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A review article on micro-encapsulated phase change materials

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ABSTRACT

This article offers an exhaustive overview of micro-encapsulated phase-change materials (PCMs), addressing thermal-energy storage mechanisms, operating principles, classifications (eutectic, inorganic, organic), encapsulation techniques, shell materials, fields that incorporate microencapsulated additives—including textile applications—and drawing on more than 50 up-to-date sources. Microencapsulation encloses active agents within ultra-small capsules, a method already utilized in textiles, agriculture, printing, food processing, and defense sectors; PCMs store or release substantial latent heat when shifting between solid and liquid states. Challenges arose in harmonizing disparate synthesis pathways and core-shell pairings from various disciplines and in surfacing safety issues scattered throughout the literature. Nonetheless, the work contributes by systematically grouping PCMs and shells, compiling physical, chemical, and physico-chemical encapsulation methods into a comparative decision matrix, illustrating organic PCMs' textile superiority despite reduced fabric strength, expanding application maps to biomedicine, solar-to-thermal and electric-to-thermal storage beyond buildings and aerospace, and assembling over 50 studies into one consolidated reference. Thus, microencapsulation proves to be a flexible platform for customizing PCMs toward efficiency, safety, and broad practical deployment—paving the way for advanced energy solutions.

Keywords: *Microencapsulated phase change materials (PCMs),Thermal energy storage(TES),Latent heat, Core materials, Shell materials, Microencapsulation techniques, Phase Changing Material, Microencapsulation, etc.*

Introduction

The process of microencapsulation involves enclosing material in a tiny shape called a capsule [1]. By producing a continuous film of polymeric material, microencapsulation offers the covering of solid, liquid, and gaseous components. In 1931 [2], Bungen Berg de Jong and Kahn published the first study in this field. It can aid in the solidification of liquids by altering their surface and colloidal characteristics [1]. For the dispersion of tiny liquid droplets or solid particles, microencapsulation offers a thin covering [3]. Microcapsules have a homogeneous wall surrounding them and have a spherical shape [1].

Phase change materials are substances that go through the phase change process (PCM). They absorb heat when they return to their liquid state after becoming solid, and they emit heat as they do so [4]. The temporary storing of high- or low-temperature energy for later use is known as thermal energy storage (TES). It closes the time gap between energy consumption and energy production. The ability to offer large storage densities at almost isothermal circumstances makes covert heat storage one of the more alluring methods of heat storage among the numerous ones of interest. Other benefits of phase-change thermal energy storage systems include smaller units, lower weight per unit of store capacity, and a smaller temperature difference between the storage and recovery cycles [5].

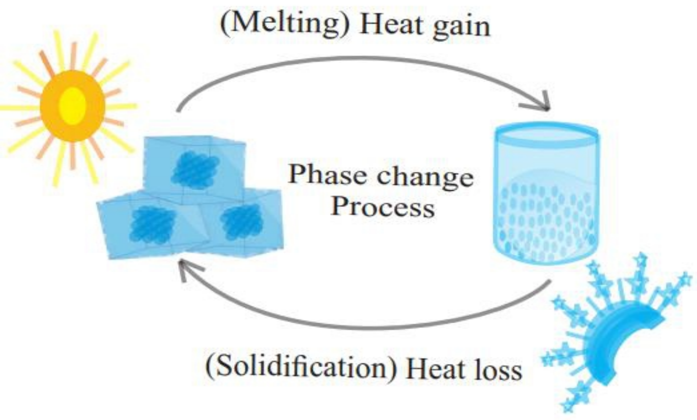

Fig.1. Pictorial presentation of phase change process

Technology and economic development are essential for the improvement of societies worldwide, and energy is the primary requirement [3]. The tendency has been a tendency to change in favor of the usage of sustainable energy resources due to the relentless depletion of non-renewable resources and the growing global warming scenario [2,3]. To meet the needs for both electrical and thermal energy conversion and storage, it is essential to investigate renewable and sustainable resources. Integrating renewable energy sources with various thermal energy storage devices that have round-trip efficiencies of >96% will enable the energy sector to become decarbonized [4,5].

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Currently, renewable energy sources account for nearly 18% of global energy consumption [6]. Due to their ongoing accessibility, environmental friendliness, and long-term availability, renewable energy sources are indisputably preferred over the use of nonrenewable resources [7]. However, the intermittent nature of renewable energy sources, notably solar and wind energy, is a major impediment to their ability to provide energy continuously and requires unique measures for flexibility [8]. A complementary approach is being used in the deployment of integrated/hybrid energy systems, which combine several technologies to reduce peak power consumption (load leveling) [9, 10]. To compensate for the erratic nature of renewable energy sources, most hybrid systems use an auxiliary heater as a backup energy source based on carbon-based fuels [11].

However, by applying thermal energy storage (TES) to efficient and cleaner energy systems, increasing the reliability of thermal energy from renewable sources, and ultimately reducing the use of carbon-based fuels, the dependence on secondary energy sources and fuels can be reduced [12,13]. Additionally, TES systems can be used to store excess energy and provide power during times of peak power demand if energy output exceeds energy consumption. [14,15].

