

Advancements in Phase Change Materials: Stabilization Techniques and Applications

Soumen Mandal

Industry-University Cooperation Foundation,
Hanyang University ERICA, 1271 Sa-3-dong,
Sangnok-gu, 15588, Ansan, South Korea.
E-mail: sou.chm@gmail.com

(Received on July 15, 2024; Revised on August 3, 2024; Accepted on August 5, 2024)

Abstract

Phase Change Materials (PCMs) are innovative materials that absorb and release thermal energy during phase transitions, making them ideal for thermal energy storage applications. This paper provides a comprehensive overview of PCMs, focusing on their functioning mechanisms, classifications, and shape stabilization methods. PCMs operate by storing latent heat during melting and releasing it upon solidification, thereby maintaining a stable temperature during phase changes. They are classified into three main categories: organic, inorganic, and eutectic. Organic PCMs, such as paraffins and fatty acids, offer high latent heat storage but suffer from low thermal conductivity. Inorganic PCMs, including salt hydrates and metals, provide better thermal conductivity but face challenges like supercooling and corrosiveness. Eutectic PCMs, which are mixtures of compounds, offer customizable melting points and enhanced thermal properties. To address leakage and improve thermal conductivity, shape stabilization methods are employed, such as encapsulation, stabilization by porous matrix, and polymer hybridized shape stabilization. These techniques enhance the structural integrity and thermal performance of PCMs, making them more suitable for practical applications. The paper highlights the potential of PCMs to improve energy efficiency and outlines future research directions for optimizing their performance in various industries.

Keywords- Phase change materials, Enthalpy, Thermal management, Latent heat, Phase transition.

1. Introduction

Phase change materials (PCMs) have attracted significant interest recently for their special capacity to store and release substantial amounts of thermal energy while undergoing phase transitions (Bora et al., 2024; Huo et al., 2018; Sivanathan et al., 2020). This quality makes them extremely important in various uses, from thermal control systems to energy storage options. The key concept of PCMs is their ability to store or release latent heat during a change in physical state, such as melting or solidifying. This method allows for effective control of temperature across different settings, improving energy efficiency and sustainability. The foundation of phase change material is based on the fundamental laws of thermodynamics (Dutil et al., 2011). When heat is absorbed by a PCM, it usually changes from a solid to a liquid state during a phase transition. Throughout this transformation, the substance can take in a large quantity of heat without experiencing a notable increase in temperature (Costa & Kenisarin, 2022; Zare & Mikkonen, 2023), all due to the latent heat of fusion. On the other hand, as the material cools off, it gives off the heat it had stored while turning into a solid. The process of absorbing and releasing heat in a cycle makes PCM suitable for tasks needing precise temperature regulation.

One area with great potential for PCM application is in the field of building and construction, where they are utilized to improve the thermal efficiency of buildings (Tripathi & Shukla, 2024). By incorporating PCMs into construction materials like walls, ceilings, and floors, it can help regulate indoor temperature, decreasing the reliance on heating and cooling systems (Nghana & Tariku, 2016). This doesn't just reduce energy usage, but also adds to a more enjoyable living space. During the day, when the outside temperature

increases, phase change materials in the construction materials soak up extra heat, stopping the inside temperature from getting too hot. During the night, when the temperature decreases, the heat that has been stored is slowly released, thus keeping the indoor environment warmer (Elhamy & Mokhtar, 2024).

PCMs are utilized for thermal control in electronic devices as well as in construction materials (Li et al., 2024b; Qu et al., 2024). As electronic components gain more power, they also produce more heat, impacting their efficiency and durability. Integrating phase change materials (PCMs) into electronic devices improves heat dissipation, leading to better operating conditions and longer component lifespan (Eswaramoorthy & Bhagat, 2023). This is especially important for devices that run non-stop or in high-temperature settings. PCMs are having a noticeable influence in the transportation industry as well. In electric vehicles (EVs), thermal management is crucial in order to uphold battery performance and safety (Hekmat et al., 2024; Kim et al., 2024). PCMs are utilized in battery thermal management systems to control temperature, ultimately improving battery performance and increasing driving distance. PCMs assist in averting overheating and thermal runaway by soaking up extra heat produced during charging and discharging processes, ultimately avoiding potential battery failure (Li et al., 2024a).

In addition to these uses, PCMs are also being incorporated into textiles and apparel (El Majd et al., 2023; Gu et al., 2024). By integrating PCMs into textiles, it is possible to design clothing that enhances thermal comfort by absorbing, retaining, and releasing heat based on the wearer's body temperature and the ambient conditions. This new technology is especially handy for outdoor clothing and sports gear, where keeping the right temperature is vital for comfort and peak performance. PCMs are highly versatile and crucial components in energy storage systems within the renewable energy sector. Solar energy, for example, is naturally not constant, as the amount of energy generated changes depending on the weather and time of day. PCMs have the ability to retain extra heat produced during times of high sunlight and then release it at a later time, helping to balance out the discrepancy between energy supply and demand and boosting the effectiveness of solar energy systems. Likewise, PCMs in wind energy applications can save energy when there is a lot of wind and then release it when the wind is calm.

Although PCMs have many benefits and uses, there are also obstacles that must be overcome in order to fully utilize their potential. The cost of PCMs is often higher than that of traditional materials, posing a significant challenge. Finding affordable ways to produce and uncovering low-cost PCM formulations are essential research areas. Moreover, it is important to guarantee the long-term stability and durability of PCMs, particularly in situations where there are frequent changes in temperature. Another crucial factor to take into account is the environmental effects of PCMs. Even though a lot of PCMs come from natural sources like paraffin and fatty acids, the environmental effects of their widespread use must be thoroughly assessed. Ongoing research is being conducted on biodegradable and environmentally friendly PCMs in order to reduce any potential adverse impacts on the environment (Okogeri & Stathopoulos, 2021). However, to effectively harness their potential, stabilization methods are necessary to address issues related to leakage, thermal conductivity, and long-term stability. Several innovative techniques have been developed to enhance the performance and durability of PCMs, ensuring their suitability for various applications. The primary stabilization methods include encapsulation, shape-stabilization, and composite formation.

To sum up, phase change materials are an innovative technology that could transform multiple industries through improved thermal management and energy efficiency. Their capacity to hold and release significant quantities of heat energy while transitioning between phases allows for a variety of uses in fields such as construction, electronics, transportation, and renewable energy. As research progresses and new challenges are addressed, PCMs are positioned to be vital in building a more sustainable and efficient future. Therefore,

in this article, efforts are made to sum up the different categories of PCM and their stabilization procedures for their applications in diversified fields.

