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# An Appraisal of Phase Change Materials: Characteristics, Categorization, Benefits, Drawbacks and Utilizations. A Review

Bilyaminu Musa[1*], Salisu Nasir[1], Mustapha Balarabe Idris[1], Yahaya Abdullahi Muhammad[2], Nasiru Muhammad[2], Ma'aruf Nuhu[3].

[1]Department of Chemistry,
Federal University Dutse,
P.M.B. 7156, Dutse, Jigawa State;
Nigeria.

[2]Department of Chemistry,
Jigawa State College of Education Gumel,
P.M.B 1002, Gumel,
Jigawa State;
Nigeria.

[3]Department of Chemistry,
Jigawa State College of Remedial and Advanced Studies Babura,
P.M.B 2020, Babura,
Jigawa State,
Nigeria.

## Abstract

*A new era of energy-efficient solutions has arrived thanks to the revolutionary class of substances known as phase change materials (PCMs), which have the extraordinary capacity to store and release thermal energy during phase transitions. The defining characteristics of PCMs, such as their well-defined melting and freezing temperatures, high latent heat of fusion, and variety of material types, including organic and inorganic PCMs, as well as eutectic combinations, are thoroughly examined in this thoroughly analysis. PCMs are divided into groups according to the physical shape they take and the temperature range in which they are used. These groups include low-temperature variations, high-temperature variants, encapsulated forms, and nanocomposite forms. PCMs provide a wide range of advantages, including effective thermal energy storage, cost-effective energy use, consistent temperature maintenance and small light designs. However, they do have some restrictions, such as compatibility issues and slow heat transfer rates. However, PCMs are used in a wide range of industries, from electronics and renewable energy to building and construction, revolutionizing temperature control, thermal management and energy efficiency. The future of PCM technology offers promise, with ongoing improvements aiming at improving heat transmission, integrating with renewable energy sources and enhancing encapsulation processes. This technology's vital position in a sustainable and efficient energy future is apparent, as it continues to transform our world in the hunt for responsible and green energy solutions.*

**Keywords:** Phase change materials (PCMs); thermal energy storage (TES); latent heat; nanocomposite; thermal conductivity.

*Author for Correspondence*

## INTRODUCTION

Energy is a crucial element required for socioeconomic development in our modern society. World's modernity, urbanization, industrialization and population growth have all increased the need for energy for a variety of daily activities. More than 80% of the world's carbon emissions originate in urban areas, and more than one-third of all fossil fuel generated worldwide is consumed there (Vince, 2013). The rapid increase in global energy use has led to serious issues like environmental degradation and the depletion of fossil fuels.

Statistics show that between 2012 and 2040, global energy consumption would increase by 48% as reported by International Energy Outlook; U.S. Energy Information Administration in 2016. Energy policy makers and experts are closely monitoring the building sector because it accounts for about 30% of all global energy usage (Dong *et al*., 2016; Cui *et al*., 2014).

Due to quick economic expansion and high standards of living, the world is forced to utilize a lot of conventional energy resources (fossil fuels), which contribute to environmental pollution and climate change (Nasir *et al*., 2019). Moreover, the reliance on traditional energy sources will cause supplies to run out more quickly. As a result, energy efficiency has suddenly become a major problem. To improve energy efficiency, various renewable energy technologies, such as the thermal energy storage (TES) system, were developed. TES is the medium utilized to temporarily store energy for use. It offers practical solutions to improve the effectiveness of managing and utilizing energy. This attractive energy technology can be employed in many different industries, especially the building industry (Jankowski and McCluskey, 2014; Memon *et al.,* 2015; Zang et al., 2012).

Switching from fossil fuel energy to diverse renewable energy sources, including solar, wind, and hydro energy, is primarily motivated by the greenhouse effect. Popular renewable sources for producing electricity and storing thermal energy include solar energy (TES). According to comparison research on global energy consumption published by the International Energy Agency, solar array installations will meet around 45% of the demand for energy globally in 2050 (Mekhilef *et al.,* 2011). TES's capacity to address energy shortages and lessen pollution is expanding quickly (Liu *et al*., 2017). One of the most promising methods for TES is the use of phase change material (PCM) (Al-Hinti *et al*., 2010). With a modest temperature change during phase, PCM can store heat energy due to its high latent heat. To conserve energy for later usage, reduce reliance on fossil fuels, and lower greenhouse gas emissions into the atmosphere, efficient and affordable energy storage devices must be created (Dincer & Rosen, 2021).

