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Role of Phase Change Materials in Solar Cooking for Thermal Energy Storage Applications: A Review

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Abstract- Using a solar cooker to prepare food will fill a huge need in the transition to renewable energy. Solar cookers may be categorized into four main types: panel, box, parabolic, and tube. Solar cookers come in several forms, but the most common is the box type, which is also the most popular. The main problem with solar cookers is that they don't work during the day since the sun doesn't shine as brightly. However, this disadvantage may be eliminated by using thermal storage materials like Phase-change Material (PCM). Solar cookers have come a long way in the last quarter of a century, with several new versions featuring enhanced reflectors, cooking pots, and glazing coatings. Recent improvements to solar cookers have added the ability to store thermal energy. A range of sensible and latent heat materials were used to encapsulate the storage tanks and pots. This research focuses on several PCM types that have the potential to be used as thermal storage materials (TSM) in solar cookers. A variety of PCMs that can be utilized as thermal storage materials [TSMs] in solar cooking are reviewed here, along with other thermal storage materials. The research proved that organic heat storage materials are practical. Eutectic PCM has the benefit of combining the characteristics of both organic and inorganic PCMs, and there are less limitations when employing them. The material compatibility of the storage container and the operating temperature range of the PCM limit its application. This study reviews and discusses solar cookers using PCM to shed light on the characteristics of a PCM that are advantageous for solar cookers.

Keywords. Thermal energy storage, Sensible thermal energy storage, Phase change materials, NanoFluid, Solar cooking

Introduction

Energy from natural phenomena, such as the sun, wind, tides, and waves, is becoming more developed and will continue to do so in the years to come. Nevertheless, most of these resources are transitory in character due to intensity fluctuations caused by various climatic and environmental factors [1]. Solar power and thermal energy are reportedly being used more and more on a huge basis. It gets more difficult to use solar power since its primary drawback is that it is intermittent. The availability of waste heat and the periods of usage are not always the same, which creates similar issues in heat recovery systems [2]. Power usage changes drastically between the hours of daylight and nightfall. Consequently, energy storage during sunshine hours is necessary, with the energy being supplied either at night or when weather conditions are cloudy. Throughout the phase change process, the Phase Change Material (PCM) latently stores thermal energy. You can use this as a means to store energy that is currently available and then use it when the sun doesn't shine [3]. Paraffin wax is a commonly used

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phase change material (PCM) for latent heat energy storage due to its transparency and ease of availability before, during, and after melting. Due to its poor thermal conductivity, paraffin wax requires long charging and discharging times to store energy [4-5].

One of the most promising forms of renewable energy is the usage of solar thermal energy. There are significant limitations to the development of solar collectors that operate at medium and low temperatures, despite the fact that they have the advantages of having a simple structure and a low cost. Increased usage of solar energy may be accomplished in a number of key ways, one of which is through the employment of thermal energy storage systems (TES) to improve solar thermal efficiency. For a solar thermal system, the incorporation of TES would be highly beneficial since it would increase the system's flexibility, which would in turn speed up the system's commercial uses [6-7].

Through the use of a solar cooker, solar radiation may be harvested for the purpose of cooking. In addition to lowering the need for traditional sources of energy, solar cooking has the potential to be a sustainable solution for cleaner manufacturing at the same time. When compared to other cooking appliances and the fuel that they use, solar cookers are more cost-effective and, in many instances, a more desirable option. Despite this, there are a few drawbacks associated with them, including the following: (i) a lack of social acceptance [8-10], (ii) slower cooking than other techniques [11], (iii) not being accessible all the time [12], and (iv) the requirement for additional cooking gear [13]. The most current developments in solar cooking technology are discussed in this article. This article provides the summary of previous research avctivities that was carried out in the field of phase change material (PCM) as thermal energy storage (TES) based on the utilization of a variety of phase change materials (PCMs) and the technique of study that was taken into consideration for the application of solar cooker.

