MEDICINAL APPLICATIONS OF PHASE CHANGE MATERIALS

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CANDIDATE'S DECLARATION

I, Varsha, (24/MSCCHE/50), declare that the work reported in the dissertation entitled "**Medicinal applications of Phase Change Materials**" submitted in partial fulfilment of the requirement for award of the Degree of Master of Science in Chemistry to the department of Applied Chemistry, Delhi Technological University, Delhi, for the academic session 2025-2026 is an record of our own research work carried out during the period of study (2025-2026) under the supervision of Dr. Raminder Kaur.

The matter presented in the thesis has not been submitted by us for the award of any other degree of this or any other Institute.

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CERTIFICATE

It is certified that Varsha (24/MSCCHE/50) has done their project work as disclosed in this thesis entitled **"Medicinal applications of Phase Change Materials"** for the partial fulfilment of their degree of Master of Science in Chemistry by Department of Applied Chemistry, Delhi Technological University, Delhi, under my guidance. The dissertation reflects the results of original work, and studies are conducted by the students themselves, and the content of the thesis does not serve as the foundation for awarding any other degree to the candidate or any other body from this or any other University/Institution.

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ABSTRACT

As the world pushes harder for sustainable energy, thermal energy storage (TES) systems-especially phase change materials (PCMs) are slowly becoming a centre of attention. This review explores the latest enhanced phase change materials (EPCMs) designed for high-performance TES. There is an in-depth analysis of how PCMs actually work and the usual problems associated with them like lousy thermal conductivity, leakage, supercooling, and issues with using for over time. This report breaks down different strategies to tackle these problems, from mixing in nano-additives and using smarter encapsulation, to creating shape-stabilized or composite materials. After that this report also tries to enlighten some practical application of PCMs like medicinal applications. In medicinal application PCM helps in temperature-sensitive drug storage and transport, Cryotherapy and Hyperthermia Treatments, temperature-regulated drug delivery and designing various biomedical devices for patient comfort. And to summarise it outlines what still gets in the way and points out where future research should go to get more efficient, affordable, and greener PCM-based storage.

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ABBREVIATION

PCM Phase change materials

TES thermal energy storage

EPCMs enhanced PCMs

LHTS Latent heat thermal storage

NEPCMs Nano-enhanced phase change materials

CHAPTER 1
INTRODUCTION AND LITERATURE SURVEY

Environmental concerns are developing as a result of the rapidly expanding global energy needs and the depletion of fossil resource, researchers are now under pressure to find more effective energy storage methods. Thermal energy storage (TES) devices are one obvious front-runner, where energy is generated from sources like solar, wind etc., TES are useful in balancing the energy storage and utilizing it during the requirements [1], [2]. Latent heat thermal energy storage (LHTES) devices especially phase change materials (PCMs) are unique in the field of TES. The primary benefit of these PCMs is their capacity to store large amounts of energy without experiencing significant temperature fluctuations during melting and freezing [3].

PCMs absorb or release the heat during its reversible phase transition from solid to liquid, but its temperature essentially remains constant. Because of there this unique feature, PCMs are ideal for the applications that requires a steady and regulated temperatures. The reversible melting and solidification processes provides basic operating mechanism of PCMs, during the heating cycle the material used starts to absorbs the spare thermal energy from the surroundings when the temperature rises above the PCM's melting point and the energy that was absorbed is used to break intermolecular interactions and changes the material from a solid state to a liquid state in spite of quickly raising the temperature. Due to this mechanism, PCMs are able to store extra heat. Any extra heat that is applied after the material has completely melted raises the liquid PCM's temperature slowly. On the other hand, the liquid PCM starts to solidify during the cooling cycle when the temperature falls below the required freezing point. The stored latent heat is released back to the environment during that phase transition, by supplying thermal energy and controlling the maintenance of a constant temperature. Their this property makes them way more useful than regular sensible heat storage devices [4].

PCMs has various application from buildings materials to solar panels, cooling electronics devices to storing waste heat. Recently, these materials started to gain attention in medicinal science and healthcare devices, where precise temperature control is essential. So, PCMs are also being studied for vaccine storage, pharmaceutical transportation, thermal management in medical applications, smart drug delivery systems, and also cancer hyperthermia treatment, where controlled heating is required to demolish tumor cells without causing any harm to the

healthy tissues. Their tendency to manage a stable temperature makes them more suitable for biomedical and healthcare applications. But even though PCMs seem to be a major development, they faces various difficulties in regular real life like conventional PCMs usually are unable in speedly transfer of heat, sometimes they divide into layers, due to which they can undergo supercooling or leakage during their continuous melting and freezing, and transfer heat slowly[5]. All these problems affect PCMs efficiency, which creates issue for development of high-performance systems. Recent development show that these problems continue to be the primary cause of PCM-based TES system not being accepted at wider scale[6] .All these issues leads us to the concept of Enhanced Phase Change Materials (EPCMs).

