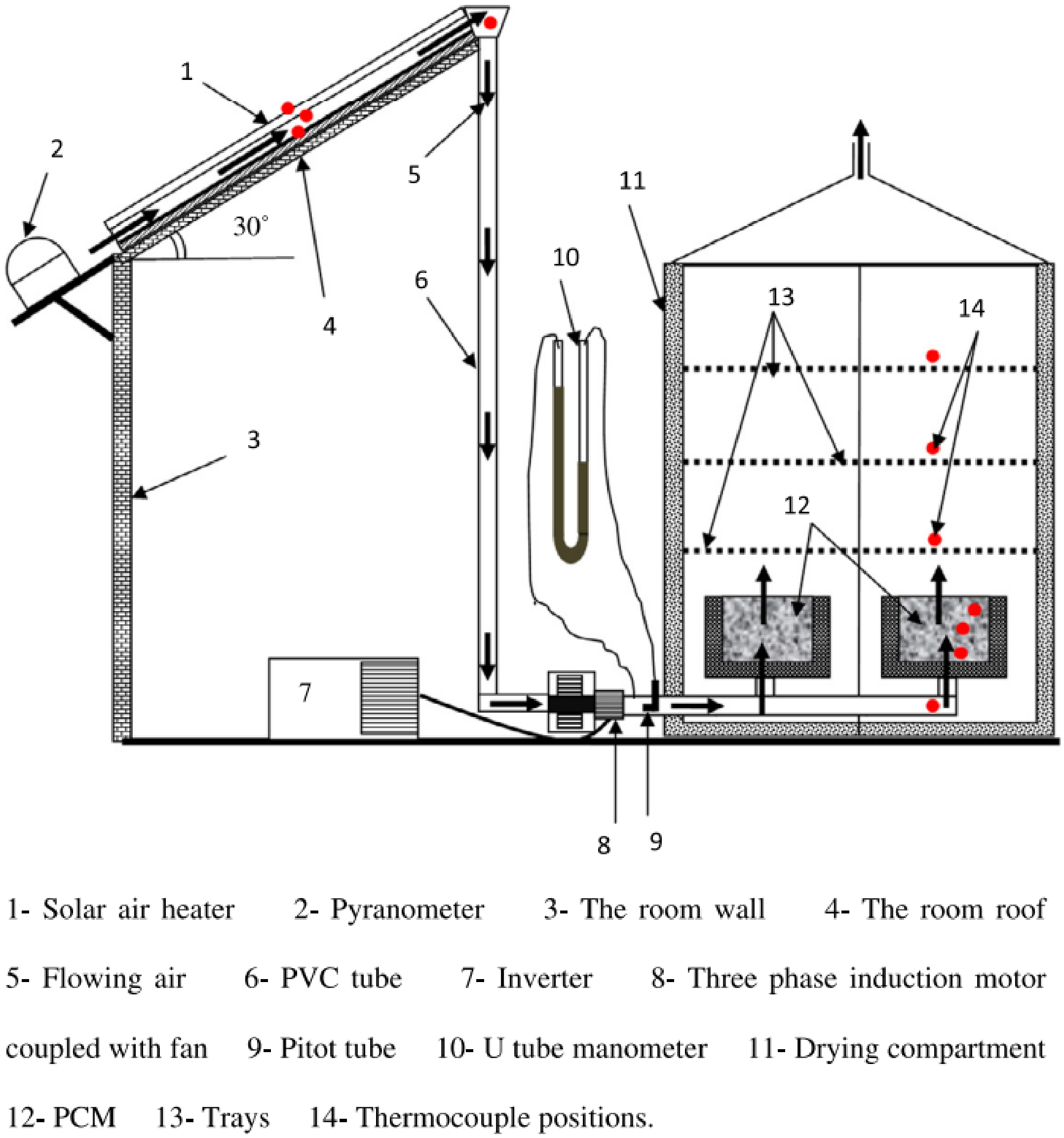

Figure 3: Indirect solar dryer with PCMs [19]

2.3. Mixed-Mode Solar Dryers (MSDs)

This model integrates a combination of a DSD (Direct Solar Dryer) and an ISD (Indirect Solar Dryer) as shown in Figure 3. It incorporates a solar air collector (SAC), a drying cabinet, and a chimney. The SAC harnesses heat from both solar air collectors and direct sunlight, which in turn facilitates the evaporation of moisture from food products within the drying cabinet [20].