Role of Phase Change Materials and its importance

Recently, there has been an increase in the amount of research attention and emphasis placed on the utilization of PCMs in the context of energy efficiency. Many studies have been conducted to investigate the theories, designs, and analyses of PCMs for the purpose of storing latent heat [14]. These are some of the classifications, kinds, and procedures that will be addressed in the next paragraphs. PCMs may be divided into four distinct categories, and these categories are solid-solid, solid-liquid, solid-gas, and liquid-gas. These categories are determined by the phase shift that they undergo. The act of cooking is one of the primary contributors to the amount of energy that is consumed in underdeveloped nations. Kerosene and liquid petroleum gas (LPG) are the sources of energy that are used for contemporary cooking techniques in urban regions [15]. On the other hand, traditional fuels such as firewood, cow dung, and agricultural waste are utilized in rural areas. There is a possibility that solar cookers might be the solution to global problems such as limited fuel sources and emissions of carbon dioxide [16].

To effectively commercialize solar cookers as a viable substitute for conventional cooking equipment, therefore, there is a need for more research activities. Solar cookers have the potential to have a beneficial effect on the environment by lowering the amount of carbon dioxide emissions into the atmosphere and contributing to a reduction in the reliance on fossil fuels. The parameters of cost and performance are not the only ones that must be met in order for anything to be completely marketed and extensively utilized [17-18]. Certain societal factors must also be necessary. Additionally, the utilization of solar cookers is restricted in the sense that they may only be utilized in situations that are clear and sunny. They are not useable on days that are cloudy or during the nighttime hours. In order to circumvent these constraints and impracticalities during the hours when the sun is not shining, solar cookers need to have the capacity to retain heat. In India, where there is a significant amount of solar radiation, there is a considerable potential for the practical application of solar cookers [19]. On the other hand, the fundamental cause for the underutilization of solar radiation-based cooking solutions is the problem of irregular or restricted supply of solar radiation. This disadvantage can be mitigated by the utilization of energy storage technologies.

Using the concept of storing latent heat as a way of heating meals in the late evening, Mulu Bayray Kahsay et.al. [20] built and tested a solar-powered cooker. A thermal energy storage substance that was composed of commercial grade stearic acid was put underneath the absorbent plate. This material had a melting point of 55 degrees Celsius and a latent heat of fusion of 161 kilojoules per kilogram. It was more difficult to prepare food in the evening because the rate of heat transfer during PCM discharge was slow, and it took longer to cook food. During the time when the sun is not shining, Chauhan et al. [21] conducted research on the exploitation of PCMs by employing magnesium nitrate hexahydrate ($Mg(NO_3)_2.6H_2O$) as the heat storage medium for a box-type solar cooker. The researchers Battocchio C et al. [22] developed a PCM storage unit in the form of a cylinder for a hot box solar cooker that uses commercial grade erythritol with a temperature of 118°C. This unit is intended to be utilized for the purpose of preparing meals in the evening or during the overnight hours. There was no discernible impact on the efficiency of the solar cooker during the daytime hours, as demonstrated by the findings of their trial. The PCM range of melting temperature should be between 105°C and 110°C for evening cooking, according to their

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recommendation. Xabier Apaolaza-Pagoaga et.al. [23] proposed a unique box-type cooker that was modified in a research that was published not too long ago. In order to accommodate the various cooking utensils, the cooker was designed in an inclined layout and had three shelves. When compared to conventional box cookers, they said that their cooker is capable of absorbing anywhere from 16% to 54% more solar thermal energy. During the performance testing of the cooker, they also revealed that it is capable of reaching temperatures of up to 100°C and 80°C, respectively, with and without booster mirrors. Following is a comprehensive analysis of the most current developments on solar cookers that make use of phase change materials are shown in Table 1.

Table 1. Various types of PCM tested in solar cookers for thermal energy storage applications [24-39].