The main idea is to physically or chemically modify PCMs to enhance their heat conduction, to control leakage and to make handling of charge/discharge cycles easier. With all these modifications there was requirement of keeping its old properties like constant temperature and energy storage capacity same. So, the common way to achieve all this was mixing them with highly conductive materials like metal nanoparticles, carbon nanotubes, or graphene. This can generally improve heat transfer in even small scales, fasten up the process of absorbing and releasing energy[7] .Anyhow, it's not always perfect because sometimes the small particles clumps together and makes the PCM more thicker and harder to handle properly[8] .As we focus on their stability and leakage factor, encapsulating PCMs (wrapping them up in shells) helps in holding them in place which makes them to last longer through various heating and cooling cycles[9] .This is the reason there is wide use of Encapsulated PCMs in building materials, heat exchangers, and majorly in biomedical applications such as smart bandages, organ transport systems, and temperature-sensitive pharmaceutical packaging due to their improved stability and safety[10] . Recent progress can also be seen towards shape-stabilized PCMs, where permeable or polymer materials give the PCM extra backbone so that they do not flow or gets deformed, even during the phase change[11]. Researchers are also thinking of all other possible ways as Eutectic PCMs are very helpful in changing melting points and other properties, so finding the suitable material becomes an easy job. Composite PCMs are a mixture of several properties together such as better conductivity, less supercooling, more strength, etc. As the trend of nanotechnology and advanced materials increases, the speed of research based on PCM has really levelled up. Nowadays, digital tools are also a contributing factor in this such

as machine learning and mathematics models help in predicting properties and choosing right formulas even without visiting a lab[12] . All this speeds up material discovery process, helps to cuts costs and also helps to get high-performance PCMs ready for real use.

Little adjustments made at the system level also have a significant impact. The speed at which heat can enter or exit the system is increased by methods such as the use of metal foams, heat pipes, extended surfaces, or layering several PCMs together. When a few of these strategies are combined, they frequently produce even more effective TES systems[13] .EPCMs are accepted widely and are used in buildings materials to reduce energy costs and maintain consistent interior temperatures. In a same way, installing PCMs on walls or ceilings increases comfort and lowers the need for heating or cooling [14]. EPCMs are crucial for thermal storage of renewable energy, particularly concentrated solar energy systems. These cutting-edge materials are now being used for heat control in batteries, electric cars, and electronics.

Despite all of these improvements, there are still some significant obstacles like the price is still heft, increasing productivity is difficult. Environmental effects and long-term dependability cannot be disregarded. Additionally, it is difficult to compare results among studies in the absence of uniform testing protocols, which hinders advancement[15]. Teams from manily all science backgrounds are needed to solve these problems, and everyone is working to provide EPCMs that can be affordable, effective, and long-lasting.

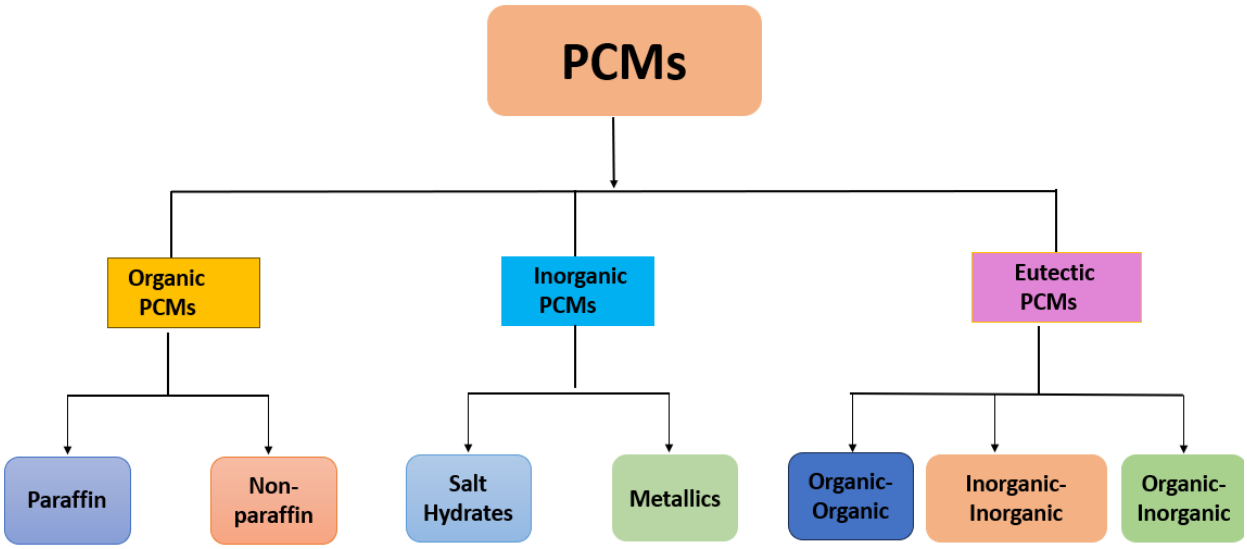
This assessment summarizes our current state of affairs, including everything from the newest and most innovative applications to the best enhancing techniques and cutting-edge material design. We also explore how machine learning is revolutionizing material selection and optimization, as well as system-level enhancements. There is a close look at EPCMs and their applications which are in real world use, and see what still needs to be done to advance these fields, and learn which research avenues are most likely to result in the next significant advancements in reasonably priced, sustainable energy storage.