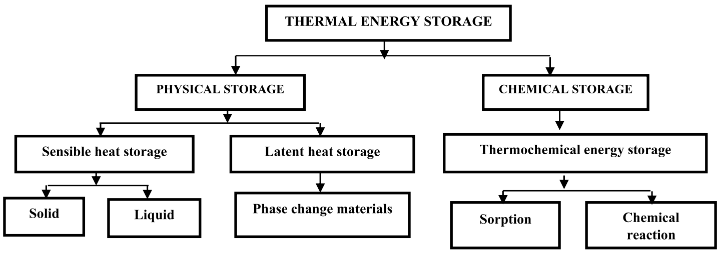

Fig: 2. classification of thermal energy storage

Thermal energy storage

There are several methods for incorporating TES into energy systems that use non-renewable resources, such as waste heat recovery, or even renewable energy sources, like solar, wind, geothermal, and hydro [13]. Both chemical and physical approaches, as seen in Fig. 3, can be used to store thermal energy, as will be addressed further below.

2.1. Physical methods of thermal energy storage

In physical TES, the heat transfer processes result in the storage of the heat energy, and the capacity to do so depends on the thermophysical characteristics of the material. Physical storage includes both sensible and latent heat capacity (LHS and SHS). In the SHS, thermal energy is stored as internal energy brought on by an increase in the temperature of the specific material due to heat transmission by conduction, convection, or radiation, whereas in the LHS, heat is accumulated at the molecular level in a material, causing phase transformation [28,34,35].

The mass, heat capacity of the storage material, and temperature difference between the initial and final states all have a role in how much heat is stored in SHS. As depicted in Fig. 3, the SHS can be carried out in either a solid or liquid storage medium. Metals and non-metals are commonly utilized in the case of a solid storage medium. Non-metallic materials such as concrete, rock, gravel, brick, marble, granite, sandstone, and so forth are candidates, but their low specific heat capacity and thermal conductivity are the main challenges to the reliability of this method of storage [36,37,38,39].For high-temperature SHS, metals including copper, aluminium, cast iron, and pure iron are suitable, along with other alloys, but the greater cost of the TES system using these metals is a significant barrier to commercialization [40].

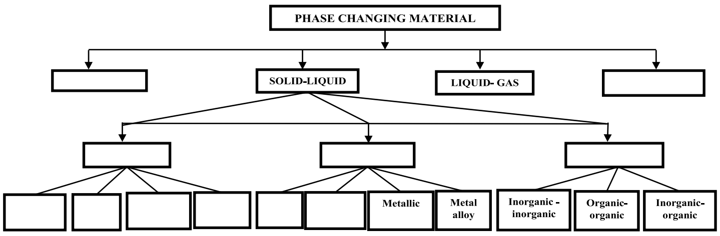

Fig : 3. classification of phase-changing materials

Rock, gravel, and stone have low thermal diffusivities and are more appropriate for applications involving long charging and discharging cycles. Metals and graphite, on the other hand, have high thermal diffusivities and are thus suitable for applications involving fast charging and discharging. Molten salts, water, thermal oils as Calorie HT43, and other commercially available materials are examples of liquid storage media for SHS, however, due to their low energy density and thermal conductivity, these TES are not as widely applicable [40]. Water has a high specific heat capacity, making it one of the most promising SHS candidates for temperatures below 100 C [41,42]. Molten salts, on the other hand, have very good thermophysical properties and are being used in a variety of high-temperature TES applications [43]. To stop corrosion, special precautions must be taken for storage assembly, which raises the cost of the storage system as a whole [44,45,46].

The mass and latent heat of fusion of the PCMs affect the heat storage capacity of LHS. Due to the phase change caused by the material's temperature increase, the sensible and latent heat equations are both included in the energy storage equation for PCMs. According to the phase of the material being considered, the latent heat absorbed during this process is either called the latent heat of vaporization or the latent heat of fusion, which is how PCMs function by absorbing a significant amount of heat when reaching the phase change temperature, which is required for phase transition [19,47].

Table:1a. Physical properties of some paraffin's

Paraffin[a]	Freezing point/ range (◦C)	Heat of fusion (kJ/kg)	Group[b]
6106	42–44	189	I
P116[e]	45–48	210	I
5838	48–50	189	I
6035	58–60	189	I
6403	62–64	189	I
6499	66–68	189	I

[a] = Manufacturer of technical Grade Paraffin's 6106, 5838, 6035, 6403 and 6499: Ter Hell Paraffin Hamburg, FRG.

[b] =Group I, most promising; group II, promising; group III, less promising; — insufficient data.

[c] =Manufacturer of Paraffin's P116: Sun Company, USA.