2. Functioning Mechanism of PCMs

Phase Change Materials (PCMs) function by absorbing and releasing thermal energy as they undergo phase transitions, particularly during melting and freezing. As the surrounding temperature increases, a phase change material takes in heat until it reaches its melting threshold. At this point, the phase change material changes from a solid to a liquid form, taking in a large amount of hidden heat without a significant rise in temperature. This absorption mechanism enables PCMs to function as heat reserves, keeping the temperature steady even when the surrounding conditions get hotter. This ability makes them very efficient in tasks that need thermal control.

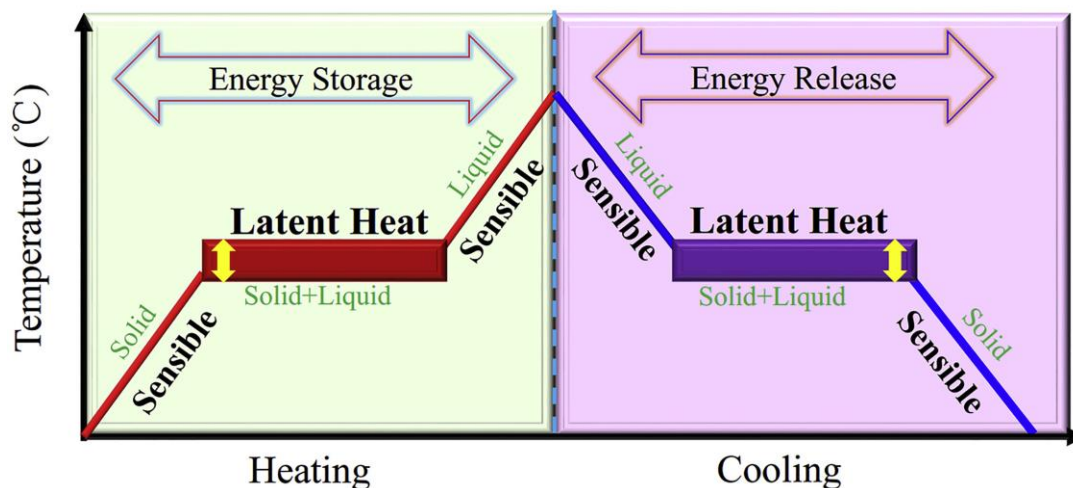


Figure 1. Solid-liquid PCMs function based on their working principle (Chen et al., 2020).

On the other hand, if the surrounding temperature drops, the PCM will activate and release heat as it turns from a liquid to a solid. In this stage of transition, the PCM gives off the stored heat it had initially taken in, once more ensuring a consistent temperature. The ability to absorb extra heat and release stored heat makes PCMs very useful in controlling temperature changes. This temperature control is especially useful in areas like construction materials, where PCMs can aid in lowering heating and cooling requirements, and in electronics, where they prevent excessive heat. **Figure 1** shows the schematic representation of working principle of a solid-liquid PCM.

Despite their advantages, the use of PCMs does come with challenges. The cost of high-performance PCMs can be significant, and there are technical issues such as phase separation and supercooling that need to be addressed to ensure material stability and performance. Additionally, material compatibility and long-term durability are critical factors that must be considered in PCM applications. Furthermore, the direct usage of PCMs can pose risks of leakage and contamination, which can deteriorate the properties of the materials in their applications. Leakage can lead to the degradation of surrounding materials and contamination of the system, reducing the efficiency and lifespan of the PCM-integrated solution. Nevertheless, the unique thermal properties of PCMs provide a versatile and efficient solution for thermal energy management, offering significant benefits in energy efficiency and temperature regulation across various industries.

3. Categories of PCMs

Phase Change Materials (PCMs) are classified according to their chemical makeup and the distinct properties of their phase changes. Organic PCMs, inorganic PCMs, and eutectic PCMs are the main categories (Bora & Joshi, 2023) of phase change materials (**Figure 2**). Each category comes with its specific characteristics, advantages, and constraints.

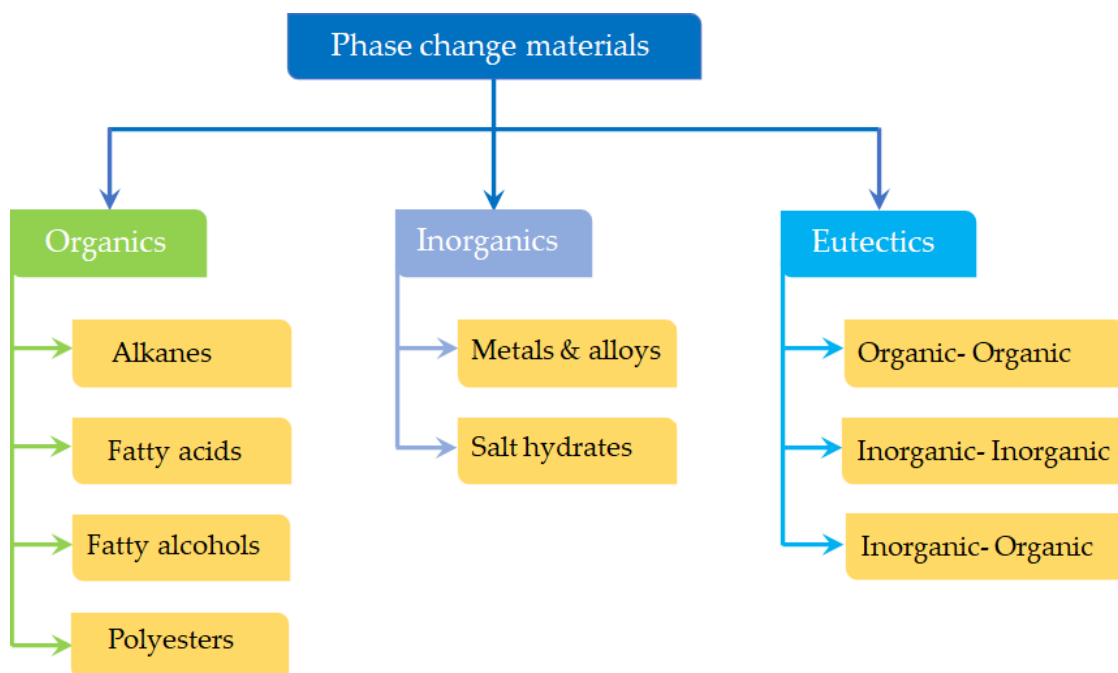


Figure 2. Categorization of phase change materials.