Phase change materials (PCMs) are a developed substance that can be crucial in improving efficient energy operations, control, and use. This material is known as thermal energy storage (TES).

## PHASE CHANGE MATERIALS

Materials that undergo phase changes are ones that, as they melt and solidify, both absorb and release thermal energy, or heat. They acquire their name from the fact that, throughout the process of heat cycling, they alternate between a solid and a liquid form. When temperatures drop at night, phase-change materials (PCMs) generate energy and convert it from a liquid to a solid. They also serve as energy stores, converting stored energy from solid to liquid over the day. Because PCMs are so effective at storing and dispersing large amounts of thermal energy with very small and partial temperature changes, thermal energy storage can profit from their application (Zhao *et al*., 2010).

Figure 1: Image of n-octadecane PCM

The materials that exploit the latent heat of phase transition to minimize temperature within a peculiar range are called phase change materials. The chemical bonds within the materials begin to break when the temperature increases to some specific level, and they will absorb heat endothermically from where the transition from solid to liquid takes place. With the fall in temperature, the materials release energy and return to the solid phase. The energy used to affect the state of the materials, given that the state transition temperature is near the desired core room temperature, will lead to a much more stable and comfortable indoor climate, as well as cut peak cooling and heating loads (Baetens *et al.*, 2010).

Due to the energy crisis and environmental concerns, phase change materials (PCMs), which have the ability to absorb, store, or release significant amounts of latent heat within a defined temperature range, have received more and more attention in recent years (Li *et al.,* 2011). With their high energy storage density and restricted operating temperature range, PCMs, such as n-alkanes, fatty acids, and fatty acid esters, have found widespread use in energy-efficient buildings heat transfer mediums (Sari et al., 2009), solar energy storage (Zeng *et al.,* 2013), waste heat recovery, and smart textiles (Sánchez-Silva *et al.,* 2010).

**PROPERTIES OF PHASE CHANGE MATERIALS (PCMS)**

The perfect PCM should fulfil a number of requirements, including thermo-physical, kinetic, and chemical properties, as reported by Waqas (2013). The temperature for a phase transition, higher latent heat, because PCMs have a high latent heat of fusion, they can store large amounts of energy without experiencing a significant change in temperature elevated specific heat, and high fusion heat are the thermal characteristics of phase change materials. Low vapour pressure at the operating temperature, appealing phase equilibrium, reliable PCM melting, a modest volume transition during phase conversion, and high density are some of the physical properties. The chemical properties are long-lasting chemical stability and simplicity of contact with the container without making it harmful, poisonous, polluting, flammable, or explosive. And the economic properties include a lower cost of acquisition, being easily accessible in great quantity, and that recycling and treatment are easier.

PCMs change from their solid to their liquid states, absorbing or releasing latent heat in the process. They have clearly defined melting and freezing points, which determine the temperature range in which they may operate.

## WORKING PRINCIPLES OF PCMs

Figure 2 illustrates the solid-liquid PCMs' operation. In summary, solid phase change materials (PCMs) first store thermal energy as sensible heat when exposed to heat. The temperature rises in direct proportion to the PCMs' stored thermal energy, reaching the PCM melting point. At this point, thermal energy is stored as melting latent heat, solid PCMs begin to melt and turn liquid, and PCMs stay in the melting temperature range without changing temperature. Over time, all of the heat that is produced is stored inside PCMs. The temperature then rises as a result of more heat absorption, and the melted PCMs once again store thermal energy as perceptible heat. Conversely, when liquid PCMs begin to fall below the freezing point of PCMs, the melting PCMs solidify and release almost an equivalent amount of latent heat (crystallization enthalpy). The temperature can be stabilized by applying the latent heat from melting or crystallization. Unfortunately, when pure PCMs go through a solid-liquid phase transition, they typically leak; hence, in practical applications, encapsulation is necessary (Wang *et al.*, 2022).