CHAPTER 2

CLASSIFICATIONS OF PCMs

PCMs are categorized into:

- **Organic PCMs** (paraffins, fatty acids): stable but low conductivity
- **Inorganic PCMs** (salt hydrates): high energy density but phase instability
- **Eutectic PCMs**: tailored melting temperatures[16]



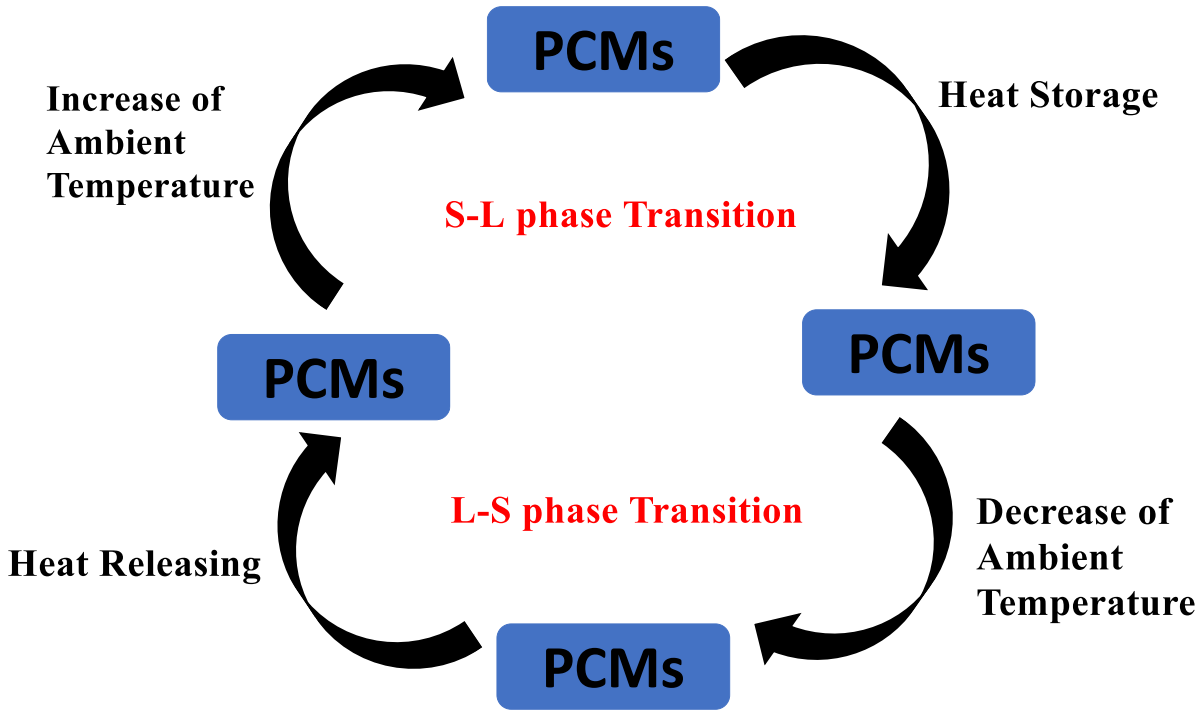
2.1 Organic Phase Change (PCMs)

Organic PCMs are carbon-based substances that mainly use solid-liquid phase transitions to store and release thermal energy. Paraffin waxes (CnH2n+2) and fatty acids (such as lauric acid and stearic acid) are the most commonly utilized organic PCMs[17] .

2.1.1 Mechanism of Operation

As the material's molecular chains reorganize during heating, organic PCMs absorb latent heat and transform from solid to liquid without experiencing a noticeable

temperature change. The substance solidifies and releases stored heat at a temperature that is almost constant while cooling. This characteristic makes it possible for organic PCMs to retain thermal stability over a limited temperature range, which is especially useful for applications including medical thermal management, electronics cooling, and building temperature regulation[1], [18].



The diagram illustrates how the PCM absorbs and releases latent heat during the phase transition while maintaining nearly constant temperature.

2.1.2 Benefits-

1.Chemical Stability: After hundreds of heat cycles, organic PCMs retain their same characteristics.

2.Non-Corrosive: They require less system maintenance because they don't react with common container materials.

3.Congruent Melting: There is no phase separation and the material melts evenly.

4.Broad Melting Temperature Range: Adaptable to certain application conditions.

2.1.3Limitations-

1. Low Thermal Conductivity (~0.2 W/m·K): This slows down the heat transfer, which requires enhancement techniques like nanoparticles, metal foams, or fins[19] .

2.Flammability: as paraffins are flammable, so there should be appropriate encapsulation and precautions are required. As compared to the certain inorganic PCMs, in which moderate latent heat (~150–250 kJ/kg) is lower.

