



# **A Comprehensive Analysis of Investigation on the Use of Different Phase Change Materials in Solar Cooking for the Storage of Thermal Energy**

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## **Abstract:**

Solar cookers offer a sustainable source of energy that may be utilized for cooking purposes. On the other hand, their most major disadvantage is that they cannot be employed when there is a lack of sunshine. By using thermal energy storage, it is possible to significantly overcome these limits. The purpose of this study is to give a comprehensive literature evaluation of the uses of phase change materials as thermal energy storage mediums to enhance the performance of solar cookers. This review takes a retrospective look at the recent years by reviewing the progress made in the area of phase change materials and their applications in various heat transfer devices such as solar cooker, heat exchange and thermal storage system. In addition, the many types of phase change materials, nanofluids, and the challenges associated with enhancing the thermophysical properties of phase change materials are discussed.

**Keywords:** Phase Change Material, Thermal Energy Storage, Solar Cooking, Nanofluids, Solar Energy.

## **1. Introduction**

Two of the most pressing global challenges now are the energy crisis and environmental degradation. Greater efficiency in the utilization of renewable energy sources is being propelled by rising fuel costs, steadily increasing energy demand and the release of greenhouse gases [1]. Problems with health, the environment, society, and the economy have resulted from the use of non-renewable resources, which are particularly prevalent in developing countries [2]. To meet demand in light of fossil fuels' finite supply, renewable energy alternatives must be considered. There are a few drawbacks to using renewable resources, too. These include energy source availability, energy source inconsistency, and the need to store surplus energy. There is a vast array of potential uses for solar energy, which makes use of this abundant energy source. When it comes to thermal uses of solar energy, solar cooking is seen as one of the most appealing, easy, and simplest solutions [3]. Solar cookers that have thermal energy storage can continue cooking even when the sun isn't directly



above, making them more versatile. Two practical ways to store thermal energy for solar cookers are sensible heat thermal energy storage and latent heat thermal energy storage. Particularly during the cold and wet seasons, the strength of solar rays may be rather unpredictable. Transporting and incorrectly processing the obtained energy reduces the device's overall performance [4]. The meal takes more time to cook since heat can't be stored. Clean and safe for both humans and the environment, solar energy is an ideal thermal energy source for the kitchen. Lightweight and efficient heat storage devices are being considered, and phase change materials with a high storage density and a constant working temperature have been named as a potential area of focus [5]. The rapid application of a large amount of heat is possible with the help of a miniature phase change material storage device.

Nevertheless, the difficulty that is linked with certain renewable energy, such as sun and wind, is that they are only available for a specific amount of time. Since the supply of renewable energy is dependent on weather-related natural phenomena like rain, wind, and solar energy, it is difficult to exert control over the supply of this type of energy [6-7]. If renewable energy can be stored, then it is feasible to make better use of it. This is because storing renewable energy reduces the need for fossil fuels, which in turn reduces the cost of system maintenance and, ultimately, minimizes the amount of energy that may be wasted. In order to achieve a state of equilibrium between the production and consumption of energy, it is essential to store any extra energy for either the short or long term [8]. Hence, phase change material is an excellent option for capturing solar energy throughout the day and utilizing it for cooking later on when the sun doesn't shine. A material's ability to absorb or release heat during a phase shift is the basis of latent heat storage (LHS). Phase change materials have a number of limitations that make them unsuitable for use in solar energy storage, including low specific heat, high melting point, and poor thermal conductivity [9]. Due to their distinct nanoscale characteristics, particles are crucial in this context. It follows that the precise proportions of nanoparticles mixed with phase change materials can rejuvenate phase change materials characteristics. The purpose of this work is to present a critical evaluation of current research that has been conducted on the application of various phase change materials for the storage of solar energy in the context of solar cooking. The most recent literature of research and solar cooking systems that are combined with latent thermal energy storage devices are the primary topics of discussion in this study.