The poor thermal conductivity of non-metal PCMs is a major disadvantage that impacts their efficiency in thermal energy storage (TES) systems (Zhang et al., 2016). This restriction impedes the effective movement of heat in these materials, diminishing their efficiency in situations that need quick thermal exchange. Therefore, it is important to increase the thermal conductivity of PCMs to enhance their overall effectiveness. Dealing with this problem is crucial not just for saving energy but also for staying financially viable, as enhanced heat transfer can result in lower energy expenses and better system efficiency.

Organic PCMs, like paraffins and fatty acids, are commonly utilized because of their advantageous characteristics like high latent heat storage, chemical stability, and non-corrosive nature (Mandal et al., 2022c). Yet, their intrinsic poor thermal conductivity restricts their use in high-performance TES systems (Singh et al., 2018). Researchers are investigating different approaches to improve the heat transfer efficiency of organic PCMs. Investigations are being conducted on methods like adding high thermal conductivity additives (like metal particles, carbon-based materials), utilizing porous supporting structures, or creating composite materials (Xu et al., 2022). These methods intend to establish routes for better heat conduction in the PCM, enhancing their thermal performance and increasing their practical usability.

Unlike organic PCMs, inorganic PCMs such as salt hydrates, salts, metals, and alloys typically show higher levels of thermal conductivity (Man et al., 2023). Of these, salt hydrates are especially known for being appropriate for storing thermal energy. Salt hydrates have many benefits: they can store a significant

amount of energy during phase transitions due to their high phase change enthalpy, experience minimal structural stress as a result of low volume change, and have high energy storage density and thermal conductivity (Hua et al., 2022). Furthermore, salt hydrates are both fireproof and more cost-effective than organic PCMs, making them a desirable choice for extensive thermal energy solutions (Dixit et al., 2022).

However, salt hydrates also pose various difficulties despite their advantages. The corrosive nature of these substances can cause metal deterioration and system breakdown if not adequately controlled (Farrell et al., 2006; Graham et al., 2016). Salt hydrates also experience supercooling, decomposition, and phase separation (Liu et al., 2024; Tang et al., 2011). Supercooling has the potential to slow down the freezing process, which in turn decreases the effectiveness of energy release. Decomposition and phase separation may impact the consistency and reliability of the PCM throughout several thermal cycles, resulting in decreased thermal efficiency (Xie et al., 2019). Moreover, salt hydrates have a tendency to separate into phases and lack thermal stability, making them challenging to use in extended applications.

Overall, inorganic PCMs have extra disadvantages when compared to organic PCMs. They have a slight toxicity and may exhibit inconsistent melting and dehydration when subjected to thermal cycling. Inconsistent melting happens when the PCM doesn't melt evenly, resulting in unequal heat distribution and lower effectiveness. Dehydration can alter the characteristics of the material, making it more challenging to be used in multiple thermal cycles. These problems require thoughtful analysis and solutions like corrosion inhibitors, encapsulation methods, and composite formulations to enhance stability and performance.

Eutectic phase change materials provide a different option for storing thermal energy. These substances are combinations of two or more compounds that melt and freeze at the same temperature, improving the thermal characteristics of the mixture (Sun et al., 2023). Eutectic PCMs are customizable to achieve precise melting points, allowing for versatility in various applications (Singh et al., 2021). The specific compounds utilized in the mixture determine the primary benefits of eutectic PCMs. Through the meticulous selection and blending of various materials, one can develop eutectic PCMs that have enhanced thermal conductivity, latent heat storage, and stability. This versatility and effectiveness of eutectic PCMs make them suitable for different TES uses. In theory, Equation (1) is used to create the eutectic mixture (Singh et al., 2021; Yang et al., 2020):

$$\begin{cases} -\frac{H_A}{T_A}(T_m - T_A) + RT_m \ln(X_A) + G_{A, ex} = 0 \\ -\frac{H_B}{T_B}(T_m - T_B) + RT_m \ln(X_B) + G_{B, ex} = 0 \end{cases} \quad (1)$$

where, component A and component B's respective enthalpies are denoted by H_A and H_B . The melt temperatures of component A, component B, and the mixture are denoted by T_A , T_B , and T_m (K). The mole percentages of components A and B are represented by X_A and X_B . The excess enthalpy of the constituents is denoted by $G_{A, ex}$ and $G_{B, ex}$. R stands for the universal gas constant.

Although non-metal phase change materials have restrictions because of their low thermal conductivity, current research and development efforts are working to overcome these obstacles. Improving the heat efficiency of organic PCMs and addressing the challenges of inorganic PCMs, like salt hydrates, are essential for the progression of thermal energy storage technologies. Eutectic PCMs offer a hopeful option due to their customizable characteristics. By making these efforts, PCMs have the potential to be more effective and financially feasible for various uses, leading to better energy control and environmental sustainability.

4. PCM Stabilization and Approaches

PCMs are receiving considerable interest due to their capacity to store and release substantial thermal energy when undergoing phase transitions. Nevertheless, utilizing PCMs directly can pose difficulties because of problems like leakage, changes in volume, and chemical instability. Researchers have come up with different methods to stabilize PCMs, which are referred to as "shape-stable PCMs" (SSPCMs), in order to tackle these difficulties. Stabilization techniques play a vital role to enhance the efficiency and longevity of phase change materials. Encapsulation, shape-stabilization, composite formation, and chemical modification provide distinct benefits, tackling particular issues related to PCMs. As advancements in research and development progress, these stabilization methods will allow for a wider and more effective utilization of PCMs in diverse applications, leading to enhanced energy efficiency and sustainability.

4.1 Encapsulation

Encapsulation is a very efficient technique employed for protecting and maintaining the stability of PCMs. This method requires encasing PCM droplets in shell materials, that could be either organic or inorganic. Encapsulation uses physical, chemical, and physio-chemical methods to create encapsulated PCMs, allowing for better manipulation of their characteristics and behavior. There are two primary forms of encapsulation: microencapsulation and macroencapsulation.

4.1.1 Physical Encapsulation Methods

Different coating and spray-drying techniques can be used for physical encapsulation methods. These techniques form a barrier around the PCM, stopping any leaks and conserving the PCM's structure when it undergoes phase changes. One way to enhance the thermal stability of PCM is by utilizing microencapsulation methods, which involve coating PCM droplets with a polymer shell to prevent leaks. **Figure 3** represents the overall process of spray drying techniques.