2.1.4 Applications –

Because of their good thermal stability, chemical stability, and their capacity to store and release required amounts of latent heat during phase transitions, organic phase change materials (PCMs) are largely used in various applications. Organic PCMs can be usually seen in building materials for its passive solar heating and cooling in the construction industry. By absorbing extra amount of heat during the day and releasing it later during the night, they help to control indoor temperatures, which enhance thermal comfort, and lowers energy usage. These materials are also used into the textile industry and offers thermal comfort by retaining the body temperatures under shifting environmental circumstances.

Organic PCMs are also commonly used in electronics cooling systems, where they usually absorb and throws away the excess heat generated by the electronic components, that leads to improving the device performance, its efficiency, and lifespan. They also play an important role in medicinal and healthcare applications. In medical storage systems, they are used for temperature-sensitive drugs, vaccines, blood products, and biological samples, as they help in maintaining required temperature ranges during their transportation and storage, ensuring the safety, stability, and effectiveness of these pharmaceutical products.

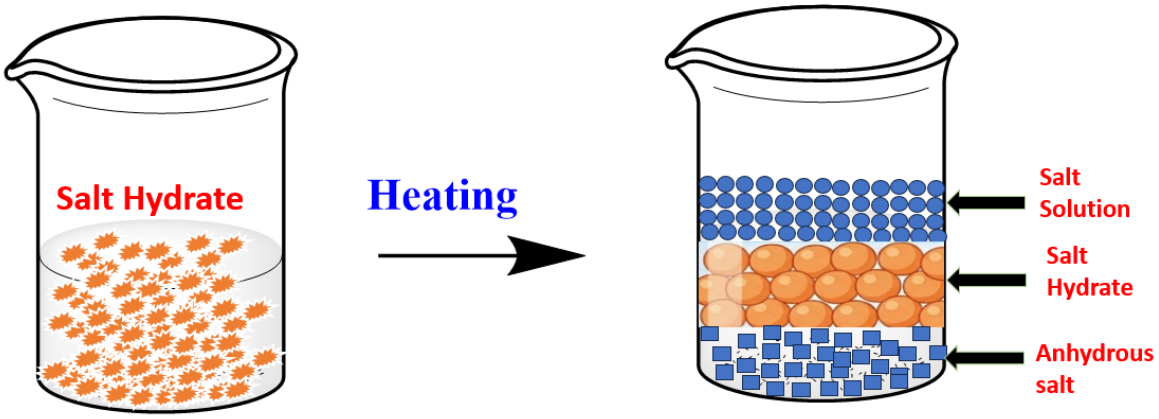
1.2 Inorganic Phase Change Materials (PCMs)

Inorganic PCMs generally includes salt hydrates (for e.g., calcium chloride hexahydrate, $CaCl_2 \cdot 6H_2O$) and metallic materials, which usually stores thermal energy through solid–liquid phase transitions. These materials are largely applied in high-energy-density thermal energy storage (TES) systems, as in industrial waste heat recovery and solar thermal storage[20].

1.2.1 Mechanism of Operation

When there is an addition of water molecules or their removal from the salt lattice during their melting and solidification, the energy is stored as latent heat into the salt hydrates. Strong atomic bonds are timely broken during solid-liquid transitions in metals and metal alloys in respect to absorb the thermal energy. When the material is hard, the stored energy is released, which allows the effective heat transfer at a temperature which is almost constant [21].

Diagram: Phase Separation Issue in Salt Hydrate PCM



This figure illustrates how phase separation during thermal cycling can reduce the effectiveness of inorganic PCMs if not properly stabilized.

1.2.2 Benefits

1.High Latent Heat Storage Capacity: Usually stores more than many organic PCMs, at 200–400 kJ/kg.

2.High Thermal Conductivity: It enhances the rates of its charging and discharging.

3.Non-Flammable: they are considerd safe for high-temperature applications than organic PCMs.

4.Cost-effective: Salt hydrates are typically easily accessible and available at reasonable price.

1.2.3 Limitations:

1.Supercooling: Improper crystallization below their melting point can affect the

efficiency of energy release.

2.Phase Segregation: Salts can separate from the water hydrate with their repeated cycles, decreasing their dependability.

3.Corrosion: Salt hydrates can lead to corrosion of metallic vessels to, which can leads to the use of encapsulation or protective coatings.

4.Limited Thermal Stability: there can be chances of decomposition in high-temperature applications.

To reduce these problems and enhance their long-term performance, encapsulation, additives, or hybridization with supporting matrices are widely used[22] .They are ideal for the large-scale or high-power applications while organic PCMs usually used because of their high energy density and their thermal conductivity.

1.3 Eutectic Phase Change (PCMs)

Eutectic PCMs are mixtures of two or more compounds that melt and solidify at a single, well-defined temperature, known as the eutectic point. These materials combine the advantages of their individual components, providing tailorable thermal properties for specific thermal energy storage (TES) applications[16], [23] .

1.3.1 Mechanism of Operation

They can absorb or release latent heat at a temperature which is almost constant while simultaneously solidifying and melting all of their constituent parts in the eutectic composition. In it there are chances of avoiding the phase segregation, and consistent thermal performance can made possible. By the choice of right component ratios, the melting temperature may be changed, which enables the PCMs to be designed for a number of operating temperatures [24]

1.3.2 Benefits

1.Predictable Melting Point: there is an accurate temperature control of phase shift for their particular uses.