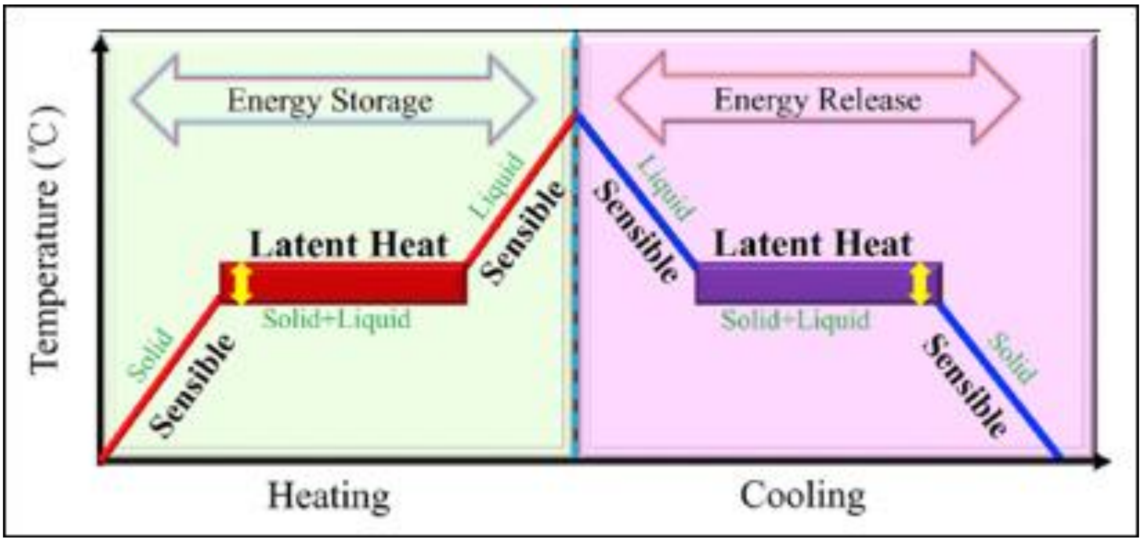


Figure 2: The Working Principle of Solid-Liquid PCMs (Chen, 2020).

## CLASSIFICATION OF PHASE CHANGE MATERIALS

Chemical composition, type of phase transition, application of temperature range and the physical are the characteristics that can be used to classify phase change materials. According to (Sharma et al., 2009) (Zalba et al, 2003) PCMs are categorized depending on their chemical makeup and type of phase change.

## CLASSIFICATION BASED ON CHEMICAL COMPOSITION OF MATERIALS

These PCMs fall into three categories organic (paraffin and non-paraffin), inorganic (metal salts and salt hydrates), and eutectic blends (organic-organic, inorganic-inorganic and inorganic-organic). Organic PCMs can be made from substances found in nature or synthetically.

Examples include fatty acids, sugar alcohols like erythritol, and paraffins (alkanes). This is the class of PCMs that have melting temperatures ranging between 0 °C and about 200 °C. Due to the covalent bonds present in organic PCMs, most of them are not stable at higher temperatures. The density of organic PCMs is smaller when compared to that of inorganic materials, i.e., smaller than 103 $kg/m^3$ (Fleischer, 2015). Organic PCMs are further classified into paraffin and non-paraffin.

They are commonly used as a means of storing thermal heat, particularly for the preservation of energy in buildings, because of their nontoxicity in nature, high thermal energy storage capacities, and good thermal stability, in addition to other applications such as transportation, solar energy systems, thermal insulation, and textiles (Khudhair & Farid, 2004). Within organic PCMs family, alcohols are categorized as solid-solid organic PCMs (Zhang & Yang, 1990). Fatty acids, PEGs, and Paraffins are categorized as solid-liquid organic PCMs.

Paraffin: The typical formula for paraffin is $CnH_{2n+2}$. They are straight-chain saturated compounds with a wide range of phase transition temperatures and a melting temperature between 23 and 67 °C (Rathod and Banerjee, 2013).

The most widely used commercial organic PCM for thermal energy storage is paraffin wax, whose volume increases by around 10% when it melts. They do not dissolve in water, and they do not interact chemically with the majority of chemical reagents (Fleischer, 2015). The materials are environmentally friendly and non-toxic (Zalba *et al*., 2003).

The figure below are properties of paraffin derived from phase change materials adapted from (Hale, Hoover, & Oneill, 1971).