Table: 1b. Melting point and latent heat of fusion: paraffins

No. of carbon atoms	Melting point (◦C)	Latent heat of fusion (kJ/kg)	Group[a]
14	5.5	228	I
15	10	205	II
16	16.7	237.1	I
17	21.7	213	II
18	28.0	244	I
19	32.0	222	II
20	36.7	246	I
21	40.2	200	II
22	44.0	249	II
23	47.5	232	II
24	50.6	255	II
25	49.4	238	II

[a]= Group I, most promising; group II, promising; group III, less promising; — insufficient data

2.2. Chemical methods of thermal energy storage

Due to the reversible reaction, energy is stored and released in chemical TES. Thermochemical energy storage and sorption storage are two categories of chemical TES technologies [48–51]. Solid-gas, liquid-gas, and gas phase systems are included in thermochemical energy storage. Because of a dissociation reaction that is followed by a chemically reversible reaction, energy is stored in thermochemical heat storage, and its thermal cycle entails charging, storing, and discharging [54].

The quantity of heat stored in solid-gas thermochemical energy storage relies on the gas pressure, whereas Kuwata et al. found that the heat transfer coefficient in liquid-solid systems is much higher than that in gas-solid systems [55]. In the case of the solid-liquid reaction of strontium chloride and ammonia for thermochemical heat storage, they have also reported the short-term cyclic stability. According to their operating temperature and reaction enthalpy, different metal carbonates, oxides, and hydroxides have been reported as promising thermochemical energy storage materials by Andre et al. based on solid-gas reversible reactions [53].

2.3. Comparison of sensible, latent, and chemical thermal energy storage

Fig. 4 provides an overview of the operating temperature range, storage density, commercial viability, and durability of the TES made up of sensible, latent, or chemical energy storage methods. Due to the significant enthalpy shift during the phase transition, the storage density of LHS medium is often higher than that of SHS medium, while thermochemical energy storage has the highest density in comparison to the other two modes. There are currently no commercially available systems; however, several thermochemical energy storage materials are in the development stage.

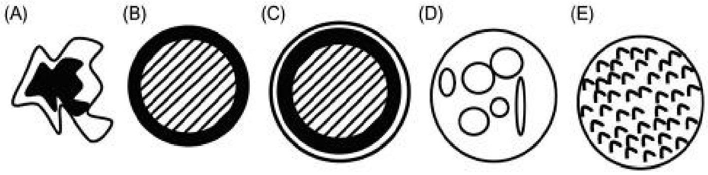

Fig: 4. Possible morphologies of microcapsules (a) irregular shape; (b) simple; (c) multi-wall; (d) multi-core; and (e) matrix particle. (https://images.app.goo.gl/VnZa6brtoUJNNSAN6)

In contrast to SHS, which has been heavily marketed, the LHS is in the development stage due to material properties that limit its commercial feasibility. In contrast to thermochemical energy storage, which has a lifespan of only about one-tenth that of SHS materials and LHS materials, which have a lifespan of around one-fourth of that of SHS materials, it is clear from Fig. 4 that the durability of SHS materials is approximately 20 years [56]. The operating temperature range for LHS, which is one of several forms of TES, is the broadest, followed by the significantly smaller operating temperature ranges for sensible and thermochemical energy storage [33]. The advantage of employing latent heat over sensible heat storage technology is that it has a 10 times greater TES density, a capacity of 50-150 kWh/t, and a round-trip efficiency of 75–96% [57, 58].

Working principle of phase change materials (PCMs)

A crucial method for using thermal energy is thermal energy storage [13]. The use of sensible heat, use of latent heat, use of reversible chemical heat, and use of heat of dilution are the four options for thermal energy storage. Solid, liquid, gas, and plasma are the four states of matter.

The phase change is the term used to describe the transition of a material between two states. There are four different types of phase changes, including (a) liquid to gas and (b) liquid to liquid. solid to solid, solid to gas, and solid to solid. The phase transition process involves the absorption or release of heat. Latent heat is the term for the absorbed or released heat energy. The most popular latent heat storage material is PCM, which can change from a solid to a liquid or a liquid to a solid state. It may be used to make fabrics and garments that can store heat and control body temperature.

Modes of heat transfer are strongly depend [14] on the phase of the substances involved in the heat transfer processes. For solid substances, conduction is the predominant mode of heat transfer. For liquids, convection heat transfer predominates, and for vapors, convection and radiation are the primary mode of heat transfer. For textile applications, we will only consider the phase change from solid to liquid and vice versa.

Phase change materials as such are not new [15,16]. They already exist in various forms in nature. The most common example of a PCM is water at 0 C, which crystallizes as it changes from liquid to solid (ice) [16]. A phase change also occurs when water is heated to a temperature of 100 C at which point it becomes steam. To compare the amount of heat absorbed by a PCM during the actual phase change with the amount of heat absorbed in an ordinary heating process, water can be used for comparisons. When ice melts into water, it absorbs approximately a latent heat of 335 kJ/kg. When water is further heated, the sensible heat of only 4 kJ/kg is absorbed while the temperature rises by one degree Celsius.

1. Methods of encapsulation of PCM

The system core/shell is a key point in the fabrication of microcapsules, being the shell function to protect the core, and the core function to contain the active material, in this case the PCM. The MPCM morphology can be diverse as Fig. 4 shows, but the most common are the spherical and the irregular ones. The microcapsule description and their morphology depend on the core material and the deposition process of the shell. There are four types, as Fig. 5 shows:

a. Mononuclear (core/shell): a single core wrapped with a continuous shell material.

b. Polynuclear: many cores coated with a continuous shell material.

c. Matrix encapsulation: in which the core material is distributed homogeneously into the shell material.

d. Multi-film: a continuous core coated with a multilayer continuous shell material.