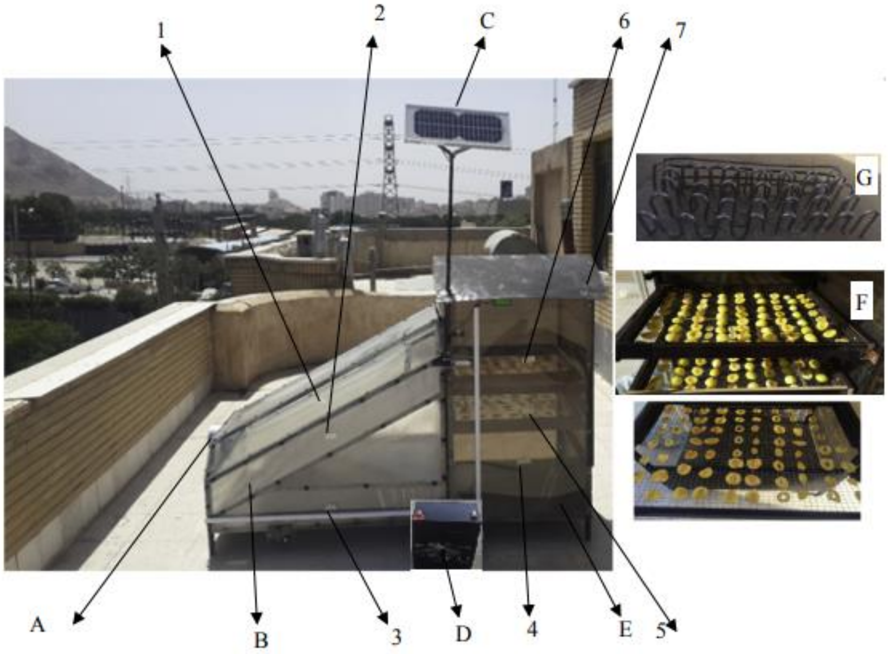

Figure 4: mixed solar dryer with PCMs [21]

2.4. Hybrid Solar Dryers (HSDs)

In addition to solar energy, HSD (Hybrid Solar Dryers) makes use of various auxiliary energy sources such as biomass, electricity, waste heat, and other forms of energy to facilitate the evaporation of moisture in food products [22].

Figure 5: PVT hybrid solar dryer with PCMs [23]

3. A brief Overview of Materials that Store Sensible Heat (SHS) and Latent Heat (LHS)

3.1. Thermal Energy Storage Classification

Thermal energy refers to the alteration in the internal energy of an object caused by a change in temperature within a well-insulated solid or fluid. It encompasses both sensible heat and latent heat, or a combination of the two. *Figure 6* offers a concise overview of the primary techniques and devices employed for the storage of solar thermal energy [24]. This form of heat storage, known as sensible heat storage (SHS), involves storing energy by raising the temperature of a solid or liquid. By utilizing the material's heat capacity and its temperature change, thermal energy can be stored when the material is charged or discharged. The quantity of heat stored in a medium is influenced by various factors, including its specific heat, the extent of temperature change, and the amount of material being stored. Water is considered the most suitable material for SHS due to its affordability and high specific heat. Alternatively, for temperatures exceeding 98 degrees Celsius, liquid metals, liquid oils, and molten salts are utilized. Rock beds are utilized as storage materials for air-conditioning applications.

