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Review

Fabrications, Classifications, and Environmental Impact of PCM-Incorporated Textiles: Current State and Future Outlook

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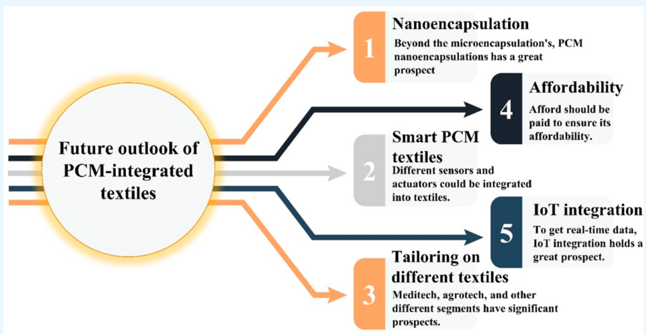
ABSTRACT: Phase change materials (PCMs) are an extraordinary family of compounds that can store and release thermal energy during phase changes. In recent years, the incorporation of PCMs into textiles has attracted considerable interest, since it represents a unique way to improve the comfort and usefulness of textiles. This article examines the advancements achieved in the preparation, classifications, and environmental effects of PCM-integrated textiles, along with a roadmap for the future. Progress of different PCM has been reported including its pros and cons. In addition, fabrications of the PCM on the apparel have been highlighted. Moreover, this Review analyzed the positive environmental impact of PCM-integrated textiles including improved insulation, extended product lifespan, and energy savings along with negative effects like higher energy consumption in the manufacturing process, added chemical additives tending to have a negative impact on the environment, less disposal features textiles and many more with recent references. Moreover, the future outlook also reports more research on nanoencapsulation, making it energy efficient, ensuring affordability, and more applications in smart PCM textiles. It seeks to stimulate additional research, encourage innovation, and contribute to the creation of high-performance, energy-efficient textiles by investigating the possibilities of PCM-enhanced textiles. The future of PCM in textiles is hopeful, with continuous research and technological advances resolving the aforementioned difficulties.



1. INTRODUCTION

The incorporation of phase change materials (PCM) into textiles has emerged as an interesting and potentially fruitful option for improving the operational performance of fabrics as well as their thermal comfort. PCM-incorporated textiles offer unique properties that enable them to regulate temperature and provide adaptive heat management.[1] Because of these capabilities, PCM-incorporated textiles are highly relevant for a wide range of applications, ranging from clothing and outdoor textiles to building materials[2] and home furnishings.[3,4] The increasing interest in PCM-incorporated textiles can be attributed to the potential of these materials to improve energy efficiency, decrease reliance on conventional heating and cooling systems, and contribute to the creation of a living environment that is both more sustainable and more comfortable.

In addition, when researchers and engineers have a firm grasp on how to categorize PCM, it paves the way for more effective and individualized thermal management solutions across a wide range of sectors using PCM-incorporated textiles.[5] The chemical composition and origin of textile PCM allows for several categorizations. PCM's unique features and prospective textile engineering applications can only be understood through its categorization. One common scheme divides PCM into organic, and inorganic, and those categories are divided into subcategories. Natural or manufactured organic compounds are used to create organic PCMs, and these materials have a high latent heat storage capacity and may have their phase transition temperatures adjusted.[6] Salts, metals, and other inorganic materials are used to make inorganic PCMs, which are characterized by high heat conductivity and stability.[7] Much research is progressing by using various types of PCM with various polymers and its unique features.[8−10]

Moreover, the techniques of PCM incorporation in textiles is classified into fiber technology, coating, and lamination. In fiber technology, PCM particles or capsules are directly woven

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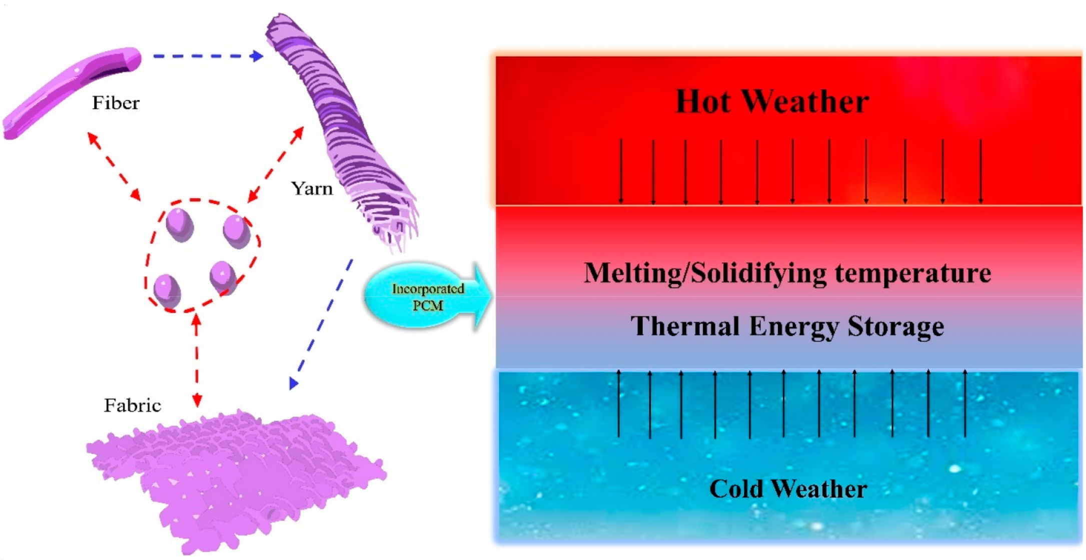

Figure 1. Basics of incorporation of PCM in textiles.