There are three different methodologies to microencapsulate PCM based on the mechanisms of microparticle formation: chemical, physical, and chemical, or physical and mechanical mode.

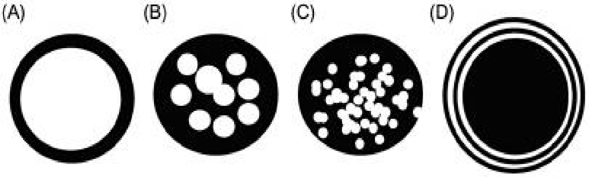

Fig: 5. Scheme of the types of MPCM, adapted from (a) mononuclear; (b) polynuclear; (c) matrix encapsulation; and (d) multi-film (https://images.app.goo.gl/VnZa6brtoUJNNSAN6)

Type of Phase change materials (PCMs)

Phase change materials are theoretically able to change state at nearly constant temperature and therefore to store large quantity of energy [17]. Using the thermal energy storage (TES) of phase change material (PCM) which has a melting point from 15 to 35 ◦C is one of the most effective ideas for the effective utilization of this kind of material in the textile field. In addition to water, more than 500 natural and synthetic PCMs are known [18]. These materials differ from one another in their phase change temperature ranges and their heat storage capacities. The required properties for a PCM for a high-efficiency cooling system with a thermal energy system (TES) for specific application [19] such as in textile fields are as follow; melting point between 15 and 35 C, large heat of fusion, little temperature difference between the melting point and the solidification point, harmless to the environment, low toxicity, non-flammable, stability for repetition of melting and solidification, large thermal conductivity, for effective heat transfer, ease of availability and low price.

A wide spectrum of phase change material is available with different heat storage capacities and phase change temperatures. A simple and classical example of phase change materials is the paraffin wax leads ranging from 15 to 40 um in size, which can be microencapsulated and then either integrated into a fiber or used as a coating. Some of the PCMs are described in the following paragraphs:

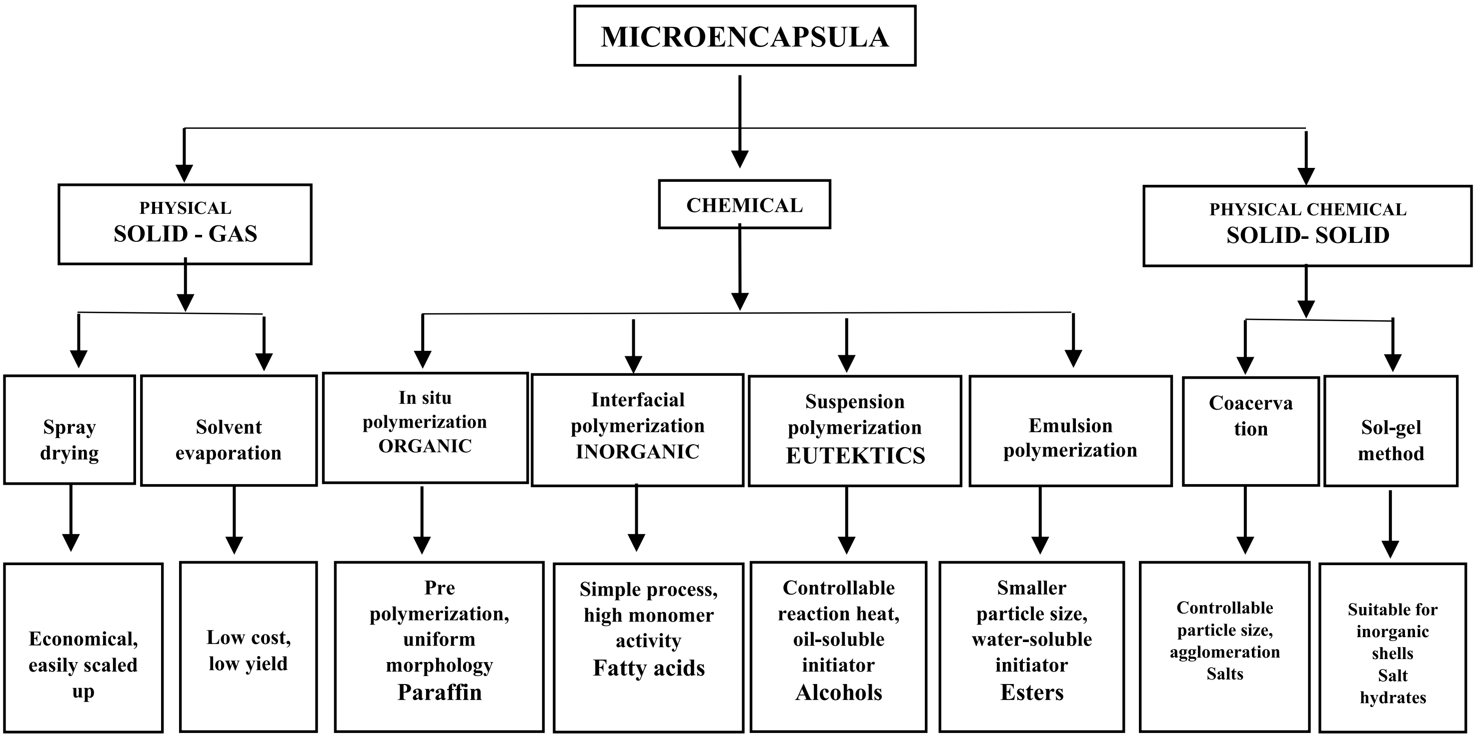

Fig: 6. classification of microencapsulation methods for PCMs

Organic phase change materials

Organic materials are further described as paraffin and nonparaffin. Organic materials include congruent melting means melt and freeze repeatedly without phase segregation and consequent degradation of their latent heat of fusion, and self-nucleation means they crystallize with little or no supercooling and usually non-corrosive.

Non-paraffins

The non-paraffin organic are the most numerous of the phase change materials with highly varied properties. Each of these materials will have its own properties unlike the paraffin's, which have very similar properties. This is the largest category of candidates' materials for phase change storage. Abhat et al. [11] , Buddhi and Sawhney [9] have conducted an extensive survey of organic materials and identified several esters, fatty acids, alcohol and glycols suitable for energy storage.

These organic materials are further subgroups as fatty acids and other non-paraffin organic. These materials are flammable and should not be exposed to excessively high temperatures, flames, or oxidizing agents. Few non-paraffins are tabulated in Table 2. Some of the features of these organic materials are as follows: high heat of fusion, inflammability, low thermal conductivity, low flash points, varying levels of toxicity, and instability at high temperatures.

Table: 2. Melting point and latent heat of fusion: non paraffins

Material	Melting point (◦C)	Latent heat (kJ/kg)	Group^a
Formic acid	7.8	247	III
Caprilic acid	16.3	149	_
Glycerin	17.9	198.7	III
D-Lattic acid	26	184	I
Methyl palmitate	29	205	II
Camphenilone	39	205	II
Docasyl bromide	40	201	II
Caprylone	40	259	II
Phenol	41	120	III
Heptadecanone	41	201	II
1-Cyclohexylooctadecane	41	218	II
4-Heptadacanone	41	197	II
p-Joluidine	43.3	167	_
Cyanamide	44	209	II
Methyl eicosanate	45	230	II
3-Heptadecanone	48	218	II
2-Heptadecanone	48	218	II
Hydrocinnamic acid	48.0	118	_
Cetyl alcohol	49.3	141	_

Inorganic phase change materials

Inorganic materials are further classified as salt hydrate and metallics. These phase change materials do not supercool appreciably, and their heats of fusion do not degrade with cycling.

Eutectics phase change materials

A eutectic is a minimum-melting composition of two or more components, each of which melts and freeze congruently, forming a mixture of the component crystals during crystallization. Eutectic nearly always melts and freeze without segregation since they freeze to an intimate mixture of crystals, leaving little opportunity for the components to separate. On melting both components liquefy simultaneously, again with separation unlikely.

Types of shell

There are over 50 different polymers known that can be used as wall materials in microencapsulation: both natural and synthetic polymers, controlling release under specific conditions. The shell coating materials must have some properties or requirements. The polymer should be capable of forming a thin film that must be cohesive with the core material, being tasteless, pliable, and stable. It should be chemically compatible and non-reactive with the core material, and soluble in an aqueous media or solvent. Moreover, it should provide the desired coating properties such as strength, flexible, impermeability, optical properties, and stability. The film thickness can be varied considerably depending on the surface area of the material to be coated, and other physical characteristics of the system. Besides, the shell coating material must be non-hygroscopic, with medium/low viscosity, and low cost.