3.2. Solar Dryers Use Phase Change Materials (or LHS)

When a substance undergoes a phase transition, such as changing solids into liquids or liquids into gases, there is a transfer of latent heat. Transitions between phases can either absorb or release this latent heat, while the temperature remains relatively constant within a certain range [25]. A thermochemical system provides an example of this process, where heat is absorbed or released during a reversible chemical reaction that involves breaking and reforming molecular bonds. In this case, three factors determine the amount of heat stored: the quantity of storage material, the heat produced by the endothermic process, and the degree of conversion. There are many methods available for storing thermal energy, but latent heat storage in particular has gained a lot of attention. In operation, it is nearly isothermal because of its high density in terms of volume and mass. There is a constant temperature at which the heat is stored, corresponding to the phase transition temperature of the PCM.

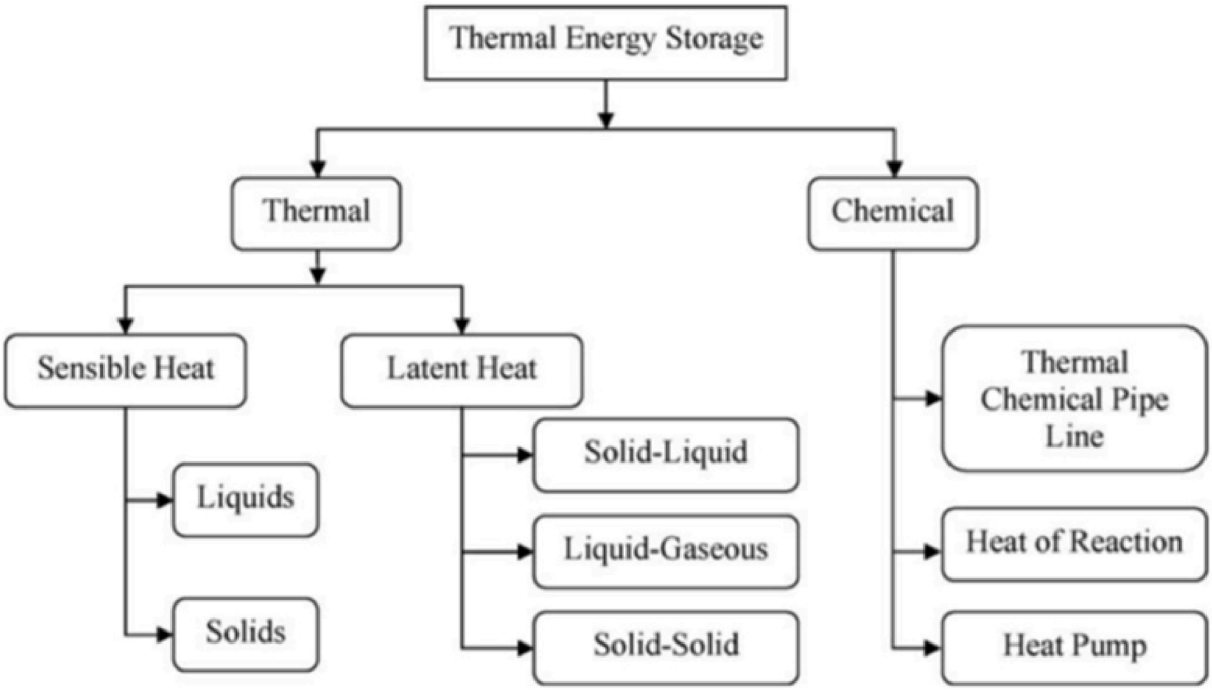

Figure 7: Thermal Energy Storage classification [26]

3.2.1 Classification of PCM

The categorization of PCM based on their organic types is depicted in Figure 8. Organic compounds are further classified non-paraffinic and paraffinic compounds. Additionally, based on their chemical properties, organic compounds can be further divided in metallic and salt hydrates compounds.

3.3. Enhancing Solar Dryer Efficiency Through the Integration of LHS or PCM

3.3.1 Organic PCMs.

PCMs of this category are categorized as either paraffins or non-paraffins depending on the arrangement of carbon and hydrogen atoms in their molecular composition. During the process of melting and solidifying, these substances exhibit a consistent melting behavior known as congruent melting. This implies that they maintain their latent heat of fusion without undergoing phase separations or permanent loss. Furthermore, these materials have the ability to self-nucleate with minimal or no supercooling, and they generally do not cause corrosion. Paraffin wax is the PCM most commonly utilized in commercial applications, and it is priced at approximately $2 per kilogram [27,28].