2.No Phase Separation: Eutectic mixes harden uniformly, in contrast to salt hydrates.

3.Customizable Properties: The components can be chosen to attain the required temperature range, latent heat, and thermal conductivity.

4.Temperature Stability: Stable throughout a number of temperature cycles.

1.3.3 Limitations

1.Complex Formulation: A lot of components are carefully chosen and proportioned.

2.Greater Material Costs: In compare to the PCMs which have a single component.

3.Limited Commercial Availability: specially for the specific temperature ranges.

Eutectic PCMs are commonly used in industrial TES systems, solar thermal storage, and thermal management of electronics and batteries, where precise temperature control is very critical[25] .

CHAPTER 3
Enhanced Phase Change Materials (EPCMs)

3.1 Need for Enhancement

Conventional phase change materials (PCMs) store a lot of heat, but when it comes to the real world, PCMs face some serious problems such as they don't conduct heat well, they generally tend to supercool, they can be separated into various phases, and worst of all these is they leak when changing from solid to liquid or vice versa. These problems signifies that heat does not move through them the way it should, so thermal energy storage systems end up wasting energy and working less properly[26]. Most organic PCMs such as paraffin wax have very low thermal conductivity, somewhere between 0.1 and 0.3 W/(m•K), this usually makes them slow to charge and discharge, due to which they are not really useful when fast heat response is required. On the other hand they're unstable and starts to break down if they are charged and discharged too many times, which affects their long-term reliability.

Scientists have researched on this and bring out the concept of enhanced phase change materials (EPCMs), with the help of material engineering tricks to fix all these problems and keeping their high storage capacity same[27]. All these improvements helps to actually make it possible to think about using PCM-based energy storage systems on a larger scale, especially in advanced applications where heat transfer and their durability really matters.

3.2 Enhancement Techniques

There is a large list of enhancement techniques which have been invented to enhance the performance of PCMs. All these techniques firstly focus on enhancing the thermal conductivity, structural stability, and heat transfer efficiency.

3.2.1 Nano-Enhanced PCMs (NEPCMs)

NEPCMs are developed by mixing the high thermal conductivity nanoparticles such as graphene, carbon nanotubes (CNTs), and metal oxides (e.g., Al_2O_3, CuO) into the base PCMs. The presence of these nanoparticles enhances the heat transfer process, which improves the effective thermal conductivity of the composite material[28].

The effective thermal conductivity of NEPCMs can be expressed as:

$$k_{\text{eff}} = k_{\text{pcm}}(1 + \beta\phi)$$

Where: k_{eff} is the effective thermal conductivity, k_{pcm} is the thermal conductivity of the base PCM, ϕ is the nanoparticle volume fraction and β is the enhancement coefficient depending on particle properties[29] .

Even after these major improvements in thermal conductivity, challenges such as nanoparticle agglomeration, sedimentation, and increased viscosity remain to be carefully addressed.

3.2.2 Encapsulation Techniques

Encapsulation is a practical way for making PCMs more stable and easier to use. Basically, in this method PCM are embedded in a shell or container to prevent it from leakage during the phase transition and make it rigid. There are two possible ways to achieve this- One is Microencapsulation in which there is coating of tiny PCM particles with a very thin layer polymer or inorganic substances etc. which boosts their surface area and helps with heat transfer. Another possible way is Macro encapsulation, in this way PCM are enclosed in big containers like tubes, panels, or spheres. The whole point of doing all these is to prevents leakage and to make the thermal performance more reliable, also to make sure the required material is holds at same place even after a lots of heating and cooling cycles[30], [31]. Even after doing all this, there is a need to keep an eye on the thermal resistance added by the shell such as the less the thermal resistance added more the better way it is.

3.2.3 Shape Stabilized PCMs

In this method the PCM is incorporated with a porous supporting matrix, such as graphite, silica, or polymer networks, to create a shape-stabilized PCMs (SSPCMs). Which also reduces the requirement for encapsulation, the matrix can physically confines the liquid phase, limiting leakage.

These materials also exhibit excellent structural stability and are capable of maintaining their shape even above the melting temperature. Additionally, porous matrices also enhances the thermal conductivity, which further improves the heat transfer performance[32], [33].SSPCMs are particularly suitable for the applications in

building materials and thermal management systems where structural integrity is critical.

3.2.4 Fin-Based Enhancement and Metal Foam

Another effective way to improve the heat transmission in PCM systems is by using the high conductivity structures such metal foams, fins, and heat exchangers.

Fast heat conduction throughout the whole PCM is made possible by the larger surface area and very porous structure offered by the metal foams. Likely, expanded surfaces (fins) enhances the melting and solidification processes by increasing the effective heat transmission surface[34], [35].

These methods work generally well in large-scale TES systems that requires a constant temperature distribution.

3.3 Performance Improvements

The incorporation of enhancement techniques significantly improves the thermophysical and operational performance of PCMs. A comparative summary is presented in Table 1.