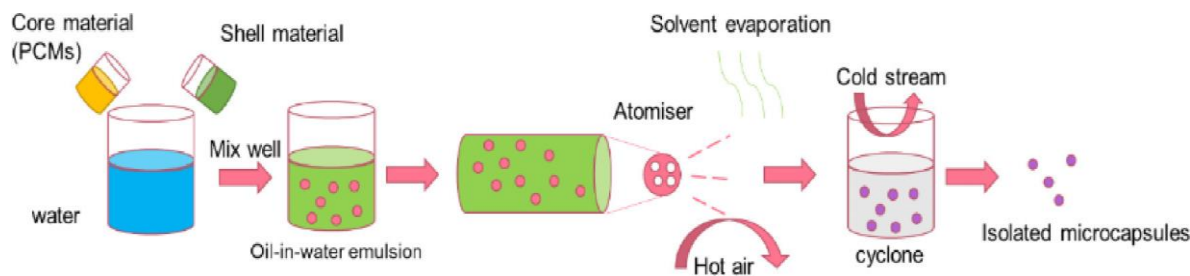


Figure 3. PCM synthesis by spray drying method (Huang et al., 2023).

4.1.2 Chemical Encapsulation Methods

Chemical procedures, such as in-situ polymerization and solvent extraction, lead to the creation of a durable shell surrounding the PCM. These methods improve the strength and dependability of shape-stabilized PCMs. The process of in-situ polymerization involves dispersing the PCM in a solution of monomer and then polymerizing it to form a strong polymer shell that fully encloses the PCM. A scheme of in-situ polymerization is represented in **Figure 4**.

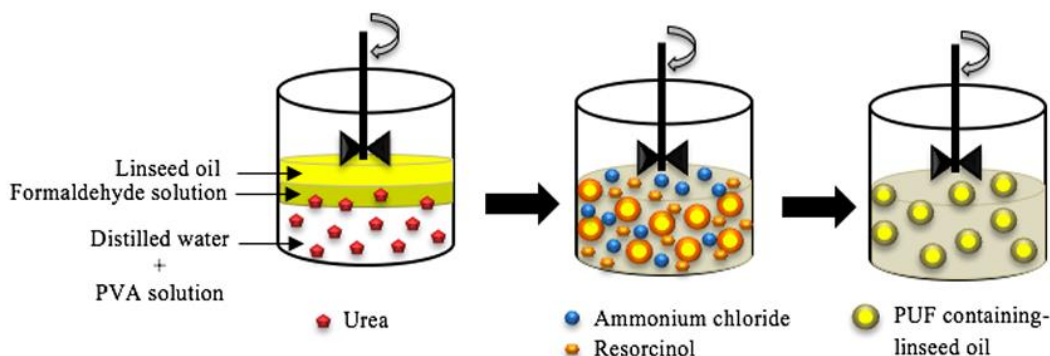


Figure 4. Encapsulation by in-situ polymerization (Alias et al., 2021).

4.1.3 Physio-Chemical Encapsulation Methods

Moreover, PCMs have also been encapsulated using physiochemical methods like the sol-gel method. The sol-gel process merges the benefits of physical and chemical encapsulation, providing a strong technique for producing shape-stabilized PCMs. The PCM is mixed with a sol-gel precursor solution in this technique, which is then transformed into a gel to create a durable, porous silica coating around the PCM. Encapsulation of silica on lauric acid via sol-gel technique is illustrated in **Figure 5**.

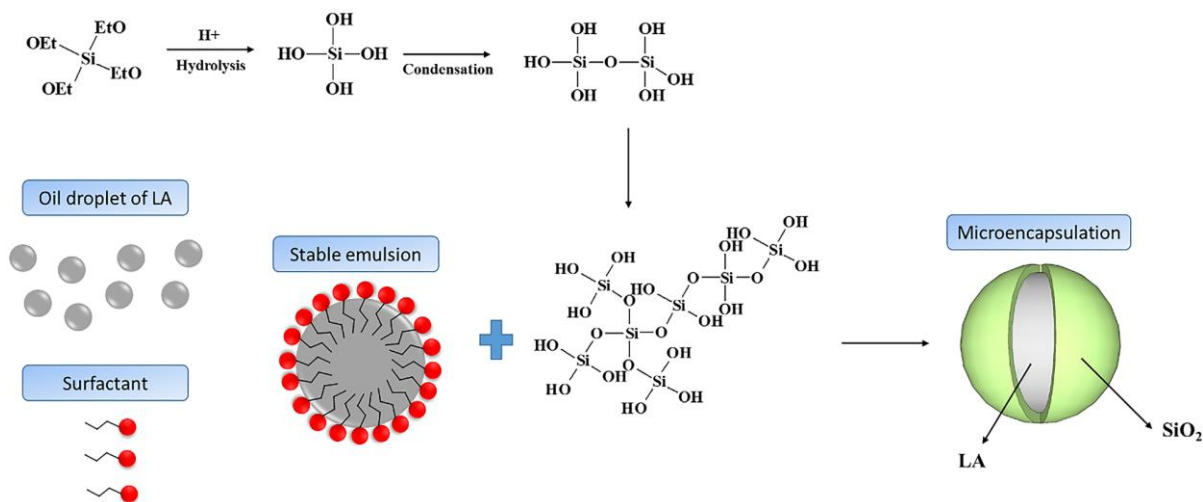


Figure 5. Synthesis of SiO₂ encapsulated lauric acid via sol-gel synthesis (Ishak et al., 2021).

However, selecting appropriate shell constituents for PCM encapsulation is crucial, as certain characteristics are needed to guarantee efficient encapsulation. The material for encapsulation needs to create a uniform and thin layer that is stable and compatible at a chemical level with the PCM core. Additionally, it needs to show non-reactivity with the PCM and have the ability to dissolve in aqueous solutions or solvents while being prepared (McCord & Baniasadi, 2024). Moreover, the shell material should exhibit favorable coating characteristics, such as durability, pliability, and reliability (Giro-Paloma et al., 2016; Gui et al., 2021). A wide variety of materials, including both inorganic and organic types, are used to encase PCMs, providing different benefits based on the particular application.

Organic shell materials, like polymers such as poly (methyl methacrylate), polystyrene, and melamine-formaldehyde, offer excellent encapsulation abilities and flexibility while remaining compatible with the PCM. However, ceramic inorganic shell materials can provide improved thermal stability and durability, especially crucial for high-temperature PCMs. The appropriate choice of PCM, shell material, encapsulation method, and size vary based on the specific needs of the application. Thoroughly analyzing these factors is essential for creating efficient and dependable PCM-based systems for different thermal energy storage and management purposes.