3.3.1.1. Inorganic PCMs.

Inorganic PCMs can be distinguished by the absence of carbon atoms in their molecular structure. These PCMs are typically water-based and referred to as aqueous PCMs. One notable characteristic of these PCMs is that they do not experience significant supercooling, and their heat of fusion remains consistent even with repeated cycling. Additionally, they exhibit favorable thermal conductivity and have the ability to store a substantial amount of energy within a small volume. However, it is important to consider limitations such as causticity and the potential for leakage.

In terms of composition, there are two main types of inorganic PCM salts: salt hydrates, such as calcium chloride, which can be obtained at a cost of $0.20 per kilogram, and metal salts, which are available at a cost of $0.15 per kilogram [29,30].

3.3.1.2. PCM in the Form of Eutectics

Eutectics consist of a combination of two or more components, each with a minimum melting point. Upon melting and freezing, eutectics undergo simultaneous phase changes, leading to the formation of crystallized mixtures comprising component crystals. The nature of eutectics makes it highly unlikely for segregation to occur during the melting or freezing process, as the crystals freeze together, creating a closely integrated mixture that offers minimal chances for component separation. When the components are in a molten state, they both undergo liquefaction simultaneously, with only a slight possibility of separation taking place [31,32].

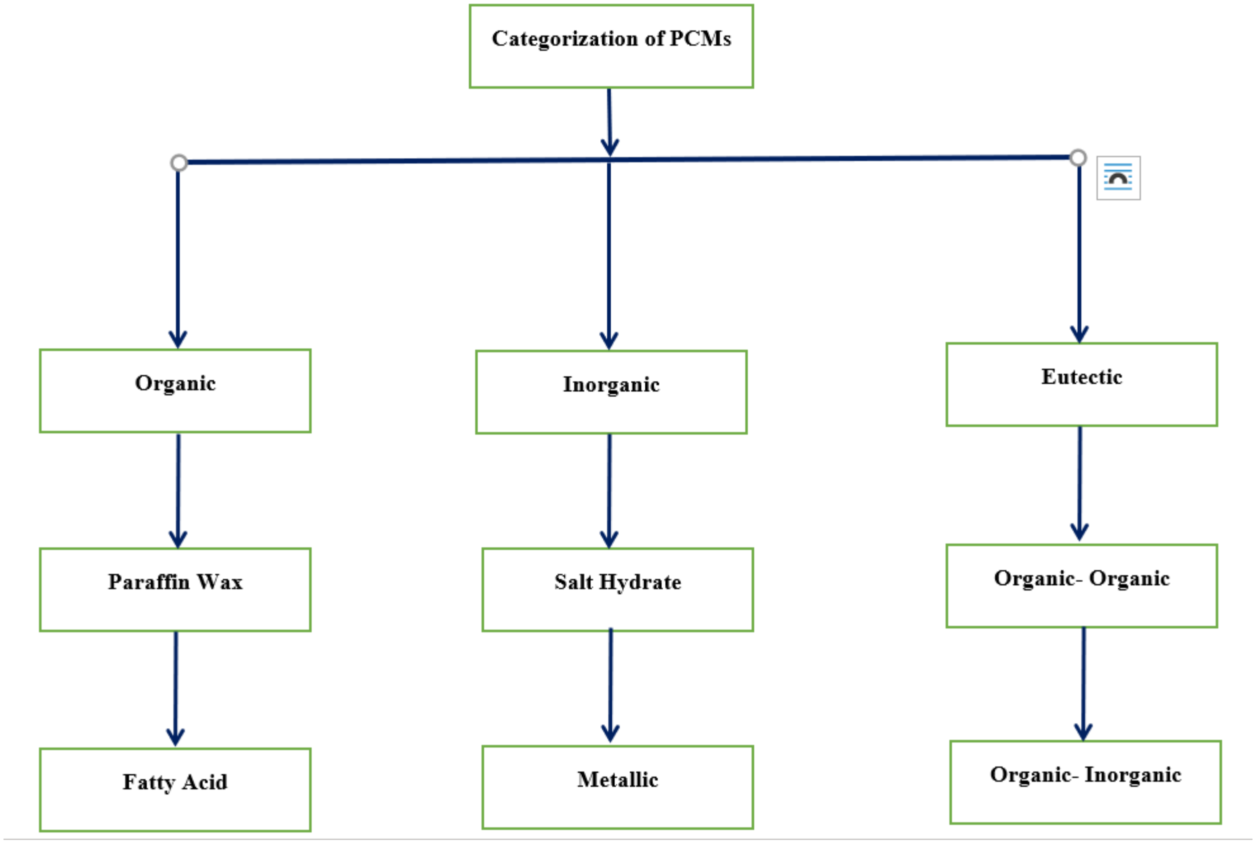

Figure 8: Classification of PCMs [33–40]

Based on ***Table 1***, extensive research has been conducted to assess the drying efficiency of different types of dryers over the past few decades. Biomass dryers and solar dryers utilizing direct radiation exhibit lower efficiency compared to other types. However, it is important to acknowledge that variations in efficiency across different drying processes are inevitable. Both indirect solar dryers and gas dryers have demonstrated effective drying methods with higher efficiency. Hybrid dryers, which utilize solar energy as a secondary source, heavily rely on the effectiveness of this secondary source for their efficiency. Solar thermal systems that store solar energy offer the advantage of providing drying even in the absence of direct solar incidence, thereby reducing drying costs by eliminating the need for auxiliary energy sources.

Table 1: The average efficiencies of different types of dryers over a specific period.

Dryer types	Products	Average efficiency	Reference
Indirect solar	Onion	35.0%	[41]