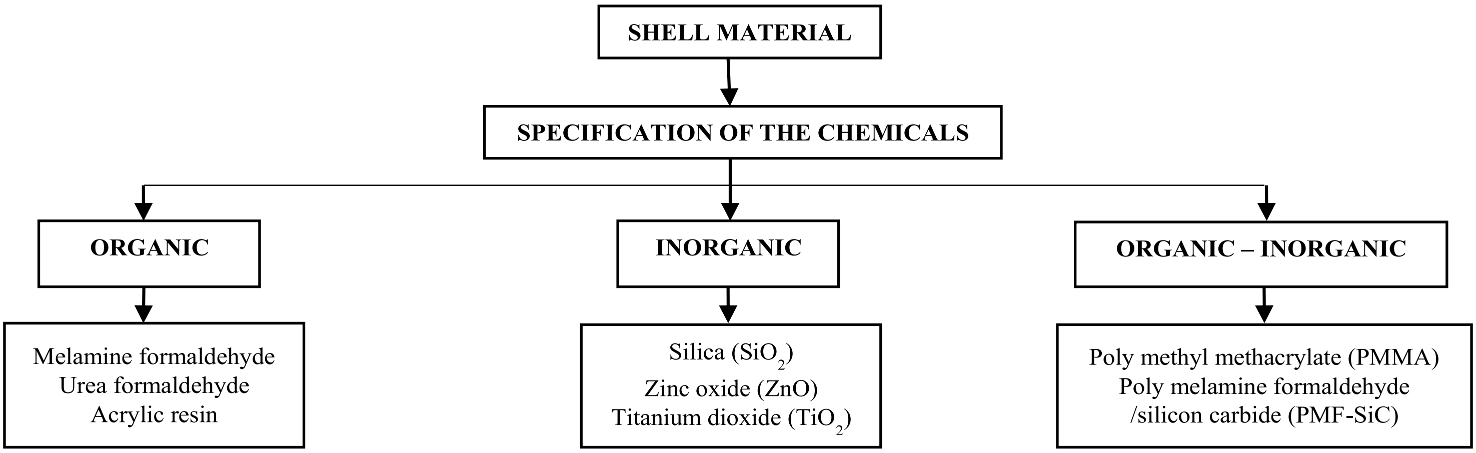

Fig: 7. different type of shell material

Types of microencapsulated phase change materials (MPCM)

There are several studies about MPCM, where choosing the combination shell/core is the most important point. The proportion of core material in the capsule is usually between 20% and 95% by mass [46]. The microcapsules may consist on a single particle or clusters of particles. Paraffin wax is one of the most employed PCM in MPCM systems. Among paraffins, n-octadecane is the PCM most used microencapsulated in building applications [47–51].

There are a lot of studies about the shell. One possibility is the transparent and thermoplastic acrylic polymer for the shell [6], such as poly(methyl methacrylate) (PMMA) [56–60]. It has good mechanical properties and good protection against the environment. For these reasons, PMMA is an adaptable material and it is a good polymer as shell material in the preparation of MPCM for thermal energy storage applications. Moreover, as an example of commercial MPCM, BASFs has a variety of products with PMMA as shell material. As examples of studies with BASFs materials, Tzevetkov et al. [61] studied one of the products, Micronals, using scanning transmission X-ray spectroscopy. This PMMA has good compatibility with a wide variety of PCM, for example with fatty acids, such as stearic acid, palmitic acid, myristic acid and, lauric acid as studied by Alkan et al. [62]. Besides, Giro-Paloma et al. [63] evaluated in detail the physical, chemical, and mechanical properties of Micronals DS 5001.

Another polymeric shell very employed is the melamine–formaldehyde (MF). Su et al. [64] studied the influence of temperature in deformation, concluding that the yield point of MPCM decreased with the increase of temperature. Also, Palani k Kumaran et al. [65] used the MF shell to contain n-octadecane as PCM using the in-situ polymerization technique.

In Table 3 list of some manufacturers trademark name, the PCM they use, the shell material, and the particle size distribution (PSD), and its application is shown.

Table: 3. Manufacturers of MPCMs

Trademark name	PCM	Shell material	PSD	Application
Cristopia ClimSel/climator	Eutectic salts Sodium acetate, sodium sulfate	polyolefin	77 mm	Industrial refrigeration, conditioning, clothing, air-conditioning, electronic cooling, fire protection
Rubitherm	Paraffin, salt hydrate in granulate, powder and compounds forms	Plastic	–	Storage and transport food, medical equipments, storage materials for textile
LatestTM/TEAP Energy	glauber's salt, soda ash, sodium acetate, and paraffin wax	polyethylene	25.4 mm	Hot pads and solar heating telecom enclosure, back-up air-conditioning, cold storage
PCM Products Ltd.	Eutectics, salt hydrates, organic materials, and high temperature salts	Rubber, HDPE plastic	40 mm	Space International space station, automotive passive cooling, solar heating and heat recovery
MPCM Microtek Laboratories Inc	Paraffin	Polymer	17–20 µm	Active wear clothing, woven and non-woven textiles, building materials, packaging, and electronics
Micronals /BASF	Paraffin wax	Polymer	5 µm	Building conditioning, surface cooling
Aegis	Inorganic salts	High density polyethylene	75 mm	Cold storage, boilers, solar water heaters, transport of blood, frozen food, fruits and vegetables

Applications of PCMs applied in the field of textiles

Due to its distinctive qualities, such as; chemical and thermal stabilization, a higher number of energy changes and a suitable solid-to-liquid phase transition, PCM microcapsules broaden the application fields of PCMs. PCM microcapsules offer a dependable method for combining PCMs with polymer and other structural materials, which lowers toxicity and shields core material from the effects of the environment.