## 2. Phase change materials

Recently, there has been an increase in the amount of research attention and emphasis placed on the utilization of phase change materials in the context of energy efficiency. Many studies [10-11] have been conducted to investigate the theories, designs, and analyses of phase change materials for the purpose of storing latent heat. These are some of the classifications, kinds, and procedures that will be addressed in the next paragraphs. There are four distinct types of phase change materials (PCMs) that may be distinguished from one another based on their characteristics: solid-solid, solid-liquid, solid-gas, and liquid-gas. As can be seen in (Fig. 1), solid-liquid phase change materials (PCMs) are the most ideal for storing thermal energy among these four categories. Other forms of phase change materials include organic phase change materials, inorganic phase change materials, and eutectics.

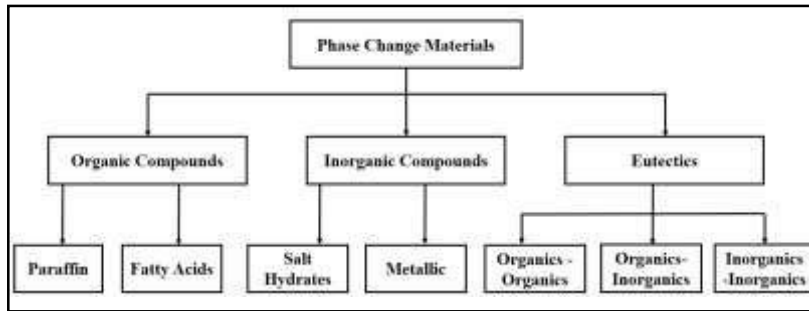


Figure 1. Classification of phase change materials (PCMs)

Organic phase change materials (PCMs) exhibit consistent performance and structural integrity, with no observable alterations such as phase separation, even after undergoing several phase change cycles. Furthermore, it is not possible to witness supercooling events in organic phase change materials (PCMs) [12]. The categorization of organic phase change materials (PCMs) is distinctive. This distinction mostly relies on their respective application environments. Typically, they are categorized into two primary sections: paraffin and non-paraffin. Paraffins are the predominant phase change materials (PCMs), but non-paraffinic organic PCMs are recognized as the most extensively utilized groups. Aside from their distinct characteristics in comparison to paraffins, they exhibit very comparable qualities to one another. Scientists have employed many categories of ether, fatty acid, alcohol, and glycol as materials for storing thermal energy. These materials are often combustible and have lower resistance to oxidation [13-14].

Non-paraffin organic phase change materials (PCMs) possess a significant latent heat capacity. However, they are susceptible to drawbacks such as flammability, limited thermal conductivity, low combustion temperatures, and temporary toxicity. Fatty acids, glycols, polyalcohols, and sugar alcohols are the most significant non-paraffinic phase change materials (PCMs) [15]. The primary characteristics of inorganic PCMs include a greater thermal conductivity and a large capacity for thermal energy storage, which is about double that of organic PCMs. They are commonly categorized as both metals and salt hydrates. Among the several inorganic PCMs used in latent thermal energy storage systems, salt hydrates stand out as the most crucial. The combination of inorganic salts with water is known as a salt hydrate. In fact, salt hydrates lose all or almost all of their water during phase shift, which is quite similar to the thermodynamic melting process in other materials.

Other components of inorganic PCMs include metals. Among metals' many benefits, their excellent mechanical qualities and strong heat conductivity stand out. Various metals are accessible throughout a broad melting point range. Further applications include high-temperature PCMs. Metals like zinc, magnesium, aluminum, etc. are used for high-temperature PCMs, whilst indium, cesium, gallium, etc. are utilized for low-temperature PCMs [16]. For very high temperature systems, several metal alloys have been utilized that have melting points ranging from 400°C to 1000°C. You may find these metal alloys utilized in solar power systems as high-temperature PCMs. Additionally, they have use in businesses that deal with high-temperature reactors or furnaces that need to be regulated.