Table 1. Comparison between Conventional PCMs and EPCMs

Property	**Conventional PCMs**	**Enhanced PCMs (EPCMs)**
Thermal Conductivity	Low	High
Thermal Stability	Moderate	High
Heat Transfer Rate	Slow	Fast
Leakage Resistance	Poor	Excellent
Cycling Reliability	Limited	Improved

These improvements enable the EPCMs to meet the performance requirements of high-efficiency TESs

CHAPTER 4
MEDICINAL APPLICATIONS OF PHASE CHANGE MATERIALS

Phase Change Materials (PCMs) are increasingly used in medicinal and biomedical applications due to their ability to maintain a stable temperature during heat absorption and release, providing accurate thermal regulation essential for drug storage, patient care, and therapeutic treatments[4], [36] .

In medical applications, where even small temperature changes can affect the efficacy of medications, biological samples, and treatment procedures, so their ability to regulate the temperature is very important. So PCMs put up the long-term maintenance of a regulated thermal environment by absorbing excess heat and releasing it when the surroundings temperature is low. The application of these materials into biomedical devices has made easier to the development of new technologies that requires an accurate heat management for their top performance. PCMs are also being analysed in the pharmaceutical industry to provide the proper storage conditions for the preservation and transportation of the medications and vaccines that are temperature-sensitive. In the same way, they have been tested for tissue engineering and wound care, thermal therapies, and for controlled medication let go in healthcare devices. The emerging need for a true, effective, and creative solution that can enhances treatment results while promising the stability and safety of pharmaceutical products is factor that is driving the increasing interest in PCMs for medical needs.

4.1 Temperature-Sensitive Drug Storage and Transport

Medicines, vaccines, biologics, blood samples, and a variety of pharmaceutical products that needs to be stored and transported at a definite temperature to avoid their chemical degradation, power loss, and dropped therapeutic regulations. Sensitive medical devices specially vaccinations and biologically active items, can be damaged by even minute temperature changes. Phase change materials (PCMs) are being embraced into medical cold-chain systems more often in order to pass this difficulty as they can endure steady temperatures for a long interval of time without the need for constant external sources[37] .

PCMs stores and releases the latent heat during phase transitions, which allows them to

properly regulate temperature within a specific required range. In place of conventional ice packs, that could result in uneven cooling and freezing damages, PCM-based vaccine carriers can usually sustain temperatures between 2 and 8°C for significantly large hours and even days. These systems are widely useful in isolated and rural areas with improper infrastructure for refrigeration and energy storage. PCM-based solutions helps us to maintain the safety, stability, and effectiveness of medications and vaccines by reducing temperature changes during storage and transportation[38]. This increases healthcare timely delivery and reduces pharmaceutical waste. Modern pharmaceutical management and biomedical storage devices can benefit largely from the leakage resistance, improved thermal reliability, and increased operating life of modern encapsulated and shape-stabilized PCMs.

Table 4.1 Temperature Requirements and PCM Applications in Medical Cold Chain

Medical Product	**Recommended Storage Temperature (°C)**	**Suitable PCM Melting Point (°C)**	**PCM Function**
Vaccines	2–8	5	Maintains safe cooling during transport
Insulin	2–8	5–6	Prevents thermal degradation
Blood Samples	2–6	4–5	Preserves biological integrity
Plasma	Below –20	–22	Maintains frozen storage conditions
Biologics	2–8	5	Stabilizes temperature-sensitive compounds
Diagnostic Reagents	2–8	5–8	Protects chemical activity

Table 5.1 illustrates the temperature requirements of common pharmaceutical and biomedical items along with the required PCM melting temperatures used for thermal regulation. Most vaccines, insulin formulations, biologics, and diagnostic products require storage within the range of 2–8°C, making PCMs with melting temperatures around 5°C highly acceptable. These PCMs absorb excess heat when surroundings temperatures rise and releases the stored cooling

energy when temperatures drop, thereby maintaining a stable environment. For products such as plasma that requires frozen storage, low-temperature PCMs with melting points near –22°C are very helpful. The combination of PCMs into vaccine carriers, insulated containers, and cold-chain packaging reduces temperature fluctuations, minimizes product spoilage, and ensures the therapeutic effectiveness during transportation and storage.

4.2 Cryotherapy and Hyperthermia Treatments

As phase change materials can absorb, store, and release thermal energy around a controlled temperature, they are also being explored widely in therapeutic heating and cooling devices. Organic PCMs generally used in cryotherapy to minimize the swelling, inflammation, discomfort, and muscle damage by absorbing excess heat from damaged or irritated tissues. PCM-based cooling devices provides a more regulated and compatible temperature range than old cooling packs, reducing the chances of tissue injury from long exposure to cold temperatures. Similar to that, PCM composites are made to release heat moderately and sustain the therapeutic temperatures required for targeted cancer treatment in hyperthermia therapy. Controlled heating is adopted in order to damage the tumor cells or make them more exposed to radiation and chemotherapy and also preventing the surrounding healthy tissues from overheating[39].