Indirect solar	Mango slices	33.8%	[42]
Indirect solar	Orange	34.4%	[43]
Indirect solar	Okra	26.1%	[44]
Indirect solar	Apple	39.0%	[45]
Indirect solar	Medicinal plants	26.1%	[46]
Solar-electric hybrid	Garlic cloves	79.7%	[47]
Biomass-solar hybrid	Rice	15.4%	[48]
Hybrid PV/T	crops	18.0%	[23]
Hybrid geothermal	food	20.5%	[49]
Hybrid	products	75.0%	[50]

4. Future Trends

PCMs have garnered significant attention and advancements in diverse applications including district cooling, drying, and heating processes. However, in terms of applications involving high temperatures such as thermal energy storage in industrial process heat or solar thermal power sectors, there is still relatively less development. As a result, current research and development efforts mainly concentrate on concentrating solar power systems for high-temperature thermal storage (CSP) Further exploration and alternative applications are being investigated to mitigate the supercooling tendency of PCMs, high-temperature TES must be used.

The effectiveness of discharge and charging energy rates can be hindered by the low thermal conductivity of PCM during phase transformations. Therefore, in order to facilitate efficient phase transformations, having a high thermal conductivity is crucial in order to facilitate the rapid transfer of thermal charge as well as its discharge. Conversely, certain PCMs may remain in a solid state even when the temperature of the substance is lowered below its normal freezing point, it will become liquid. The PCM transforms into a liquid state as soon as it reaches its freezing temperature. However, when the temperature drops significantly below the melting point of the PCM, it undergoes the solidification process and becomes solid again. This phenomenon, known as supercooling, can restrict the usability of the PCM in specific applications according to its specifications. Consequently, efforts are made to reduce the temperature after a phase change, which triggers crystallization, to a level that allows the release of latent heat, which is only liberated once the crystallization process has been initiated. In the context of energy storage applications, this condition would be undesirable [51–54].

In this section, the significant advancements and emerging research trends related to the properties of PCMs are examined. These include the improvement of thermal conductivity, the mitigation of supercooling through nanoencapsulation techniques, and the incorporation of nanomaterial additives. Various strategies are employed to address these challenges, and an overview of these approaches can be found in Figure 14.