The use of PCM microcapsules in the textile industry is an old topic, but academics are becoming more and more interested in it. For added protection from extremely cold conditions, PCM microcapsules, for instance, are utilized in outdoor clothing, including snowsuits, pants, ear warmers, boots, and gloves [78-80]. To increase their thermal storage capacities (by 2.5–4.5 times compared to the reference fabric/fiber for specific temperature intervals), PCM microcapsules can be embedded within the fiber or coated on the surface of the fabric [81]. According to Sarier et al., the PCM microcapsules with silver nanoparticles displayed increased thermal conductivity, high thermal stability, and high thermal storage capacities. This technology therefore has potential for textile sector applications such as sportswear/protective apparel, medicinal textiles, and textiles for the automotive and agricultural industries [82]. According to Nejman et al., the padding method produced modified fabric with the highest air permeability and the lowest gas permeability, whereas the printing method produced modified fabric with the lowest gas permeability and the largest enthalpy value [79]. The thermal and antimicrobial properties of cotton were studied by Scacchetti et al. using silver zeolite functionalized by a chitosan zeolite composite and PCM microcapsules [80]. They suggested using chitosan zeolite to produce textiles because it has superior antibacterial and thermoregulating properties. As additions, PCM microcapsules enhance the textiles' thermal comfort and flame-retardant qualities. The outcomes demonstrated that PCM microcapsules were uniformly dispersed over textile substrates and were stable after numerous washings [81]. The results of the thermal history measurement also provided support for the fabrics with PCM microcapsules' thermoregulating abilities.

Various coating materials used in microencapsulation:-

Coating material for microcapsules is a layer that envelops the core, must dissolve in aqueous media or solvents and enable controlled release under specific conditions; it should be flexible, strong, stable, impermeable, optically clear, chemically compatible, film-forming, pliable, tasteless, non-hygroscopic, economical, and low-viscosity [1],[76,77]. Typical examples include vegetable gums (gum arabic, agar, carrageenan, dextran sulphate, sodium alginate), celluloses (cellulose acetate phthalate, ethyl cellulose, nitrocellulose, cellulose acetate butyrate phthalate, carboxymethyl cellulose) [67], homopolymers (polyvinyl acetate, polystyrene, polyethylene, polyvinyl alcohol, polyvinyl chloride), copolymers (acrylic-acid, methacrylic-acid, maleic-anhydride), curable polymers (nitrated polystyrene, epoxy resins, nitroparaffin)[50], condensation polymers (polycarbonate, amino resins, nylon, Teflon, silicone resins, polymethane), proteins (fibrinogen, hemoglobin, collagen, casein, gelatin, polyamino acids), and waxes (paraffin, beeswax, oil, fats, rosin shellac, monoglyceride, tristearin[76],[55].

2. Common Techniques for Measuring PCMs Thermal Properties

2.1. Differential Scanning Calorimeter (DSC) is a technique that measures the thermal effects on materials as they are heated or cooled and undergo thermal transitions. DSC makes it possible to analyze and quantify the material's energy absorption and release in appropriate temperature ranges. The equipment heats and cools a sample in a controlled manner and records the material's temperature of its phase transitions (melting and crystallization). The instrument also records the amount of energy required to melt the sample and the amount of energy released when the sample crystallizes upon cooling.[80]

The diagram in Fig. 8 illustrates a phase change material. The top curve is the heating or energy increase and melting curve and the bottom curve is the cooling and crystallization data.

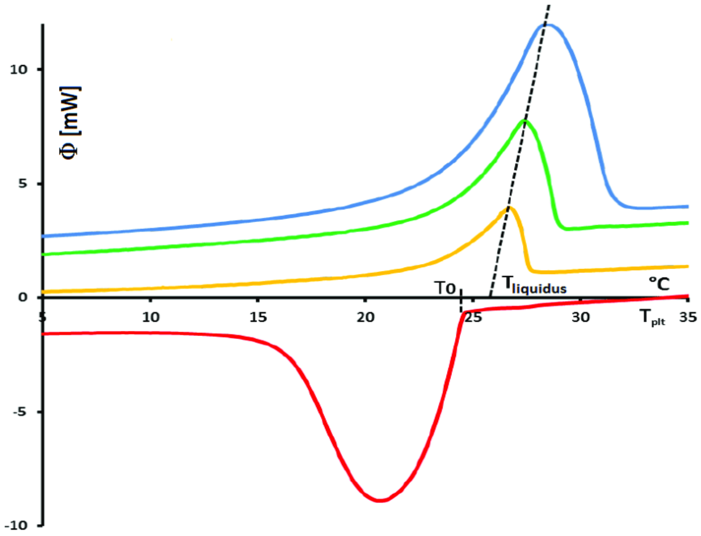

Fig. 8 – DSC curves for a PCM at the cooling rate of = 5 K/min (red curve) , the heating rate of = 5 K/min (blue curve), 2 K/min (green curve), and 1 K/min (orange curve), with drawings to determine Liquidous and TC. (https://images.app.goo.gl/WS79e6H9dBYgbbWU9)

2.2. Fourier Transform Infrared Spectroscopy (FTIR) is a powerful tool for identifying types of chemical bonds in a molecule by producing an infrared absorption spectrum. Figure 9 displays the FT-IR spectra of decanoic acid, poly (styrene-co-ethyl acrylate), and the micro- and macro-encapsulated PCM. -C-H stretching in the aliphatic groups was noted at 2,850–2,900/cm, as shown in the core material spectra, and the stretching was significantly apparent at microcapsulated and microcapsulated spectra. Core material and poly (styrene-co-ethyl acrylate) spectrums showed distinctive carbonyl -C14O strains at 1,700/cm, and co-polymer unique stretching phenyl ring oop Styrene's -C-H bending was noticed at 700/cm, and the stretching was visible in the PCM spectra of both the micro- and macro capsules. These facts show that decanoic acid successfully encapsulates at both the micro and macro levels [81].