For therapeutic control and patient safety, PCMs' latent heat storage capability ensures a constant temperature distribution and thermal stability throughout therapy. In cryotherapy devices, to regulate a controlled cooling temperature is very important which helps us to prevent the tissue damage and provides a effective treatment. PCMs can reduce temperature swings that are common with conventional cooling methods by providing prolonged cooling at a virtually constant temperature. These accurate thermal regulation increases the treatment results and patient comfort by providing a consistent cooling for a large periods of time[40]. Advanced nanoparticle-enhanced PCM composites are currently being explored for regulated thermal therapies as they can speed up heat transfer rates by allowing more precise temperature control during medical procedures. Heat exchange can be increased and made more proper with addition of nanoparticles to PCMs, also increasing their thermal conductivity. Such advancements have increased the requirement of PCM-based systems to be used in

temperature-controlled therapeutic applications and future-generation cryotherapy instruments[41].

Table 4.2 PCM Temperature Ranges for Thermal Therapies

Therapy Type	**Therapeutic Temperature Range (°C)**	**PCM Melting Temperature (°C)**	**Clinical Purpose**
Cryotherapy	10–15	12–15	Reduces inflammation and pain
Sports Injury Treatment	12–18	15	Controls swelling and muscle damage
Mild Hyperthermia	40–43	42	Enhances cancer treatment effectiveness
Localized Heat Therapy	38–45	40–44	Relieves muscle stiffness and pain
Rehabilitation Therapy	35–40	37–39	Supports tissue recovery

Table 5.2 provides the temperature ranges usually employed in cryotherapy and hyperthermia treatments along with the suitable PCM melting temperatures. In cryotherapy applications, PCMs melting between 12–15°C provides controlled cooling without exposing tissues to excessively low temperatures that may cause large injury. In hyperthermia treatments, PCMs with melting points around 42°C help maintain therapeutic temperatures necessary for destroying cancer cells or increasing their sensitivity to chemotherapy and radiation. The latent heat storage capability of PCMs provides uniform temperature distribution and required large treatment duration, which improves the patient safety and treatment effectiveness.

4.3 Temperature-Regulated Drug Delivery

PCMs are largely being used in more advanced drug delivery systems due to their capacity to release pharmacological chemicals within controlled temperatures over time. These devices permit for controlled drug release under proper physiological or externally applied thermal conditions by protecting thermosensitive medications, such as insulin, anticancer agents, and other bioactive molecules, in PCM-based carriers that molten or soften at specific temperatures. This strategy reduces adverse effects adjacent to the sudden spikes or uncontrollable medication release by also improving the pharmacokinetics and therapeutic power. Due to their tendency to hold steady temperatures and release medications regularly over large periods of time, PCM-based hydrogels, polymeric matrix, and nanocomposite carriers are particularly useful for controlled heat release[37] .

Such types of systems are very useful when it comes to the requirement of targeted therapeutics, customized medicine, and minimally affecting treatment technologies, where there is need of accurate dose and controlled release as one of the important function. PCMs can also be used as smart carriers in temperature-responsive drug delivery systems, where they control the release of therapeutic drugs in response to the particular temperature changes. These ways also improve the treatment benefits by reducing the unwanted side effects caused by the old drug delivery patterns, as they provide the medications a pathway to be released at the required location and time[42]. Researchers by properly choosing the PCMs with the right phase transition temperatures can provide delivery platforms that only responds to physiological circumstances or externally applied thermal. So, this method found to be very helpful for treating conditions like cancer and chronic inflammatory illnesses that needs a localized and regulated medication pattern.

On the top of that, the future for safe biomedical and pharmaceutical applications has been increased with the development of biocompatible and biodegradable PCMs. These substances are suitable for a prolonged and frequent use as they can carry out their therapeutic purpose without producing much toxicity or non- required biological reactions. All of these factors lead us to a system where, PCM-based drug delivery systems are offerings a hope for instruments to improve their therapeutic results and increase the efficacy of these medical therapies[43].

When the treatments which requires exact dose and controlled release as one of important step,

there these systems are very helpful in targeted therapeutics, personalized medicine, and cost - effective treatment technologies. PCMs can function as intelligent carriers in temperature-responsive drug delivery systems, controlling the release of therapeutic drugs in a reaction to a certain temperature variation. All these features makes it possible for medications to be released at the desired location and time[44].

Table 4.3 PCM-Based Temperature-Controlled Drug Delivery Systems

Drug Type	**Trigger Temperature (°C)**	**PCM Type**	**Application**
Insulin	35–37	Paraffin-based PCM	Controlled diabetic treatment
Anticancer Drugs	40–42	Fatty acid PCM	Targeted tumor therapy
Antibiotics	37–40	Biocompatible PCM Hydrogel	Sustained drug release
Anti-inflammatory Drugs	35–38	Polymer-PCM Composite	Localized therapeutic delivery
Protein Therapeutics	37	Encapsulated PCM	Controlled biomolecule release

Table 5.3 shows examples of PCM-assisted drug delivery systems and their operating temperatures. The selected PCM melts near the desired physiological or externally induced temperature, enabling the gradual release of encapsulated drugs. For example, anticancer drugs may be released at temperatures between 40–42°C during localized hyperthermia treatment, while insulin delivery systems operate near normal body temperature **(**37°C). Such controlled release mechanisms improve therapeutic efficiency, reduce dosage frequency, and minimize side effects associated with sudden drug release.