Author [Year]	**PCM type**	**PCM melting pont**	**Solar Cooker Type**	**References**
Mohamad Aramesh et al.	RT54HC	53-54 °C	Panel cooker	[24]
Chauhan, Kartikey et al.	2 PCMs, not specified	70 °C- 15 °C	Box type solar cooker	[25]
Yunsheng Zhao et al	Mixed organic PCM	5 °C	Parabolic cooker	[26]
B.C. Anilkumar et al.	Erythritol Composite PCM (3%wt EG and 97%wt erythritol)	119 °C	Box type	[27]
Balachandran, Selvaraj et al.	Stearic acid	57-60 °C	Tube type solar cooker	[28]
G. Palanikumar et al	SA-67	67.10 °C	Panel solar cooker	[29]
Shravan Kumar Yadav et al.	Paraffin wax	54-57 °C	Box type solar cooker	[30]
Xabier Apaolaza-Pagoaga et al.	Sugar alcohols Erythritol D-Mannitol	 117.7 °C 166 °C	Box type solar cooker	[31]
Rahul Khatri et.al.	eutectic mixture 60% KNO3 + 40% NaNO3	210-220 °C	Tube type	[32]
I. Atmane et.al.	Stearic acid	55	Box type solar cooker	[33]
Mohammad Hosseinzadeh et.al.	Acetanilde	85	Panel cooker	[34]
M.S. Abd-Elhady et. al.	Magnesium nitrate hexahydrate	89	Panel cooker	[35]
G. Palanikumar et.al.	$MgCl_2 6H_2O$	116.7	Box type solar cooker	[36]
Hitesh Panchal et. al.	Acetanilide	118	Parabolic cooker	[37]
Nisrin Abdelal et.al.	Paraffin	100	Parabolic cooker	[38]
Martin Osei et.al.	Salt hydrates 60% NaNO3+ 40% NO3	217 °C	Parabolic cooker	[39]

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When it comes to solar cookers, the primary purpose of thermal storage is to enable the device to continue cooking even when the sun is not there [40]. Additionally, heat storage components are typically included in the design of indirect cookers [41]. However, direct cookers are also capable of having components that are capable of thermal storage [42]. Certain cookers have distinct units for thermal storage and cooking, while others have separate units for both [43]. In certain cookers, the thermal storage and cooking units are the same. On the basis of the thermal storage method, solar cookers may be classified into two distinct categories: latent heat thermal energy storage (LHTES) and sensible heat thermal energy storage (SHTES) [44-46]. While heat is absorbed and then released during a phase-change time in the LHTES type, heat is removed and absorbed in the SHTES type by heating and cooling a material [47]. The LHTES type absorbs heat and then releases it during the phase-change period. A better performance is achieved with the use of the LHTES technology. On the other hand, the SHTES approach only results in a smaller quantity of energy storage, despite the fact that it is more cost-effective than the LHTES [48-49]. Without regard to the cost, the latent heat that is generated by the melting of materials that is utilized in the LHTES approach is significantly larger than the coefficient of specific heat that is utilized in the SHTES model [50]. As a result, the heat storage capacity in the phase-change process is significantly higher. Table 2, provides a summary of examined research, including those not included in earlier sections, to help readers so studies are arranged chronologically, and SC stands for solar cooker. Following is a comprehensive analysis of the studies on the improvement of the solar cooking technology are shown in Table 2.

Table 2**.** A summary of the studies on the improvement of the solar cooking technology [51-73]

Authors (published year)	**Brief title**	**Cooker type**	**Focused Feature**	**Highlights**	**References**
K. Kant et.al.	Evaluation of three concentrating SCs	Concentrating cooker	Performance	Comparison between three cookers for different foods	[51]
R. Jain et. al.	Design of a box SC with Insulation	Box cooker	Performance and economy	Investigating the performance and the economics of using a double reflector box SC with a transparent insulation	[52]
Misra, Navendu et. al.	SC with finned cooking vessel	Box cooker	Performance	Investigation of the effectiveness of using finned cooking vessel	[53]
Lentswe K et.al.	Energy and exergy efficiencies comparison of paraboloidal cookers	Indirect concentrating cooker	Performance	Presenting and evaluation of a domestic-size and a community-size cooker	[54]
Sunil Indora et. al.	Energy and exergy analyses of a charging storage system	Indirect concentrating cooker with thermal storage	Performance	Presenting a high efficiency concentrating cooker with a packed oil pebble bed as the thermal storage unit	[55]
K. Kant et.al.	Design of a truncated SC	Box cooker	Performance and economy	Construction of a high performance SC which is more viable than electric and LPG cookers	[56]
A. Shukla et.al.	Investigation of a light funnel cooker	Panel cooker	Performance	Presenting a novel design by using a light funnel as the SC	[57]
Hongzhi Cui et.al.	A cooker with	Concentrating	Performance	Presenting and	[58]