As many as two different kinds of phase transition materials are included within a eutectic. The



field of eutectics possesses remarkable qualities. When it comes to eutectics, the melting-solidification temperatures are often lower than the constituents, and the phase shift does not result in the components being separated out into their respective components. Because of this, the phenomena of phase separation and supercooling are not observed in these materials. A higher thermal cycle is often associated with eutectics in comparison to salt hydrates. Eutectics that are composed of inorganic and inorganic compounds are the most prevalent type. On the other hand, organic-inorganic and organic-organic variations have garnered increased attention in recent research investigations. The commercialization of eugenics is the most significant challenge that they face. It is typical for their prices to be two to three times more than those of commercial PCMs.

There are a few PCMs that are comparable to paraffins in terms of their latent heat capacity, Table 1, provides a summary of some of these PCMs along with their thermal characteristics and some thermo physical characterises AP-25 wax are discussed in Table 2.

**Table 1.** Thermophysical properties of some common PCMs with high latent heat [17-20].

Type of PCMs	Materials	Melting point (°C)	Latent heat (kJ/kg)	Density* (kg/m <sup>3</sup> )	Thermal conductivity (W/mK)
Inorganic salt hydrates	LiClO <sub>3</sub> ·3H <sub>2</sub> O	8	253	1720	
[17]	K <sub>2</sub> HPO <sub>4</sub> ·6H <sub>2</sub> O	14	109		
	Mn(NO <sub>3</sub> ) <sub>2</sub> ·6H <sub>2</sub> O	25.8	126	1600	
	CaCl <sub>2</sub> ·6H <sub>2</sub> O	29.8	191	1802	1.08
	Na <sub>2</sub> CO <sub>3</sub> ·10H <sub>2</sub> O	32-34	246-267		
	Na <sub>2</sub> SO <sub>4</sub> ·10H <sub>2</sub> O	32.4	248,254	1490	0.544
	Na <sub>2</sub> HPO <sub>4</sub> ·12H <sub>2</sub> O	34-35	280	1522	0.514
	FeCl <sub>3</sub> ·6H <sub>2</sub> O	36-37	200,226	1820	
	Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> ·5H <sub>2</sub> O	48-49	200,220	1600	1.46
	CH <sub>3</sub> COONa·3H <sub>2</sub> O	58	226,265	1450	1.97



paraffin ic organic PCMs [18]	Non- Fatty acids		Formic Acid 8.3 247 1220				
		n-Octanoic acid	16	149	910	0.148	
		Lauric Acid	43.6	184.4	867		
		Palmitic Acid	61.3	198	989	0.162	
		Stearic Acid	66.8	259	965	0.172	
	Polyalcohols		Glycerin	18	199	1250	0.285
			PEG E600	22	127.2	1126	0.189
			PEG E6000	66	190	1212	
			Xylitol	95	236	1520	0.40
			Erythritol	11	338	1361	0.38
Others			9				
		2-Pentadecanone	39	241			
		4-Heptadecanon	41	197			
		D-Lactic Acid	25-54	126,1	1220		
Eutectics [19-20]	O-O, 0-I, I-I***	CaCl <sub>2</sub> .6H <sub>2</sub> O+MgCl <sub>2</sub> .6H <sub>2</sub> O	25	127	1590		
		Mg(NO <sub>3</sub> ) <sub>2</sub> .6H <sub>2</sub> O+MgCl <sub>2</sub> .6H <sub>2</sub> O	59	144	1630	0.51	
		Trimethylolethane+urea	29.8	218			
		CH <sub>3</sub> COONa.3H <sub>2</sub> O+Urea(60:40)	31	226			
	Metals	Mg.Zn(72.28)	34	155	2850		
Al.Mg.Zn(60:34:6)		45	329	2380			
	Al.Cu(82:18)	550	318	3170			
	Al-Si(87.8:12.2)	580	499	2620			