4.4 Patient Comfort and Biomedical Devices

Phase change materials are also being incorporated into wearable healthcare devices, patient care items, and biomedical fabrics to enhance device performance, safety, and thermal comfort. Stable patient temperatures are crucial in healthcare settings, particularly for long-term patient monitoring, neonatal care, burn therapy, and post-operative care. By absorbing excess heat and releasing stored heat as necessary, PCM-coated medical textiles, blankets, mattresses, and hospital bedding systems help control body temperature and provide patients with a comfortable thermal environment. These technologies enhance patient recuperation conditions and lessen heat stress. PCMs are integrated into flexible layers in wearable biomedical devices to prevent overheating of delicate sensors, batteries, and electronic components while maintaining safe skin-contact temperatures[45].

Because PCM-based heat management systems increase operational stability, energy economy, and user comfort, they are being utilized more and more in wearables for smart health monitoring, prostheses, rehabilitation equipment, and portable medical gadgets. PCMs are extremely useful in patient-centered healthcare systems and next-generation biomedical technology because of their capacity to provide passive and dependable temperature regulation.

Table 4.4 PCM Applications in Patient Comfort and Biomedical Devices

Application	**Desired Temperature Range (°C)**	**PCM Melting Point (°C)**	**Benefit**
Hospital Bedding	28–32	30	Maintains patient comfort
Neonatal Care Systems	36–37	36	Prevents infant hypothermia
Smart Wearable Devices	30–35	32	Prevents overheating of electronics
Prosthetic Devices	30–34	32	Enhances user comfort
Rehabilitation Equipment	32–38	35	Provides thermal stability

Medical Textiles	28–34	30–32	Regulates body temperature

Table 5.4 summarizes the temperature regulation requirements of various patient-care and biomedical-device applications. PCMs with melting temperatures close to human comfort levels (30–37°C) absorb excess body heat and release stored heat when temperatures decrease. In neonatal care systems, PCMs works around 36°C helps in maintaining the body temperature of newborn infants that leads to reduced risk of hypothermia. PCM layers protect sensitive electronic components in wearable healthcare devices and prosthetics from overheating while at the same time enhancing user comfort. These indirect thermal management capabilities lead to an improved patient recovery, device reliability, and overall healthcare quality.

CHAPTER 5
CHALLENGES AND FUTURE PROSPECTIVES

6.1Challenges

Phase change materials (PCMs) appear to be promising for medicine, but their practical use is very difficult . One of the major issue in it is their leakage when they changes their phase from solid phase to liquid phase, there are chances of leaks which can compromises the safety or structural integrity of medical instruments and drug delivery systems. On the top of that, when fast and uniform heat transfer is required -the majority of organic PCMs don't transfer the heat constantly, which can cause the problems for treatments like hyperthermia therapy. Also their biocompatibility is one of another problem. Even though, the additives like nanoparticles might improves the performance of PCMs, but they can sometimes cause toxicity or non-required reactions which is one of major disadvantage and not required in medical products. PCMs have a tendency to get degrade over the time.

They don't function well when they are repeatedly heated and cooled because their mechanical and chemical stability decreases. Also there is another big issue when their melting points are compared with body temperature they do not match as per requirements which is one of the major challenge, and very significant for timely release of drugs. And another big issue is making these materials, as the processes for encapsulating and creating PCM composites are very difficult and also increase the overall productions cost. Additionally, incorporating the PCMs into real biological systems and regulating them for as per body requirements, these both are serious problems when it comes to larger clinical use.

6.2 Future Perspectives

Phase change materials or PCMs, have recently started to gain more attention in the medical field. There various features like thermal energy storage, constant temperature maintenance, and to control the release of medications makes them more promising. Due to which they can

be generally seen in smart biomedical equipment, vaccine storage, and tailored medicines. Inspite of all these there are various problems associated with them, such as during phase changes PCMs can leak out, and also their thermal conductivity is not that great. Sometimes, they don't always work well with the body. It is very difficult to modify their temperature range and also difficult to produce them on a large scale. Before utilizing these materials properly, there is a need that they must shows us a long-term stability, integrate seamlessly into complex biological systems, and pass the regulatory requirements .

Despite everything, appears to be going well. Progress in nanotech, material science, and biomedical engineering keeps pushing PCMs forward. Scientists are still working on biodegradable, non-toxic, and super-efficient PCM composites with good thermal properties[46] .Some new PCMs can responds to the different triggers or can combine multiple features, helping doctors deliver drugs exactly when and where they is required[47]. Using them in smart wearables devices or implantable devices is really good since it is opening up possibilities for the real-time health monitoring and personal treatment. However, there are still some noticeable obstacles needed to overcome before these materials become common in clinics, including their expenses, increasing production, and resolving all regulatory requirements. Success of these materials depends on researchers, engineers, and healthcare professionals collaborating and sharing ideas; on how PCMs can carve out a place in modern medicine world.

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