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	two axes tracking system	cooker		evaluation of a design with an automatic two axes tracking system	
Gulsavin Guruprasad Engoor et.al.	A box-type SC with asymmetric compound parabolic mirror	Box cooker	Performance and social acceptance	Construction of an insulated cooker with parabolic reflectors with the ability to be integrated into a wall	[59]
Gianluca Coccia et.al.	A vacuum tube SC	Indirect concentrating cooker	Performance	Presenting and evaluating an improved novel design of an indirect SC with vacuum tube	[60]
Giovanni Di Nicola et.al.	Thermal analysis of a SC with several pots	Box cooker	Performance	Testing the cooker efficiency with different number of pots	[61]
Alireza Gorjian et.al.	Comparison of thermal storage oils for SCs	SC conditions simulated	Thermal oil charging performance	Comparison the performance of the Sunflower, Shell Thermia B, and Shell Thermia C oils in the charging step by simulating solar insolation	[62]
E.A. Padonou et.al.	Impact of loads on the energy and exegy of a SC	Indirect concentrating cooker	Performance	Investigating the effects of the ambient temperature and water load amount, on the energy and exergy efficiencies of a vacuum tube based cooker	[63]
Abhishek Saxena et.al.	Testing a small hybrid SC	Box cooker	Performance	Improving the performance of the cooker by integrating with five PV panels	[64]
Solomon Tibebu et.al.	CFD analysis of double walled SC	Indirect trough cooker with thermal storage	Performance	Construction and evaluation of an indirect trough collector with an innovative double walled pot filled with PCM	[65]
H Terres et.al.	Evaluating optimum load range	Box cooker	Performance	Finding the optimum range of water load to get the maximum performance	[66]
Katlego Lentswe et.al.	Innovative portable SC using packaging wastes	Panel cooker	Performance	Investigating the performance of different designs of SCs constructed by the packaging wastes	[67]
Katlego Lentswe et.al.	Design and evaluation of a conical SC	Panel cooker	Performance	Comparison of the performance of a conical cooker with	[68]

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				and without Glazing	
Mohamad Aramesh et.al.	Analysis of SC User Needs	Parabolic, and panel cookers	social acceptance	Studying the reasons for the low acceptance of SCs in Austria and Thailand	[69]
Hafiz Abdullah Zafar et.al.	Manufacturing a high concentration SC	Box cooker	Performance	Investigating the performance of a novel box cooker with high concentration ratio using booster mirrors	[70]
Matteo V. Rocco et.al.	Characterization of parabolic SC	Parabolic cooker	Performance	Performance assessment of a low cost commercial cooker with modifications in the materials	[71]
Gulsavin Guruprasad Engoor et.al.	Community solar cooking in India	Direct and indirect parabolic cookers	Performance and economy	Economic and performance assessment of two commercial cookers with the aim of institutional cooking	[72]
C. Veerakumar et.al.	Solar thermal storage cooking	Parabolic cooker	Performance	Testing the capabilities of a commercial parabolic SC while using a double walled pot with thermal storage	[73]

Figure 1, shows that PCM may be categorized according to their chemical structure, which can be either organic, inorganic, or eutectic. Inorganic PCM comprises salt and metallic hydrates, whereas organic PCM comprises paraffin and non-paraffin. The kinds of PCM that make up eutectic PCM range from inorganic to organic, inorganic to organic, and inorganic to organic [74].

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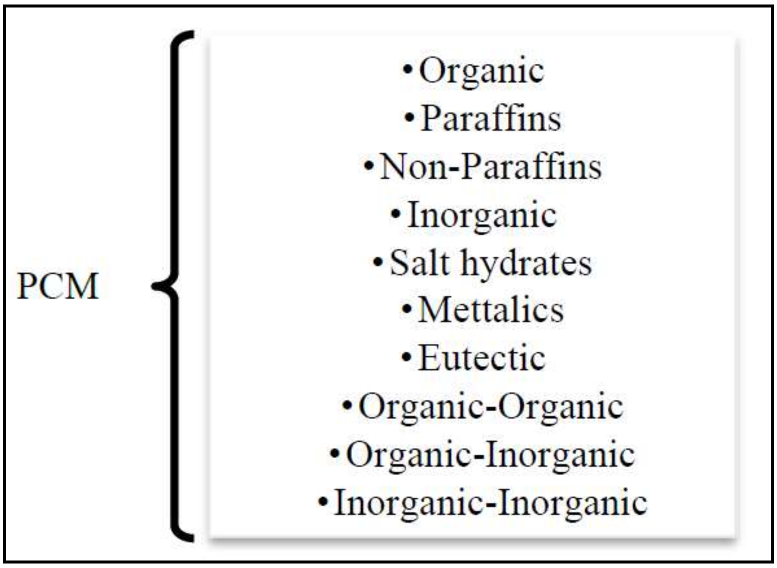