**Table 2.** Thermo physical characterization of paraffin-AP25 wax [21].

Property	Value	Unit
Melting temperature	48–53	°C
Latent heat of fusion	190	kJ/kg
Solid density	930	kg/m <sup>3</sup>
Liquid density	830	kg/m <sup>3</sup>
Thermal conductivity	0.21	kJ/kg°C
Solid specific	2.1	kJ/kg°C
Density (solid/liquid)	833/775	kg/m <sup>3</sup>
Kinematic viscosity	8.3 × 10 <sup>-5</sup>	M <sup>2</sup> /s



Due to its substantial energy storage capacity and properties such as a quick transfer of a significant amount of heat to the application region, Phase Change Material (PCM) is a suitable solution for solar heat storage. When compared to conventional arrangements, the amount of energy that is lost to the environment and the amount of energy that is held at a temperature that is stable and that dissipates over time are both significantly lower. During the charging phase, when energy is absorbed, the temperature of the storage material increases; during the discharging phase, when energy is discharged, the temperature falls. We may use Eq. [1] to find the storage capacity of a reasonable storage system:

$$Q_{\text{sensible}} = \int_{T_i}^{T_f} m C_p dT = m C_p (T_f - T_i) \quad [1]$$

Where  $Q_{\text{sensible}}$  : Storage energy (J),  $T_f$  = final Temperature (K),  $T_i$  initial Temperature (K),  $m$  = mass of the storing material (kg),  $C_p$  = Specific heat J/(Kg. K)

Lastly, latent heat storage is the primary emphasis of this evaluation and the last route. The latent heat storage makes use of phase-changing materials that undergo a limited degree of thermal energy exchange (Fig. 2). The Eq. [2] that provides the capacity of the latent heat storage system is provided below:

$$Q_{\text{latent}} = m [ C_{ps} (T_m - T_i) + f \nabla q + C_{pl} (T_i - T_m) ] \quad [2]$$

$Q_{\text{latent}}$  = storage capacity (J),  $T_m$  = melting temperature (K),  $m$  = mass of the storing material (kg),

$C_{ps}$  =

Specific heat of solid phase J/(Kg. K),  $C_{pl}$  = Specific heat of liquid phase J/(Kg. K),  $f$  = melt fraction,

$\nabla q$  = latent heat of fusion (J/kg).

The term "phase change materials" refers to the substances that are utilized in the storage mediums of latent heat storage devices. Substances that undergo phase transitions are known as phase change materials because they either release or absorb energy. While solid to gas and liquid to gas transitions offer a high energy transfer, they are not frequently employed because of the huge volume shift that occurs during phase change. The phase transitions that are most generally used for heating, cooling, and domestic heat and water applications are solid to liquid and solid to solid.

The PCM's chemical bonds dissolve during the phase transition from solid to liquid, which occurs when the temperature hits a critical point. As a result of its endothermic nature, PCM absorbs energy in the form of heat during the phase transition from solid to liquid. In the event that PCM senses a temperature change of critical value when stored, it will begin to melt. From that point on, the temperature doesn't budge until the melting is fully complete. In a phase transition, latent heat is the heat that a PCM stores. One way to quantify latent heat retention is by looking at the energy density. By utilizing sensible heat and latent heat from the exothermic solidification process, the stored energy is once again transported to the crucial area of interest when the temperature begins to decrease as shown in (Fig 2).



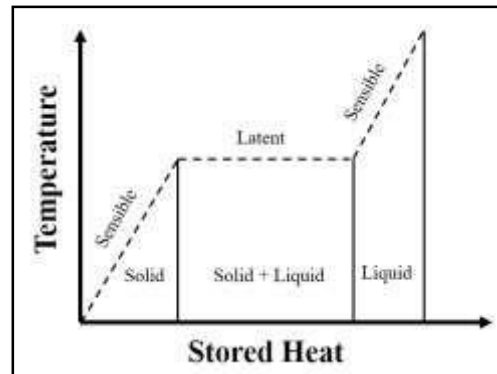


Fig 2. Phase change material temperature vs stored heat for latent heat storage system.