4.2 Shape Stabilization using Porous Matrix

The significant use of porous materials in different fields, especially in energy conversion and storage, is due to their extraordinary qualities like extensive surface area and superior pore volume. Porous materials are very well-suited for energy-related uses such as energy storage, catalysis, and thermal management due to these characteristics.

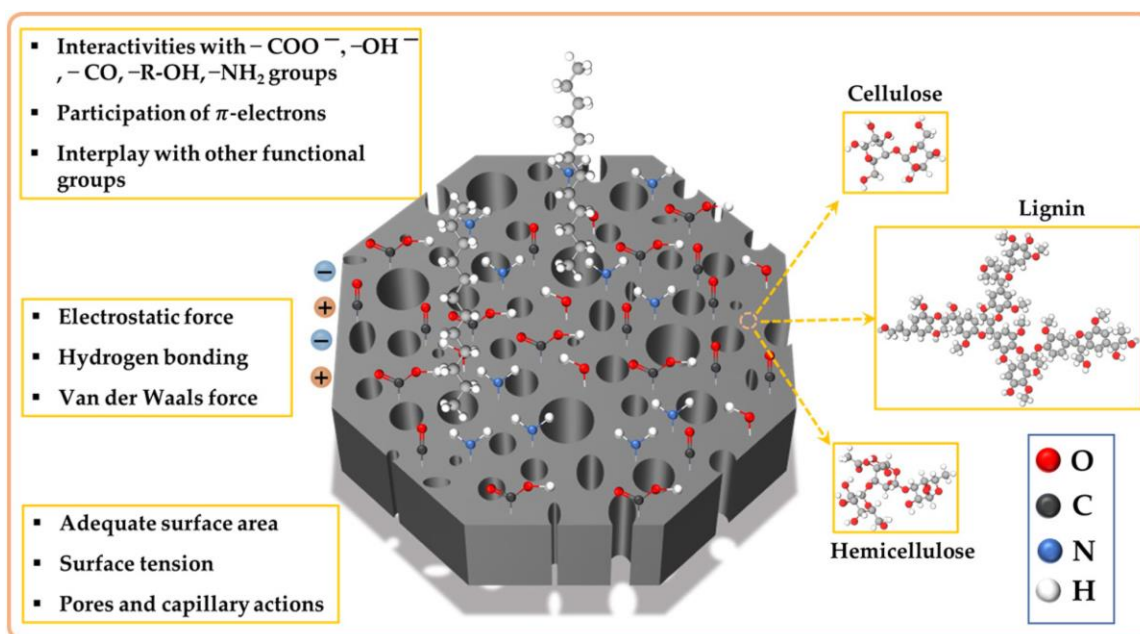


Figure 6. Surface functionalities of porous biochar (Mandal et al., 2023b).

Pore confinement has been identified as an efficient method to prevent leakage of phase change materials (PCMs) when they are in their molten state, among various other approaches. This technique takes advantage of the physical characteristics viz. surface functions, capillary actions, and space confinement effects that impact on the physical characteristics of the fluid and prevent PCM leakage in phase change procedures (Mandal et al., 2023a; Mandal et al., 2022a). The surface functionalities of the porous biochar matrix have been illustrated in **Figure 6**. The porous framework, containing a complex system of interconnected pores, offers a large surface area for efficient interactions between PCM and the matrix. The interaction of capillary forces, surface tension, and wettability properties in the porous structure aids in containing the PCM within the pores, even when it is in a liquid state. The pore restriction impact can greatly enhance the thermal resilience and dependability of PCM-powered energy storage setups, rendering them better suited for real-world use.

Moreover, the hierarchical porous arrangement, featuring pores of varying sizes, can provide added benefits for heat transfer, thermal regulation, and energy storage capabilities. The presence of macro-, meso-, and micro-pores can work together to improve the efficiency and versatility of porous materials in energy applications.

In general, the porous matrix shape stabilization of phase change materials (PCMs) is commonly carried out using the vacuum impregnation method. This technique involves the impregnation of the porous matrix with the PCM under vacuum conditions, allowing the PCM to penetrate and fill the porous structure effectively. This results in a more stable and reliable shape-stabilized PCM composite, which can be further incorporated into various energy storage and thermal management applications.

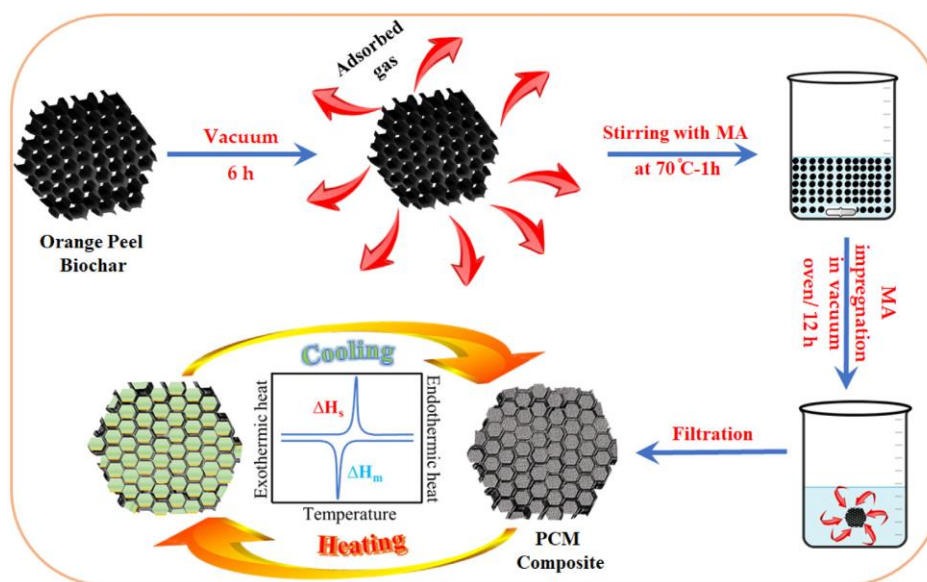


Figure 7. Schematic of porous biochar shape stabilized PCM synthesis by vacuum impregnation (Mandal et al., 2022b).