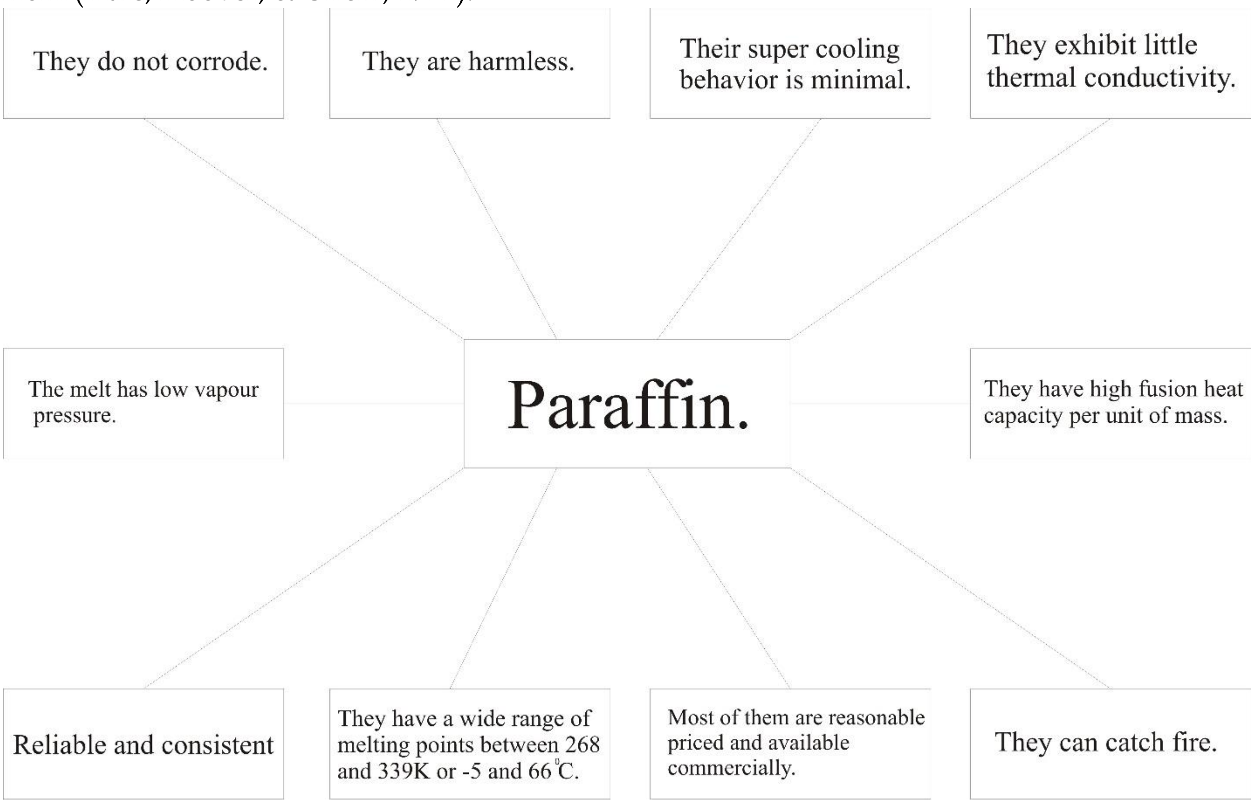


**Figure 3:** Properties of paraffin

The researchers have found non paraffin group of PCMs to be particularly useful and targeted. Fatty acids and other non-paraffin organic compounds such as alcohols, esters, glycols, etc. are also categories for the materials. Because they are readily available at adequate state transition temperatures and have a high heat of fusion, fatty acids are the most active PCMs of all non-paraffinic compounds in their class. Animal oils and simple vegetables can be used to produce fatty acids, which have the chemical formula $CH_3(CH_2)_{2n}COOH$ (Sarı and Kaygusuz, 2003).

The thermal characteristics of fatty acids (capric, lauric, palmitic, and stearic acids) and their binary combinations were examined. According to the results, they make good candidates for latent heat and thermal energy storage in space heating applications. Fatty acids were discovered to have a melting range that ranged from 30 to 65 $^0$C and a latent heat of transition that ranged from 153 to 182 kJ/kg. When creating a latent heat thermal energy storage system, these characteristics are crucial (Feldman *et al.*, 1989).

**Inorganic PCMs:** These are usually metals and salts, such as pure metals like gallium sodium nitrate potassium nitrate, and salts like sodium hydrated sulphate dehydrate. A wide range of temperatures is also available for inorganic materials. When compared to organic materials, inorganic materials typically have a similar latent heat of fusion per mass. However, because of their high density, the latent heat of fusion per volume is larger. Salt hydrates and metallic PCMs are members of the inorganic material family.

The salt hydrates are the oldest class of PCMs. The inorganic salt family's oxides, carbonates, sulphates, and nitrates are combined in a specific ratio with water molecules to form salt hydrates. Salt hydrates have the chemical formula AB. $nH_2O$ (salt compound). The three-dimensional structure of salt hydrates is sufficiently open to allow water molecules to enter and move about within the crystal lattice.