The phase change temperature must be tailored to the specific requirements of each application in order to meet the operational demands of those applications. Temperature range of phase change materials and applications are shown in (Fig 3). There are four main temperature ranges in which PCMs function. When operating in the first temperature range, which is around 20°C to 5°C, PCMs are usually employed for cooling and refrigeration in homes and businesses [22]. In the second temperature range, which is commonly between 5°C and 40°C, PCMs are used for heating and cooling purposes in buildings [23]. For solar-based heating, hot water production[24-25],and electrical applications, PCMs in the third temperature range (+40 °C to +80 °C) are often employed. In the final temperature range, which extends from +80 °C to +1200 °C, PCMs find usage in absorption cooling, wasteheat recovery, and concentrated solar applications [26].

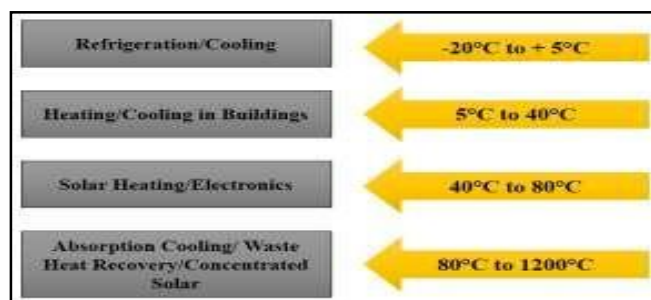


Fig 3. Temperature range of phase change materials and applications.

## 2.1. Required Properties of Phase change materials

For thermal storage system design, the PCM should have the desired thermophysical, kinetic, and chemical characteristics.

### 2.1.1. Thermo physical properties

1. Optimal melting point within the targeted operational temperature range
2. Large amount of latent heat of fusion per volume.
3. High specific heat to facilitate enormous sensible heat storage.



4. Highly conductive to heat in both solid and liquid states.
5. Variations in volume during phase transition and variations in vapour pressure at operating temperatures are negligible,
6. Keeping the material's storage capacity constant throughout each freezing and melting cycle requires phase transition materials to melt precisely at the same rate.

### 2.1.2. Kinetic properties

1. In order to prevent the liquid phase from becoming too cooled, a high nucleation rate is required.
2. In order for the system to be able to accomplish the requirements of heat recovery from the storage system, a high rate of crystal development is required.

### 2.1.3. Chemical Properties

1. The stability of chemicals.
2. Finish a cycle of reversible freezing and melting.
3. A high number of freeze-thaw cycles does not cause deterioration.
4. Low cost and non-corrosive to building materials.
5. To ensure safety, the materials must not be poisonous, combustible, or explosive.

### 2.1.4. Material characteristics

1. The unit size should be small.
2. Desired low vapour pressure.

### 2.1.5. Economic characteristics

1. Cheap and large availability.

## 2.2. Selection criteria for phase change material in solar cooker application.

1. Installation in a solar cooker necessitates temperatures between 60°C and 120°C, thus it must have critical temperatures within this range.
2. The amount of PCM needed can be reduced if it can obtain a high latent heat of fusion per unit mass.
3. An extremely high specific temperature is required of PCM in order to provide optimal sensible heat retention.
4. In order to shorten the time it takes to charge and discharge, PCM materials need to have good thermal conductivity.
5. During phase transitions, it should have tiny shrinkage coefficients and minimal volumetric expansion.

## 2.3. Difficulty with Materials Exhibiting Latent Heat

Properties such as thermo-physical, including melting point, specific heat, latent heat of fusion, and thermal conductivity, are the main considerations when choosing latent thermal materials. Yet, the number of repetitive procedures that do not alter material characteristics and the useful life of the PCM-container configuration are the essential criteria that restrict the utilization of latent heat storage. As a result, the limited use of LHS (Latent





Heat Storage) is due to the fact that it must endure for a long time.