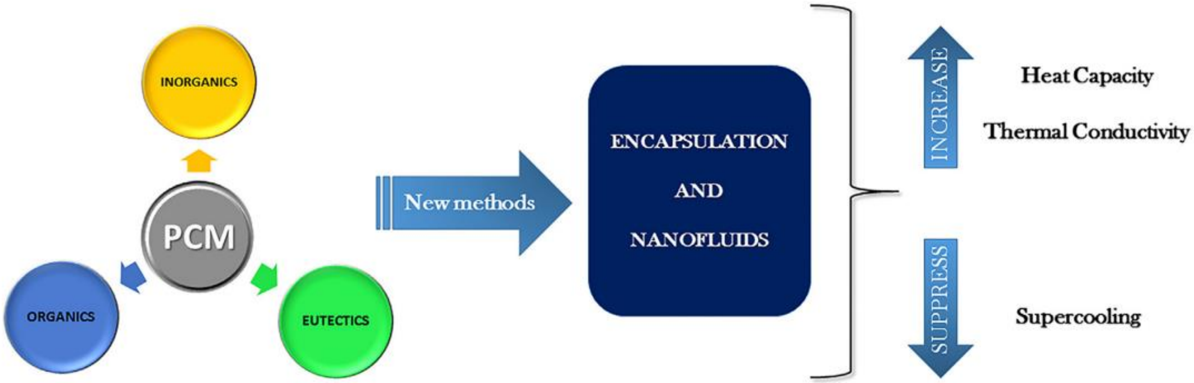

Figure 9: A sketch of how PCMs will develop in the future [55]

4.1. Encapsulated PCM

Encapsulation refers to the process of enclosing a particle within a coating material or embedding it in a matrix, resulting in the formation of a capsule where the particle is surrounded or encapsulated by the coating material or matrix. Capsules come in various shapes such as spherical, tubular, oval, and square, and can be either regular or irregular in nature. Changes in the volume have been made to accommodate these changes that occur during phase transformations, it is sometimes necessary to incorporate an additional air pocket within the core of the component. The outer shell of the phase change material (PCM) must possess sufficient strength to withstand the stresses generated during the PCM's phase change process, which is characterized by volumetric changes. There are two types of PCM: solid PCMs and those dispersed within carrier fluids. A slurry of microencapsulated PCMs is a mixture comprising a PCM and a carrier fluid. This approach serves as one of the methods to address issues associated with PCMs, the thermal conductivity of a material, for example, is low, thermal instability, reduced heat release rate, and decreased thermal system efficiency. Encapsulation of PCMs not only increases their surface area but also provides protection against environmental factors, improves compatibility, and reduces corrosion resulting from PCM utilization [56–60].

4.2. Encapsulated PCM Places and Effect on the Dryer

By incorporating PCM within the solar air heater duct, the influx of dust and microorganisms into the dryer chamber can be effectively prevented. This preventive measure not only ensures the preservation of heat but also plays a critical role in safeguarding the health and hygiene of the dried fruit. Hence, installing PCM in the solar air heater passage serves the dual purpose of heat storage and maintaining the sanitary conditions necessary for the dried fruit [61–63].

5. Conclusions and Recommendations for Future Studies

In conclusion, the present study reveals a predominance of small-scale and experimental solar drying systems incorporating PCMs. Development efforts and Extensive research are imperative prior to the widespread adoption of TES in large-scale solar dryers for successful industrial applications. For both large- and small-scale implementations, dryer systems integrated with TES must adhere to stringent criteria of affordability, reliability, environmental sustainability, efficiency, and high-quality performance. The food industry stands to gain significantly from large-scale solar drying methods utilizing PCMs to ensure superior product quality (conventional drying methods, such as fossil-fuel-based dryers, are notorious for their high energy consumption and emissions). Future research endeavors should prioritize sustainable strategies for scaling up innovative drying techniques, with a particular focus on environmental and economic consideration.

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