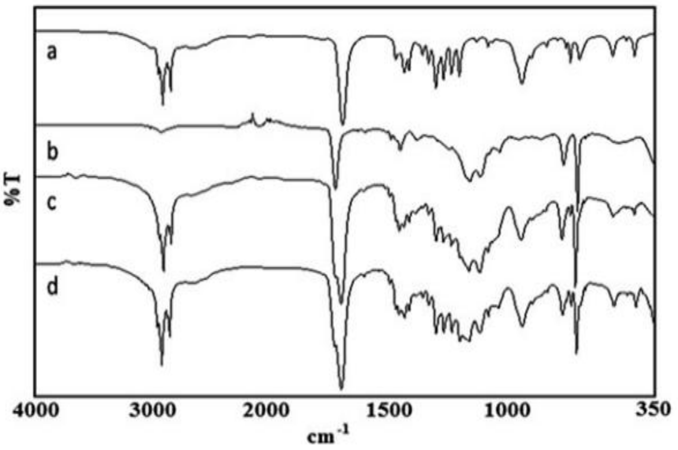

Fig: 9. Microcapsulated and macrocapsulated FT-IR spectra (a) decanoic acid, (b) poly (styreneco-ethylacrylate), (c) microPCM, (d) macroPCM

2.3. Thermal Gravimetric Analysis (TGA):

Figure 10 shows TGA curves of microencapsulated PCMs and wall material as a function of temperature. According to the DSC curves' form, n-hexadecane deteriorated before n-eicosane as the temperature of fusion rose, and the binary mixture ceased to behave as a molecular alloy. The first step began at 220 °C and reached its maximum weight loss rate at 235 °C; the second step began at 330 °C and reached its maximum weight loss rate at 370 °C because of the release of the trapped gas in the particle; and the third step occurred in the temperature range of 400 °C to 700 °C. Even though the wall material was stable up to 220 °C, n-eicosane was determined to be appropriate for textile application with a wide temperature range from -5 to 30 °C, while microcapsules were only suitable for coating processes under 150 °C[82,83].

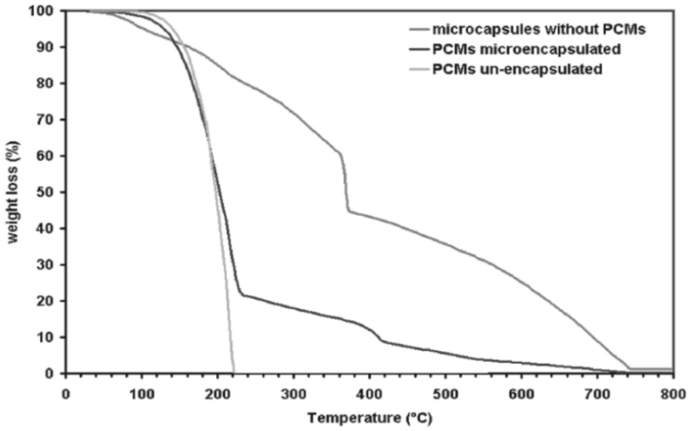

Fig: 10. Thermal Gravimetric Analysis (TGA) curves of microcapsules with and without PCM

CONCLUSION

This review unpacks microencapsulated phase-change materials (PCMs) for thermal-energy storage, presenting a crisp snapshot of the field. We spotlight three PCM families—eutectic, inorganic, and organic—plus three shell-material classes: organic, inorganic, and hybrid. Three encapsulation routes—physical, chemical, and physico-chemical—are dissected, revealing why organic PCMs dominate textile applications: they're non-corrosive, chemically stable, thermally robust, and suffer minimal undercooling—though adding them can trim fabric strength and elongation. Shell choice spans natural to synthetic polymers, dictated by core requirements and end-use, underscoring that core/shell pairing and synthesis conditions dictate thermal, physical, chemical, and mechanical performance. Applications stretch from buildings and space systems to active sportswear and medical devices, with emerging niches in biomedicine, solar-to-thermal, and electric-to-thermal storage. In short, microencapsulation offers a versatile toolbox to tailor PCMs for efficiency, safety, and diverse real-world impact—setting the stage for smarter energy solutions.

Future Scope of the study:

Advance hybrid shell designs to preserve fabric strength, unify safety standards, enable microfluidic mass-production for biomedicine and thermal storage, embed IoT sensors in buildings/aerospace for live heat tracking, and test deep-eutectic PCMs for ultra-low-temperature defense/food applications.

Ethical Considerations:

The study adhered to strict ethical principles, including transparent authorship, rigorous APA citations, plagiarism checks, no primary data, safety warnings, disclosure of conflicts, and compliance with journal ethics.

Conflict of Interest:

The authors have declared that no conflict of interest exists.

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