#### 2.4. Challenges in Using PCM Material in Solar Cookers

1. The use of PCM increases the overall weight of the solar cooker by 10 kg, making it less portable.
2. It makes installing a solar cooker more expensive.
3. It is a difficult and laborious process to empty or replenish the PCM storage tank.
4. The presence of PCM increases the stored heat within the box, making it imperative to wear gloves when handling pots.
5. For real-world use, certain thermal energy storage have extremely low stability and lifetime.

For underdeveloped nations, cooking is a major energy consumer. Most modern stoves in cities run on kerosene or liquid petroleum gas (LPG), but in more remote places, people utilize non-commercial fuels like wood, cow dung, or agricultural waste. The world's problems with finite fuel sources and carbon dioxide emissions may find a solution with solar cookers. In order to make solar cookers a mainstream alternative to conventional stoves, further studies are required. A decrease in carbon dioxide emissions and an increase in the usage of renewable energy sources are two ways in which solar cookers may benefit the environment. Some societal prerequisites, in addition to economic and performance constraints, are necessary for full commercialization and widespread use [29-31]. Additionally, solar cookers have the drawback of being ineffective on overcast days or throughout the night, rendering them useless. For this reason, solar cookers need heat storage capabilities to get around these problems and make them work even when the sun isn't shining. To make solar cookers a reality and ready for commercialization, phase change materials research and marketing campaigns are required [32].

To prepare meals in the evenings using just solar energy and the concept of latent heat storage, Junlong Zou et.al. [33] developed and evaluated a solar cooker. An absorbing plate was set underneath a thermal energy storage substance composed of commercial-grade stearic acid, which has a melting point of 55 °C and a latent heat of fusion of 161 kJ/kg. Discharging a PCM at night resulted in a slower heat transfer rate, making dinner preparation more laborious. The effect of various types of glazing on the efficiency of a box solar cooker operating without a load was studied by Battocchio C et. al. [34]. A single-glazed low-e antimony indium oxide coating showed promise for residential application, according to their findings.

For a box-type solar cooker to be utilized when the sun isn't shining, Celestino Rodrigues Ruivo et. al. [35] investigated PCMs using magnesium nitrate hexahydrate ( $Mg(NO_3)_2 \cdot 6H_2O$ ) as the heat storage medium. For a hot box solar cooker that may be used at night or in the evening, Atul A. Sagade et al. [36] created a cylinder-shaped PCM storage unit with commercial grade erythritol ( $T_m = 118$  °C). Their investigation proved that the solar cooker's performance throughout the day was unaffected by storing solar energy. They recommended a melting point range of 105–110 °C for PCMs while cooking in the evening.

Atul A. Sagade et al. [37] created an indirect solar cooker design with a flat plate solar collector, external elliptical heat pipes, and an inside PCM thermal storage. The sun rays were focused on the collector using two reflectors, while the indoor cooking unit utilized PCM composed of magnesium nitrate hexahydrate (134 kJ/kg,  $T_m = 89$  °C). The reflector facing north and south resulted in a 24% daily increase in incoming



solar energy on the collecting surface. Experiments were done with and without loads, and with various loads at various loading periods. We analyzed the pros and cons of using solar cookers for daytime cooking and overnight/early morning warming. When cooking in the evening, the ideal melting point range for PCM is 105°C to 110 °C [38].

An evacuated tube solar collector (ETSC) with PCM storage was also studied by Celestino RodriguesRuivo et al. [39] for use in a solar energy cooker. The device was created with solar energy gathering and cooking components that were later linked with a PCM storage unit. Using commercial-grade erythritol, the solar energy was stored as latent heat and then released for use in night time cooking. Throughout the day, we tested various loading durations and loads in our cooking trials, all the while experimenting with PCM storing methods. It was discovered that cooking in the evening with PCM heat storage takes less time than cooking in the middle of the day without it, and that the two cooking sessions do not depend on each other.

### 3. New development of solar cookers

With working fluid that possesses superior thermal and chemical qualities, it is feasible to harvest the majority of the solar energy that is accessible. Increasing the thermal performance of solar units is accomplished by the utilization of nano fluids.