Since 1952, researchers have explored glauber salt ($Na_2SO_4.$ $H_2O$), which comprises 44% $Na_2SO_4$ and 56% $H_2O$ by weight (Telkes,1952). One of the least expensive materials that can be used for thermal energy storage, it has a melting point of around 32.4 $^0$C, a high latent heat of 254 kJ/kg (377 MJ/m$^3$), and a melting temperature. However, its implementation has been constrained by issues with phase segregation and sub cooling. Salt hydrate materials have a high storage density, which is challenging to maintain and typically drops with cycling. This is due to the fact that the majority of hydrated salts melt concurrently with the development of the lower hydrated salt, rendering the process irreversible and causing a steady fall in their storage efficiency.

**Eutectic PCMs**

A congruent mixture of two or more components known as a eutectic melt and solidifies as a single compound. The eutectic PCM may consist of two or more compounds made of organic, inorganic, or both types of components. During crystallization, the combination of these compounds creates a crystal. They simultaneously melt and freeze to form a closeknit combination of crystals without separation (Lane, 1989). The price of these compounds is their main drawback. Compared to organic or inorganic PCMs, they are two to three times more expensive.

**Classification based on type of phase transition of materials:**

**Low Temperature PCMs**: These are suited for applications like refrigeration and cold storage since they undergo phase change at temperatures lower than room temperature (usually -20°C to 10°C).

**Medium-Temperature PCMs**: These are suited for applications in building thermal management and climate control since they undergo phase shift between room temperature (10°C and 40°C).

**High-Temperature PCMs:** These can be used for solar energy storage and industrial activities since they undergo phase change at temperatures above room temperature (40 °C to 100°C or higher).

**Classification based on Application Temperature Range and Physical Form:** Phase change materials can also be classified based on application temperature range and physical form.

**Application Temperature Range:** Depending on the temperature range that PCMs are intended to operate in, they are divided in to low-temperature e.g. paraffin wax and Bees wax. Medium-temperature which include Glauber's salt (Sodium Sulphate Decahydrate) and Calcium Chloride Hexahydrate, and high-temperature varieties. Some fatty acid esters, such as capric/caprylic triglyceride and some salt hydrates, like magnesium chloride hexahydrate are typical examples.

**Physical Form:** There are several different physical forms of PCMs. Casings that include encapsulated PCMs make it simple to integrate them into current products or systems. Microencapsulated PCMs use microscale encapsulation to increase stability and effectiveness. Nanoparticles are used in nanocomposite PCMs to enhance heat conductivity and overall performance.

**Table 1: Review on some nanoparticles used in nanocomposite PCMs**

| S/N | NANO PARTICLES | USES | REFERENCES |
|---|---|---|---|
| 1 | Carbon Nanotube | Multi-walled carbon nanotubes (MWCNTs) and single-walled carbon nanotubes (SWCNTs) are used to improve thermal conductivity in nanocomposite PCMs | (Sari *et al.*, 2009) |
| 2 | Graphene Nano platelets (GNPs) | Adding graphene Nano platelets to PCMs can significantly enhance their thermal conductivity. | (Zhao *et al.*, 2010) |
| 3 | Silver Nanoparticles | Silver nanoparticles are known for their high thermal conductivity. They can be dispersed in PCMs to improve their heat transfer properties | (Dong *et al.*, 2016) |
| 4 | Aluminium Nanoparticles | Aluminium nanoparticles can be used in nanocomposite PCMs to enhance thermal conductivity | (Liu *et al.*, 2017) |
| 5 | Titanium Dioxide ($TiO_2$) Nanoparticles | $TiO_2$ nanoparticles can enhance the thermal properties of PCMs, including thermal conductivity | (Abdelasalam *et al.*, 2020). |
| 6 | Zinc Oxide (ZnO) Nanoparticles | ZnO nanoparticles are used to improve the thermal conductivity of PCMs in nanocomposite form | (Liu *et al.*, 2017) |
| 7 | Silicon Dioxide (SiO2) Nanoparticles | $SiO_2$ nanoparticles can be incorporated into PCMs to improve their thermal performance. | (Zhang *et al.*, 2012) |
| 8 | Copper Nanoparticles | Copper nanoparticles are also effective in enhancing the thermal conductivity of PCMs | (Dong *et al.*, 2016) |
| 9 | Boron Nitride Nanotubes (BNNTs) | BNNTs are known for their excellent thermal conductivity and can be incorporated into PCMs to enhance heat transfer | (Yang., 2017) |
| 10 | Magnesium Oxide (MgO) Nanoparticles | MgO nanoparticles can be used to enhance the thermal properties of PCMs. | (Zhang *et al.*, 2012) |

## STABILITY TEST OF PCM

The repetition of storage cycles may cause the PCMs to deteriorate. Any PCM should avoid significant thermophysical property degradation over time. A PCM is said to be trustworthy if it remains thermally, chemically, and physically stable after numerous thermal cycles of operation. After numerous thermal cycles, it retains its original properties, including latent heat and melting point. If a PCM guarantees minimal change in the melting point and latent heat of fusion after a significant number of thermal cycles of operation, it is thermally stable for latent heat storage applications.