Figure 1. Classification of PCMs according to their chemical structures [75].

Paraffin (C2 H2n+n), lipids, and sugar alcohols are organic PCMs. Without supercoiling, organic PCM freezes. They melt similar. Common building materials work with organic PCMs. The chemical stability and non-reactivity of these materials make them advantageous for use [76]. In general, organic PCMs exhibit phase transition temperatures between -5 and 190 °C. Organic PCM lags behind because to poor thermal conductivity, leading to increased heat transfer rates during liquid-to-solid phase progression. Compared to other inorganic PCMs, its volumes of latent heat storage are minimal [75].

Inorganic PCMs are MxNyH2O, salt hydrates. An inorganic PCM has a significant advantage in its large volumetric latent heat storage capacity. Many inorganic PCMs have strong heat conductivity and abrupt melting points. Most inorganic PCMs are reasonably priced and easily available. The repetitive process of phase separation in inorganic PCMs results in significant loss of latent thermal enthalpy. Typically, inorganic PCMs have a phase change temperature range of -50 to 175 °C. Most building metals may be corroded by water or oxygen in their chemical structure. Solid-liquid phase change can cause supercoiling, which should be addressed during container design for PCM storage [76].

Any combination of polycyclic macromolecules (PCMs), whether organic or inorganic, is considered a eutectic mixture. A high volumetric storage density and a sharp melting point characterize it. Due to the lack of accessible data, an experimental approach will be necessary when utilizing a eutectic combination [77]. Binary eutectics allow for the incorporation of several fatty acids into TES systems with varying melting points, allowing for adaptation to a wide range of climates. Depending on the two mixed materials used, the phase change temperature range for eutectic mixture PCMs can be anywhere from -5 °C to 225 °C [78]. In order to verify the TES system's longevity, it is necessary to conduct thermal cycle health tests on the material's thermal characteristics and thermal reliability, regardless of whether it is eutectic or pure PCM.

Properties of phase change materials

The qualities of PCM are crucial in choosing PCM for cooking with solar energy. Table 3, lists the various PCM material parameters that must be met in order for them to be employed as thermal energy storage in solar cooking [79].

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Table 3, lists the various PCM material parameters that must be met in order for them to be employed as thermal energy storage in solar cooking

Sr. No	Types of Properties	Properties
1.	Thermophysical properties	1. There is a set range of melting temperatures. 2. A high latent heat of fusion per unit volume. 3. High specific heat to provide more sensible and useable storage. 4. High heat conductivity in the liquid and solid states. 5. A tiny change in volume during the transition and a tiny change in vapor pressure at operating temperatures. 6. Appropriate PCM melting and freezing for a material storage capacity that includes both processes. 7. Temperature that changes phases and is suitable for use. 8. Latent energy should be high to reduce the size of the heat storage container. 9. Have a high specific heat. 10. A defined transition temperature that was specified. 11. During a shift, there should be a lot of density. 12. A tiny change in volume when phases change. 13. A high level of thermal conductivity is desirable.
2.	Kinetic properties	1. A high crystal growth rate that permits the system to meet the needs of heat recovery from the material. 2. A high nucleation rate to avoid supercooling in the liquid phase. 3. During the freezing process, the undercooling crystallization rate should be more than adequate.
3.	Chemical properties	1. Completely reversible for cycles of melting and freezing; 2. Chemical stability throughout the operating temperature. 3. There is either no degradation or very little even after several working cycles. 4. Non-noxious, non-corrosive, non-combustible, and non-detonative material; • Non-corrosive behavior with the storage manufacturing material. 5. Excellent stability in terms of chemicals.
4.	Material characteristics	1. The unit size ought to be compact. 2. Low vapor pressure is desired.
5.	Economic characteristics	Affordable and widely available.