The schematic in **Figure 7** represents the synthesis of biochar-based shape-stabilized PCM using the vacuum impregnation method. In this process, the porous matrix is first prepared, and then the PCM is impregnated into the porous structure under vacuum conditions. This allows the PCM to be effectively confined within the porous network, preventing leakage during phase changes. The selection of the porous material for this purpose is crucial and depends on the specific application requirements. Different porous materials, such as biochar (Mandal et al., 2023a; Mandal et al., 2022a), Diatomaceous earth (Ishak et al., 2023), Vermiculite (Karaïpekli & Sarı, 2009), Kaolin (Memon et al., 2013), Gypsum (Sarı & Biçer, 2012), Perlite (Sarı & Biçer, 2012), porous alumina (Zhao et al., 2021), expanded graphite (Zhang & Fang, 2006), metal foams (Aramesh & Shabani, 2022), mesoporous silica (Li et al., 2021), carbon nanotubes (Cao et al., 2019), etc. have been explored for PCM shape stabilization. The choice of the porous matrix depends on factors such as the desired thermal properties, compatibility with the PCM, and the specific application requirements.

4.3 Polymer Hybridized Shape Stabilization

The hybridization of PCMs is dependent on the harmonious relationship and attraction amongst the PCM and the matrices (polymers), which is accomplished by a combination of blending and adsorption

techniques. By utilizing the PCM's compatibility with the polymer, it is feasible to attain form stabilization by capitalizing on advantageous intermolecular interactions. This compatibility between molecules ensures that PCM is evenly distributed in the polymer matrix, which is important for storing thermal energy effectively (McCord & Baniasadi, 2024).

The suitability and connection between PCM and polymers are mainly determined by the following factors:

- (i) **Miscibility:** Molecular level miscibility between PCM and polymer is important. High miscibility enables strong interactions between PCM and polymer, helping to form stable complexes.
- (ii) **Chemical Compatibility:** Similarity in chemical structure and polar properties between PCM and polymer is required. This allows intermolecular forces (van der Waals forces, hydrogen bonds, etc.) to form, creating a stable interface.
- (iii) **Thermal stability:** The thermal stabilities of the PCM and the polymer must be similar. This ensures stability against volume changes that occur during the phase change process.
- (iv) **Mechanical properties:** The mechanical properties (strength, flexibility, etc.) of PCM and polymer must be well balanced. This ensures the mechanical stability of the complex.

This new approach offers several advantages in comparison to traditional encapsulation methods. The hybridization method simplifies the need for complicated encapsulation processes by mixing the PCM directly with the polymeric matrix, which is a more cost-effective and straightforward approach to stabilizing PCM. Additionally, this approach increases the thermal conductivity of the PCM/polymer blend, improving its overall thermal energy storage capacity. A method for creating polymer-based PCM composite is detailed in **Figure 8**.

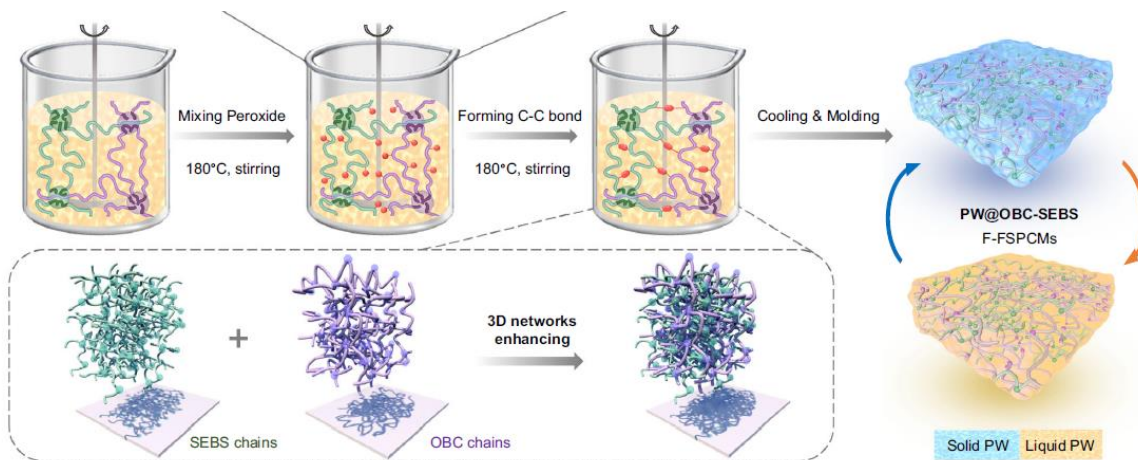


Figure 8. Fabrication procedure of ultra flexible polymer-based phase change composites (Jing et al., 2023).

5. Summary and Future Scope

Phase Change Materials (PCMs) are a major breakthrough in thermal energy storage technology, offering a dependable and effective way to keep temperatures consistent in different applications. These substances are known for their capacity to absorb and release latent heat during phase changes, providing significant advantages in energy efficiency, peak load management, and thermal control. Even though they have benefits, PCMs encounter obstacles like poor heat conduction in organic materials and problems like supercooling and corrosivity in inorganic choices. Utilizing shape stabilization methods and composite materials has proven effective in tackling these challenges, improving both the structural integrity and

thermal efficiency of PCMs. In general, the ongoing progress and enhancement of PCMs could have a considerable influence on various industries, such as construction and electronics, by enhancing energy efficiency and sustainability.

Future PCM advancements will aim to address existing constraints and increase their usage in various industries. Improving heat transfer rates without decreasing storage capacity is a key focus of research, achieved by enhancing thermal conductivity using nanomaterials and advanced composites. Additional progress in encapsulation methods is necessary to avoid leaks and deterioration, guaranteeing durability and effectiveness in the long run. Lowering production costs, particularly for high-performance inorganic PCMs, is another crucial aspect that will increase the availability of these materials for widespread use. Furthermore, the environmental effects of PCMs can be reduced by researching sustainable and biodegradable substances, in line with worldwide initiatives for environmentally-friendly energy options. In conclusion, incorporating PCMs into intelligent energy systems and employing advanced modeling and simulation methods will allow for more accurate thermal management control and optimization. By focusing on these areas, PCM technology can have a crucial impact on upcoming energy plans, advocating for a greener and more efficient global environment.

Conflict of Interest

The author declares there is no conflict of interest.

Acknowledgments

None.