Due to their wide availability and inexpensive cost, commercial grade PCMs are favoured for latent heat storage systems. Therefore, PCMs should undergo a thermal stability test before being used in actual applications. The production, leakage, thermal conductivity, and thermal storage characteristics of PCMs are all well covered in the prior literature. However, it has been discovered that the reports on the thermal stability and/or dependability of PCMs are comparatively insufficient. Lists of PCMs for which thermal cycling tests were performed by various researchers and published in the literature are presented by (Rathod *et al*., 2013) also provides a list of various PCMs tested for thermal cycling. Along with the tools and analytical settings in which the experiments were run, they also emphasize the approaches employed by the various researchers.

## ADVANTAGES AND LIMITATIONS OF PHASE CHANGE MATERIALS

### Advantages of phase change materials

Numerous and significant benefits are provided by PCMs; they include the following:
One of the main advantages of PCMs is their remarkable capacity to store and release thermal energy. Phase change materials have high energy storage capacity and latent heat of fusion, environmentally friendly and are readily available. For applications needing precise temperature regulation, this characteristic is important. PCMs provide a substantial contribution to improving energy efficiency. They can save energy by lowering the demand for active heating or cooling by utilizing their latent heat storage capacities. Phase change materials can also have an advantage in temperature fluctuation reduction, by absorbing excess heat and releasing it when temperatures decrease, PCMs assist maintain stable conditions in places that are sensitive to temperature swings, such as electronics and data centres. Space and Weight Savings is another benefit of phase change materials, PCMs enable compact designs and lower total system weight when integrated into thermal energy storage systems.

**Limitations of Phase Change Materials:** Although PCMs provide several advantages, there are some drawbacks as well:
**Slow Heat Transfer:** When compared to direct conduction, the rate of heat transfer during the phase shift process may be slower. The rate at which energy is stored or released may be constrained by this feature.
**Subcooling and supercooling:** PCMs may undergo Subcooling, in which they remain solid below their freezing point, or supercooling, in which they remain in the liquid state below their nominal melting point. The predictability of their conduct may be impacted by these impacts.
**Compatibility Problems:** Some PCMs might not work with specific materials, which could restrict the range of things they can be used for.
**Cost Considerations:** Particularly in applications with stringent financial restrictions, the cost of PCM materials and their integration into systems can be of issue.
**Poor Conductivity**: Although PCMs outperform other TES technologies in many ways, their fundamental disadvantage is their poor thermal conductivity, which in the solid-state ranges from roughly 0.2 W/(mK) to 0.7 W/(mK) for organic PCMs and from roughly 0.6 W/(mK) to

1.3 W/(mK) for inorganic PCMs and for salt hydrates, between 0.4 and 0.7 W/mK (Zalba *et al*., 2003)
The practical possibilities of a wide range of implementations are constrained by the limited thermal conductivity of PCMs. A group of prospective PCMs or metal alloys with comparatively high thermal conductivities ought to be mentioned nonetheless (Fernandez *et al*.,2017). During energy retrieval or withdrawal, the effect of the lower conductivity value is reduced with a noticeable temperature reduction. As a result, the pace of PCM melting and solidification has not been as rapid as anticipated. In other words, even if there is enough energy, the system might not be able to use it at the required rate. Paraffin's' low heat conductivity (about 0.2 W/mK), relatively substantial volume change, and potential for flammability are disadvantages as compared to other PCMs (Zhou *et al*., 2012). These drawbacks have been addressed with the methods that have been provided by adding materials with high heat conductivity and fire-retardant additives, as described in the literature (Cabeza *et al*., 2011).

The poor nucleation rates of inorganic salts, which result in super-cooling, and their corrosive properties, both of which impair the stability of the PCM and its supporting system, are significant drawbacks (Zhou *et al*., 2012). Nucleating agents are added to prevent super-cooling, and PCM is placed in a thin layer to promote stability (Cabeza *et al*., 2011). The current problem with eutectic mixes is the scarcity of thermo-physical information. It is possible to determine the full potential of eutectic mixtures with a better understanding of these features.