#### 3.1. Role of Nano fluid

The utilization of nanofluids in the process of solar energy harvesting has discovered a considerable number of applications in the ongoing development of solar energy systems. The incorporation of nanoparticles into the base fluid has been demonstrated to be an effective method for improving the aforementioned characteristics of liquid [40]. A combination of nanoparticles that are spread throughout the base liquid is referred to as a nanofluid. When compared to the base fluid, it has a thermal conductivity that is significantly greater. Some researchers described the difficulties that occurred throughout the process of using nanotechnology in solar product applications. It was determined that the most significant challenges come from the instability of the nanoparticles suspension as well as the difficulties in the manufacturing of nanofluids.

In order to determine how various heat transfer fluids affected the energy and exergy efficiency of a novel indirect solar cooker, R.K. Sharma et. al. [41] conducted experimental investigations. Thermal oil and three nanofluids derived from thermal oil—SiO<sub>2</sub>-oil, TiO<sub>2</sub>-oil, and SiC-oil—with a weight percentage of 0.5 wt% each—are the heat transfer fluids used in the study. This study also assesses the efficiency of the indirect solar cooker's two primary components—the cooking unit and the solar collector—from an exergy and energy saving perspective. Compared to when using thermal oil in the indirect solar cooker, the time it takes to boil 2 liter of water is reduced by around 17 minutes, or 23.29%, when using SiC-oil nanofluid. Incorporating SiO<sub>2</sub>-oil, TiO<sub>2</sub>-oil, or SiC-oil nanofluid into the system improves the solar cooker's total energy efficiency by 1.17%, 3.54%, and 4.27% points, in comparison to thermal oil, respectively. A few illustrative instances are mentioned in Table 3, however there are many more nanofluid recorded in recent literature.



Table 3, Application of nanofluid in solar cookers [58-68]

**4. Current issues and challenges related to phase change material**

**4.1. Problems associated with producing the new PCMs for use in conditions with low**

Type of the Solar Cooker	Type of nanofluid	Results	[Ref.]
Box type solar cooker	Al <sub>2</sub> O <sub>3</sub>	A 0.2% weight fraction resulted in a 28% improvement in efficiency.	[42]
Parabolic Cooker	Multi-walled carbon nanotubes	Reduced collector efficiency was observed at a weight fraction of 0.2%.	[43]
Tube type solar cooker	Al <sub>2</sub> O <sub>3</sub>	Nanofluids have a 7% improvement in thermal conductivity and a 25% improvement in the convective heat transfer coefficient.	[44]
Concentrating cooker	TiO <sub>2</sub>	There was a 2.6% to 7% improvement in solar collector efficiency when compared to using the base fluid.	[45]
Panel cooker	SiO <sub>2</sub>	An 8% improvement in thermal efficiency was achieved with a 1% content.	[46]
Box cooker	CuO, TiO <sub>2</sub> , SiO <sub>2</sub> , and Al <sub>2</sub> O <sub>3</sub>	Improved thermal efficiency is achieved by reducing specific heat while increasing nanofluid density. Because of this, CuO is the optimal choice for achieving peak efficiency.	[47]
Indirect concentrating cooker	CuO/Oil	Compared to oil as the basis fluid, CuO/Oil nanofluid has better absorption.	[48]
Panel cooker	Al <sub>2</sub> O <sub>3</sub> / Synthetic oil	The distortion of the absorber reduces as the concentration of the particle size increases.	[49]
Parabolic, cookers	Cu/H <sub>2</sub> O	Thermal efficiency improves for both collectors as absorbed radiation rises.	[50]
Box cooker	Multi-walled carbon nanotube/water	Using nanofluid instead of the base fluid improved the collector's efficiency by nearly 4%.	[51]
Panel cooker	Single-walled carbon nanotube	A higher mass flow rate is associated with an improvement in efficiency, as is an increase in the volume fraction of nanoparticles.	[52]

**temperatures.**

There are a number of issues with TES systems, including energy-efficient buildings, central air conditioning, solar PV, thermo regulating fibers, temperature-adapted greenhouses, and solar thermal energy storage. One of the main problems is the lack of data on the PCMs' long-term thermal cycle performance, particularly in low-temperature applications. Scientific interest in this area has grown substantially over the past few decades due to the need to create affordable PCMs with a high latent heat of fusion for use in biomedical and other solar thermal applications at low temperatures (between 15°C and 30°C). Markets should have no trouble supplying such resources. Binary and ternary PCM manufacturing and availability are affected by the compounding cost and the cost of the constituent materials.