References

- Alias, J., Johari, N.A., Zanurin, A., Alang, N.A., & Zain, M.Z.M. (2021). Self-healing epoxy coating with microencapsulation of linseed oil for the corrosion protection of magnesium (Mg). In *Journal of Physics: Conference Series* (Vol. 2129, No. 1, p. 012008). IOP Publishing. Perlis, Malaysia.
- Aramesh, M., & Shabani, B. (2022). Metal foam-phase change material composites for thermal energy storage: A review of performance parameters. *Renewable and Sustainable Energy Reviews*, 155, 111919.
- Bora, N., & Joshi, D.P. (2023). Enhancement in thermal properties of organic phase change material (paraffin) via TiO₂ foam doping. *Prabha Materials Science Letters*, 2(1), 1-15.
- Bora, N., Joshi, D.P., & Aulakh, J.S. (2024). Influence of polyaniline conducting polymer on thermal properties of phase change material for thermal energy storage. *Polymer Bulletin*, 81(2), 1597-1621.
- Cao, R., Chen, S., Wang, Y., Han, N., Liu, H., & Zhang, X. (2019). Functionalized carbon nanotubes as phase change materials with enhanced thermal, electrical conductivity, light-to-thermal, and electro-to-thermal performances. *Carbon*, 149, 263-272.
- Chen, X., Gao, H., Tang, Z., & Wang, G. (2020). Metal-organic framework-based phase change materials for thermal energy storage. *Cell Reports Physical Science*, 1(10), 100218. <https://doi.org/10.1016/j.xcrp.2020.100218>.
- Costa, S.C., & Kenisarin, M. (2022). A review of metallic materials for latent heat thermal energy storage: Thermophysical properties, applications, and challenges. *Renewable and Sustainable Energy Reviews*, 154, 111812.
- Dixit, P., Reddy, V.J., Parvate, S., Balwani, A., Singh, J., Maiti, T.K., Dasari, A., & Chattopadhyay, S. (2022). Salt hydrate phase change materials: Current state of art and the road ahead. *Journal of Energy Storage*, 51, 104360.

- Dutil, Y., Rousse, D.R., Salah, N.B., Lassue, S., & Zalewski, L. (2011). A review on phase-change materials: Mathematical modeling and simulations. *Renewable and Sustainable Energy Reviews*, 15(1), 112-130.
- El Majd, A., Younsi, Z., Youssef, N., Belouaggadia, N., & El Bouari, A. (2023). Experimental study of thermal characteristics of bio-based textiles integrating microencapsulated phase change materials. *Energy and Buildings*, 297, 113465.
- Elhamy, A.A., & Mokhtar, M. (2024). Phase change materials integrated into the building envelope to improve energy efficiency and thermal comfort. *Future Cities and Environment*, 10(1).
- Eswaramoorthy, M., & Bhagat, A.K. (2023). An experimental study on flexible phase change material for compact electronic device applications. *Materials Today: Proceedings*, 90, 76-80.
- Farrell, A.J., Norton, B., & Kennedy, D.M. (2006). Corrosive effects of salt hydrate phase change materials used with aluminium and copper. *Journal of Materials Processing Technology*, 175(1-3), 198-205.
- Giro-Paloma, J., Martínez, M., Cabeza, L.F., & Fernández, A.I. (2016). Types, methods, techniques, and applications for microencapsulated phase change materials (MPCM): A review. *Renewable and Sustainable Energy Reviews*, 53, 1059-1075.
- Graham, M., Shchukina, E., De Castro, P.F., & Shchukin, D. (2016). Nanocapsules containing salt hydrate phase change materials for thermal energy storage. *Journal of Materials Chemistry A*, 4(43), 16906-16912.
- Gu, B., Dai, Z., Pan, H., & Zhao, D. (2024). Integration of prolonged phase-change thermal storage material and radiative cooling textile for personal thermal management. *Chemical Engineering Journal*, 493, 152637. <https://doi.org/10.1016/j.cej.2024.152637>.
- Gui, H., Li, Y., Du, D., Liang, F., & Yang, Z. (2021). High-performance phase change material capsule by Janus particle. *Materials Today Energy*, 20, 100702.
- Hekmat, S., Tavana, P., & Molaeimanesh, G. (2024). A novel compact battery thermal management system comprising phase change material, mini-channels, and fins suitable for EV battery packs. *Journal of Energy Storage*, 82, 110392.
- Hua, W., Yan, H., Zhang, X., Xu, X., Zhang, L., & Shi, Y. (2022). Review of salt hydrates-based thermochemical adsorption thermal storage technologies. *Journal of Energy Storage*, 56, 106158.
- Huang, Y., Stonehouse, A., & Abeykoon, C. (2023). Encapsulation methods for phase change materials—A critical review. *International Journal of Heat and Mass Transfer*, 200, 123458.
- Huo, X., Li, W., Wang, Y., Han, N., Wang, J., Wang, N., & Zhang, X. (2018). Chitosan composite microencapsulated comb-like polymeric phase change material via coacervation microencapsulation. *Carbohydrate Polymers*, 200, 602-610.
- Ishak, S., Lgaz, H., Mandal, S., Adnin, R.J., Lee, D.E., Lee, H.S., Harmay, N.S.M., Abdullah, M.M.A.B., Wang, X.Y., & Yang, H.M. (2023). Multi-technique investigation on the surface interaction of diatomaceous earth with organic phase change material: Experimental and molecular dynamics aspects. *Journal of Molecular Liquids*, 391, 123292.
- Ishak, S., Mandal, S., Lee, H.S., & Singh, J.K. (2021). pH-controlled synthesis of sustainable lauric acid/SiO₂ phase change material for scalable thermal energy storage. *Scientific Reports*, 11(1), 15012.
- Jing, Y., Zhao, Z., Cao, X., Sun, Q., Yuan, Y., & Li, T. (2023). Ultraflexible, cost-effective and scalable polymer-based phase change composites via chemical cross-linking for wearable thermal management. *Nature Communications*, 14(1), 8060.
- Karaipekli, A., & Sari, A. (2009). Capric–myristic acid/vermiculite composite as form-stable phase change material for thermal energy storage. *Solar Energy*, 83(3), 323-332.
- Kim, H., Hong, J., Choi, H., Oh, J., & Lee, H. (2024). Development of PCM-based shell-and-tube thermal energy storages for efficient EV thermal management. *International Communications in Heat and Mass Transfer*, 154, 107401.