Selection Criteria of phase change material for a basic Solar Cooker

It is important to consider both the qualities and requirements of PCM while choosing one for a solar cooker. Below are some of the requirements:

1. Critical temperatures within the necessary operating temperature range (60 °C to 120 °C for solar cooker installation) should be met
2. PCM should have a high specific temperature to maximize sensible heat retention.
3. PCM materials should have high thermal conductivity to reduce charging and discharge duration.
4. It should acquire a high latent heat of fusion per unit mass to lessen the amount of PCM required.
5. It should have minimal or no cooling during solidification.
6. It should have small volumetric expansion and shrinking coefficients for phase changes.
7. It should be chemically stable and non-corrosive for the storage containers.
8. It should also be non-toxic, non-flammable, or non-explosive.
9. It should be easily accessible at a reasonable price to enhance cost optimization and mass production.

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Problems associate with latent heat materials

The selection of materials with latent heat is mainly determined by thermophysical parameters, which include specific heat, latent heat of fusion, melting point, and thermal conductivity. The number of repeating procedures without altering the material's properties and the setup's valuable life of the PCM-container, however, are the crucial factors restricting the usage of latent heat storage. Thus, the requirement that LHS (Latent Heat Storage) last for a lengthy period of time is the issue that limits its utilization. [80].

Problems with usage of phase change materials in Solar Cooker

The usage of PCMs in the solar cooker brings to light some of its drawbacks. Typical problems with PCM use include the Following:

1. The mass of the solar cooker overall improves due to the use of PCM, which makes it less removable.
2. The overall price of a solar cooker setup grows.
3. Removing or refilling PCM from its storage tank is a difficult and labor-intensive task.
4. The presence of PCM causes an increase in heat trapped inside the box, necessitating the use of gloves when handling pots.
5. The stability and lifecycle of some TES are very low for practical applications.

Applications

A lot of work has gone into creating a latent energy thermal system for solar systems, where heat needs to be stored during the day for use at night. Due to their low thermal conductivity, which reduces heat transfer rate, many PCMs are impractical for their intended uses. Thus, it is important to incorporate PCM in a way that prevents a large drop in heat transfer rates during phase transition processes. Plate-type heat exchangers and other tiny, flat containers are typical PCM components. By incorporating PCM into tiny plastic components, the rate of heat transmission was significantly increased and a full bed storage unit was formed. Significantly high temperatures are achieved by phase change with direct heat transfer utilizing hydrated salt. For solar energy to be used efficiently in a structure, thermal energy must be stored. An additional benefit for solar cooking is offered by PCM storage. One naturally occurring form of solar energy storage is solar ponds. A natural process that transforms solar energy into different forms of energy is called photosynthesis. Like other uses, PCM will accumulate energy during the day and during the sun's rays. This energy can then be used during the night and during the absence of sunlight. In particular, latent heat is presented as a superior TES option for solar cooking. Another important point to consider is where the PCM is placed in the solar cooker arrangement. Co-cylindering the outside cover of the vessel allows for the filling of the empty space with PCM, which serves as a single layer of energy transmission from PCM to food in the solar cooking vessel. The base of the solar cooker, which houses the solar cooking containers, is another location where PCM Materials might be kept.

In the sun cooking vessel, however, there will be a two-layer transmission of energy from PCM to food in this arrangement. This disadvantage can be overcome by positioning the solar cooking pot and creating holes that match the vessel's size based on cost.

Conclusion

The following concepts can be used to wrap up this review paper:

1. Most salts are usable in the hydrated form, which limits the type of material used for storage tanks for TES.
2. Organic PCMs generally have a low melting point, but it is short-range to cook food.
3. The number of thermal cycles is higher when low or medium temperature range phase change materials are used compared to high temperature range PCM.
4. Thermal storage materials are a viable option for better utilization of solar energy as they provide easy, convenient, and practical application of energy storage.
5. A sound approach is necessary in the field of solar cooking to encourage its use and affordability.
6. Stearic acid and paraffin wax are frequently used due to their easy availability and financially viable options.
7. Sunflower oil and many other edible oils also act as valuable materials for TES.

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