## APPLICATIONS OF PHASE CHANGE MATERIALS

The PCMs should first be chosen based on their melting temperature in accordance with the applications. In air conditioning applications, materials that melt below 15°C are employed to store coolness, while those that melt beyond 90°C are used for absorption refrigeration. Applications for solar heating and heat load levelling can be made with any additional materials that melt between these two temperatures. These substances represent the class of substances that has been investigated the most.

**Building and construction:** PCMs help with passive heating and cooling systems, improve insulation, and lower overall energy consumption in this industry, maintaining thermal comfort in buildings by incorporating PCMs into floors, walls, or ceilings (Mathis *et al*, 2018). n-Nonadecane/cement composites have been described by (Li *et al*., 2010) as thermal energy storage materials (TESM) for use in construction. Even when heated above the melting temperature of n-nonadecane, leakage of melted nonadecane from the composites can be avoided because the nonadecane is evenly distributed throughout the porous network of cement by surface tension and capillary forces. The n-nonadecane/cement composites can be employed in structures frequently and have good thermal stability.
The topic of PCM technology for thermal energy storage in the built environment has also been examined (Whiffen and Riffat, 2013). A variety of PCMs have been tested in the vicinity of the indoor comfort temperature; organic PCMs particularly paraffins seem to be the most viable due to their long-term stability, while inorganics are hindered by toxicity and undesired sub-cooling.

When PCMs are included in building components, the structure's energy efficiency can be greatly increased. This is mainly because temperature modulation in hot and cold regions reduces energy consumption and shifts the electrical load. To enable PCM to be replenished daily for usage the following day, it is necessary to carefully select PCM so that daytime temperatures are above the melting point and nighttime temperatures are below the freezing point (Shah *et al*., 2022).

Phase-change materials has been reported to improve the properties of concrete used in construction (Berardi *et al*., 2019). The reduction in mechanical strength and workability of the PCM-concrete composite limits the amount of microencapsulated PCM that can be added to concrete. The maximum amount of microencapsulated PCM that can be added to concrete without compromising workability is limited to 6% of the total weight of the concrete.

**Electronics:** By effectively dispersing excess heat and reducing overheating in electronic equipment, PCMs are integrated into heat sinks and spreaders, resulting in increased performance and durability (Ganatra *et al*., 2018).
Phase-change materials have applications in photonics and electronics as investigated by (Colla et al., 2017). Data sets must be successively moved between the CPU, several memory and storage units, and bandwidth-constrained, energy-inefficient interconnects for each calculation, which usually results in a 40% power loss. By enabling non-volatile memory devices that can optimize the intricate memory hierarchy and neuro-inspired computing devices that can combine computation and storage in memory cells, phase-change materials (PCMs) hold out enormous promise for removing this bottleneck.

**Textiles & apparel:** By incorporating PCMs into fabrics, it is possible to make clothing that regulates body temperature and is comfortable in a variety of climates (Iqbal and Sun, 2014). Iqbal et al., (2019) conducted research on the available organic and inorganic PCMs, their characterization, their incorporation into Fiber, and their application as pads on textiles with real-world applications in the field of smart textiles. PCM has been used in clothing to provide a thermoregulating effect, reducing clothing's thermal discomfort. The assimilation of thermal energy by PCM leads to a significant reduction in skin moisture release and a delay in the microclimate temperature rising, which inhibits heat stress situations and improves thermo-physiological wearing comfort (Prajapati and Kandasubramanian, 2020). Phase-change materials have just joined the textile industry with the goal of improving clothing's thermal comfort. PCMs can give clothing exceptional qualities in such harsh applications as diving suits, skin wear, and undergarments. Their insulating qualities might shield the wearer from potentially lethal situations (Erkan and Apparel, 2004).

**Medical and pharmaceutical industries:** Substances known as phase-change materials (PCMs) have the capacity to both store and release significant amounts of thermal energy when they melt and solidify. Because of this special quality, they are valued in many industries, including pharmaceuticals and medicals, where exact temperature control is essential for the storage and transportation of goods that are sensitive to temperature, such as biological samples, drugs, and vaccinations. PCMs are utilized in the storage of pharmaceuticals and temperature-sensitive medical equipment (Lv *et al*., 2011). Throughout the cold chain, PCMs are essential to preserving the integrity of medications and medical supplies that are sensitive to temperature. Manufacturers can guarantee that items stay within the necessary temperature range during transportation and storage by adding PCMs to packaging materials or storage units. This is especially important for biologics and vaccines, as they might lose their effectiveness when exposed to temperature changes Giannola, De Caro, Sutera, and Therapy (2015).