- Li, H., Yuan, J., Yang, Z., Gu, Z., Wang, Y., Wang, T., Bao, J., Yang, T., Pei, L., & Jiang, H. (2024a). Heat dissipation performance research of battery modules based on composite phase change materials cooling and electrochemical thermal coupling model. *International Journal of Electrochemical Science*, 19(3), 100490.
- Li, J., Duan, W., Chen, Y., Chen, H., Song, M., Liao, S., Shi, E., & Sun, X. (2024b). Thermal performance of pin fin heat sinks with phase change material for electronic devices thermal management. *Applied Thermal Engineering*, 250, 123456.
- Li, J., Hu, X., Zhang, C., Luo, W., & Jiang, X. (2021). Enhanced thermal performance of phase-change materials supported by mesoporous silica modified with polydopamine/nano-metal particles for thermal energy storage. *Renewable Energy*, 178, 118-127.
- Liu, Y., Li, X., Xu, Y., Xie, Y., Hu, T., & Tao, P. (2024). Carbon-enhanced hydrated salt phase change materials for thermal management applications. *Nanomaterials*, 14(13), 1077.
- Man, X., Lu, H., Xu, Q., Wang, C., & Ling, Z. (2023). Review on the thermal property enhancement of inorganic salt hydrate phase change materials. *Journal of Energy Storage*, 72, 108699.
- Mandal, S., Ishak, S., Adnin, R.J., Lee, D.E., & Park, T. (2023a). An approach to utilize date seeds biochar as waste material for thermal energy storage applications. *Journal of Energy Storage*, 68, 107739.
- Mandal, S., Ishak, S., Ariffin, M.A.M., Lee, D.E., & Park, T. (2023b). Effect of pore structure on the thermal stability of shape-stabilized phase change materials. *Journal of Materials Research and Technology*, 25, 465-479.
- Mandal, S., Ishak, S., Lee, D.E., & Park, T. (2022a). Optimization of eco-friendly Pinus resinosa biochar-dodecanoic acid phase change composite for the cleaner environment. *Journal of Energy Storage*, 55, 105414.
- Mandal, S., Ishak, S., Lee, D.E., & Park, T. (2022b). Shape-stabilized orange peel/myristic acid phase change materials for efficient thermal energy storage application. *Energy Reports*, 8, 9618-9628.
- Mandal, S., Ishak, S., Singh, J.K., Lee, D.E., & Park, T. (2022c). Synthesis and application of paraffin/silica phase change nanocapsules: Experimental and numerical approach. *Journal of Energy Storage*, 51, 104407.
- McCord, M.R.Y., & Baniasadi, H. (2024). Materials today energy. *Materials Today*, 41, 101532.
- Memon, S.A., Lo, T.Y., Shi, X., Barbhuiya, S., & Cui, H. (2013). Preparation, characterization and thermal properties of Lauryl alcohol/Kaolin as novel form-stable composite phase change material for thermal energy storage in buildings. *Applied Thermal Engineering*, 59(1-2), 336-347.
- Nghana, B., & Tariku, F. (2016). Phase change material's (PCM) impacts on the energy performance and thermal comfort of buildings in a mild climate. *Building and Environment*, 99, 221-238.
- Okogeri, O., & Stathopoulos, V.N. (2021). What about greener phase change materials? A review on biobased phase change materials for thermal energy storage applications. *International Journal of Thermofluids*, 10, 100081.
- Qu, J., Liu, Y., Zhang, J., Jin, Z., Chen, Y., & Zhao, X. (2024). Experimental study on heat transfer during melting in metal and carbon foam saturated with phase-change materials for temperature control in electronic devices. *Applied Thermal Engineering*, 236, 121681.
- Sari, A., & Biçer, A. (2012). Preparation and thermal energy storage properties of building material-based composites as novel form-stable PCMs. *Energy and Buildings*, 51, 73-83.
- Singh, P., Sharma, R., Ansu, A., Goyal, R., Sari, A., & Tyagi, V. (2021). A comprehensive review on development of eutectic organic phase change materials and their composites for low and medium range thermal energy storage applications. *Solar Energy Materials and Solar Cells*, 223, 110955.
- Singh, R., Sadeghi, S., & Shabani, B. (2018). Thermal conductivity enhancement of phase change materials for low-temperature thermal energy storage applications. *Energies*, 12(1), 75. <https://doi.org/10.3390/en12010075>.
- Sivanathan, A., Dou, Q., Wang, Y., Li, Y., Corker, J., Zhou, Y., & Fan, M. (2020). Phase change materials for building construction: An overview of nano-/micro-encapsulation. *Nanotechnology Reviews*, 9(1), 896-921.

- Sun, M., Liu, T., Sha, H., Li, M., Liu, T., Wang, X., Chen, G., Wang, J., & Jiang, D. (2023). A review on thermal energy storage with eutectic phase change materials: Fundamentals and applications. *Journal of Energy Storage*, 68, 107713.
- Tang, Y.R., Gao, D.L., Guo, Y.F., Wang, S.Q., & Deng, T.L. (2011). Supercooling and phase separation of inorganic salt hydrates as PCMs. *Applied Mechanics and Materials*, 71, 2602-2605.
- Tripathi, B.M., & Shukla, S.K. (2024). A comprehensive review of the thermal performance in energy efficient building envelope incorporated with phase change materials. *Journal of Energy Storage*, 79, 110128.
- Xie, N., Luo, J., Li, Z., Huang, Z., Gao, X., Fang, Y., & Zhang, Z. (2019). Salt hydrate/expanded vermiculite composite as a form-stable phase change material for building energy storage. *Solar Energy Materials and Solar Cells*, 189, 33-42.
- Xu, C., Zhang, H., & Fang, G. (2022). Review on thermal conductivity improvement of phase change materials with enhanced additives for thermal energy storage. *Journal of Energy Storage*, 51, 104568.
- Yang, Y., Wu, W., Fu, S., & Zhang, H. (2020). Study of a novel ceramsite-based shape-stabilized composite phase change material (PCM) for energy conservation in buildings. *Construction and Building Materials*, 246, 118479.
- Zare, M., & Mikkonen, K.S. (2023). Phase change materials for life science applications. *Advanced Functional Materials*, 33(12), 2213455.
- Zhang, P., Xiao, X., & Ma, Z. (2016). A review of the composite phase change materials: Fabrication, characterization, mathematical modeling and application to performance enhancement. *Applied Energy*, 165, 472-510.
- Zhang, Z., & Fang, X. (2006). Study on paraffin/expanded graphite composite phase change thermal energy storage material. *Energy Conversion and Management*, 47(3), 303-310.
- Zhao, B., Wang, Y., Wang, C., Zhu, R., Sheng, N., Zhu, C., & Rao, Z. (2021). Thermal conductivity enhancement and shape stabilization of phase change thermal storage material reinforced by combustion synthesized porous Al₂O₃. *Journal of Energy Storage*, 42, 103028.



The original content of this work is copyright © Ram Arti Publishers. Uses under the Creative Commons Attribution 4.0 International (CC BY 4.0) license at <https://creativecommons.org/licenses/by/4.0/>

Publisher's Note- Ram Arti Publishers remains neutral regarding jurisdictional claims in published maps and institutional affiliations.