**4.2. The PCMs' thermal stability over the long period and associated issues.**

Since PCMs do not possess the desired thermophysical characteristics, their commercialization as LHS



systems has not been successful. A big problem with PCMs is that there is no data available on how the thermos-physical characteristics change because of the long temperature cycles. Phase segregation, incongruent melting, impurities, chemical alteration, new compound synthesis, moisture absorption, and other difficulties can lead to variations in thermophysical characteristics. Multiple heat cycles may cause the PCMs to deteriorate. No PCM is ideal if its thermophysical characteristics deviate significantly. Reliability of the PCM is defined as the degree to which its physical, chemical, and thermal characteristics remain unchanged following a battery of thermal cycle tests. Even after undergoing several temperature cycles, its qualities, such as melting point and latent heat of fusion, shouldn't degrade. Thermodynamic properties of a phase change material (PCM) include a melting point and a latent heat of fusion that are stable across a large number of thermal cycles.

### 4.3. Problems dealing with improving the thermo physical characteristics of PCMs

Low heat conductivity is a big problem with PCMs. The thermal conductivity of salt hydrates is typically 0.4 to 0.7 W/mK, while that of organic PCMs is typically 0.15 to 0.3 W/mK [53]. This irregularity manifests as temperature decreases in several areas during the energy withdrawal or retrieval process as a result of the poor thermal conductivity. This causes the phase transition process (solidification/melting) to occur at an undesirable rate. Simply put, the system is unable to utilize the energy at the desired pace, even if it is accessible to it. When it comes to the thermal system's overall performance, the PCM's improved thermal conductivity is crucial. Adding nanoparticles (nanopowders, nanowires, nanotubes), impregnation, or fin structures are a few of the several methods that might improve the thermal conductivity of the basic PCM. Improving thermal conductivity speeds up the PCM's melting rate, hence this is crucial. Nanoparticles raise the solidification point and decrease the beginning melting. The use of nanoparticles shortens the melting time and makes the basic PCM more thermally uniform. There is evidence that nanoparticle addition increases PCM dynamic viscosity, which mitigates convective heat transfer. The use of nanoparticles increases stability with respect to the melting/solidification cycle, which is another readily apparent benefit. Metals, oxides, and carbon-based compounds make up the bulk of nanoparticles utilized in energy-related applications.

## 5. Conclusion

A comprehensive analysis of phase change materials for solar cooking has covered a lot of ground in terms of its coverage. To have a solid understanding of the value of PCMs as elements is of the utmost significance. Not a single component is excellent in every aspect. Along similar segments, paraffin is not without drawbacks, the most significant of which being the fact that it has an exceptionally low level of thermal conductivity. It is necessary to combine phase change materials with other nanofluid in order to improve the thermal storage capabilities of each of these materials. Several nanofluids have been studied in depth, with their benefits and drawbacks have been analyzed and discussed in detailed. There is a tabulation that has been done that shows the impact that nanofluid, in addition to some of the significant phase change materials, have on the thermal energy storage. As a result, comprehensive research on a wide range of elements is performed. In conclusion has been held on the numerous structural uses of phase change material in the context of the thermal energy storage sectors, as well as their growth prospects and limits. The authors believe this comprehensive study on



phase change materials and their applications is beneficial to future researchers and prepares the way for developments in this field on account of the fact that these issues have been explored to a larger extent.

### Declaration of Competing Interest

None.

### Data availability

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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