Pharmaceutical items can be reliably kept effective and of high quality with PCM-based packaging solutions. These packaging options can include anything from specialized shipping boxes made to sustain a particular temperature range for a lengthy amount of time to insulated containers with PCM inserts. These kinds of advancements lessen the chance of product deterioration during transportation and help prevent temperature excursions (Fashandi, 2017). PCMs are used in temperature-regulated medication delivery devices in the fields of medical devices and drug delivery systems. These gadgets use PCMs to regulate medicine release in response to variations in body temperature. For example, PCM-based patches or implants provide a more effective and focused therapeutic strategy by delivering medications locally at a controlled rate (Kenisarin *et al*., 2007).

Additionally, PCMs are used in cryopreservation procedures to preserve biological materials such as tissues, cells, and samples. The viability of biological materials that have been kept is ensured, and cellular damage is prevented by PCMs through the maintenance of a steady temperature environment during cycles of freezing and thawing. Applications including organ transplantation, stem cell therapy, and biomedical research depend on this (Nie *et al*., 2020).

In the medical and pharmaceutical sectors, PCMs provide adaptable temperature control solutions that tackle issues with product stability, transportation, and storage. Stakeholders in these sectors can improve the productivity, dependability, and safety of their operations and products by taking advantage of the special thermal features of PCMs.

**Renewable Energy:** PCMs are crucial components in solar thermal systems, which use them to continuously generate energy by storing and releasing heat (Siahkamari *et al*., 2019).

Other applications of phase change materials include; storing thermal energy from waste heat (Li *et al*., 2019), domestic hot water systems (Abdelsalam *et al*., 2020), managing the temperature of batteries (Jiang and Qu, 2019), enhancing the effectiveness of air conditioners (Said and Hassan, 2018), in the food factory (Alehosseini and Jafari, 2019) and many other areas (Magendran *et al.,* 2019).

## FUTURE PROSPECTS AND INNOVATIONS OF PHASE CHANGE MATERIALS

A number of significant advancements are anticipated for PCM technology in the future, including:

**Accelerated Energy Storage and Release:** Current research attempts to accelerate the energy storage and release during the phase transition process, broadening their applicability.

**Renewable Energy Integration:** By incorporating PCMs into renewable energy systems like solar and wind power, we can improve our ability to store energy and further the development of sustainable energy sources. Solar energy is utilizing in diverse thermal storage applications around the world. To store renewable energy, superior thermal properties of advanced materials such as phase change materials are essentially required to enhance maximum utilization of solar energy and for improvement of energy and exergy efficiency of the solar absorbing system. PCM in solar water heating system for buildings particularly in India because 20–30% of electricity is used for hot water in urban households, residential and institutional buildings.

**Better Encapsulation Techniques:** Innovations in encapsulation methods are pursued to address challenges related to compatibility, leakage and long-term stability, making PCMs more reliable and versatile.

## CONCLUSION

Because of their exceptional capacity to absorb, store, and release substantial amounts of thermal energy during phase transitions, phase change materials (PCMs) have great potential for a wide range of applications. They are perfect for thermal management and energy storage solutions because of their high latent heat capacity and capacity to keep a steady temperature during phase shifts, which have been highlighted in this appraisal.

The four phase transition kinds of PCMs are solid-solid, liquid-gas, solid-solid, and solid-solid. Solid-liquid PCMs are the most commonly utilized form because of their large energy storage capacity and useful temperature range. Materials like organic, inorganic, and eutectic PCMs fall under these groups, and each has unique benefits and drawbacks. For instance, organic PCMs are chemically stable and non-corrosive, but they frequently have inferior heat conductivity. Similar to salts, inorganic PCMs generally have better energy storage densities and thermal conductivities, but they can also have problems with phase segregation and supercooling.

The use of PCMs has numerous advantages. By streamlining heating and cooling procedures, they can greatly increase the effectiveness of thermal energy storage systems, support energy conservation, and lower greenhouse gas emissions. They are used in solar energy systems, electronic device cooling, building temperature control, and industrial waste heat recovery, among other things.

PCMs are not without disadvantages, either. It is necessary to solve challenges such as high material costs, low heat conductivity, and problems with long-term stability and material compatibility. Moreover, PCM encapsulation, which is necessary for practical implementation, can increase costs and complexity. Notwithstanding these obstacles, continued study and technical developments are gradually removing them, opening the door for a wider application of PCM. Novel approaches to improving performance and economy of scale include composite PCMs, microencapsulation and improved material synthesis.

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