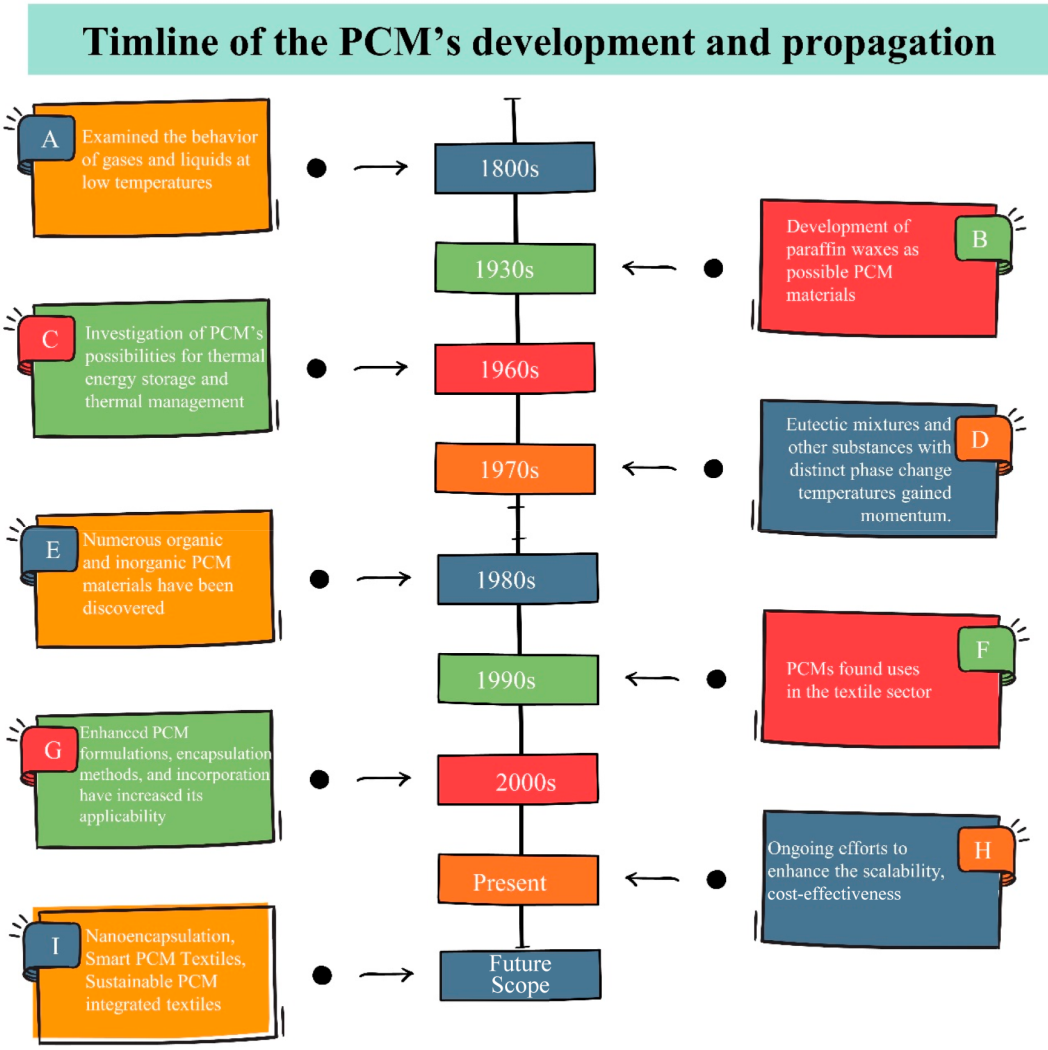

Figure 2. Chronological development of PCM.

into textile fibers while they are being spun. This makes sure that the phase change behavior is uniform and lasts for a long time. Coating, on the other hand, adds a layer of PCM to the surface of the fabric.[11] This lets the PCM content and distribution be carefully controlled. With this method, you can change how well the fabric keeps heat in different parts of it. Lamination is the process of putting a PCM layer between two textile layers to make a composite fabric.[12] This gives you great control over how much PCM is in the fabric and lets you combine different materials for different functions. Those techniques are used to do research all over the world all the time.

There has been a limited number of review papers obtained on PCM-incorporated textiles.[13−15] For instance, Mondal et al. reported an overview of PCM for smart textiles almost 15 years ago.[16] Yang et al. reported organic PMC in fiber, yarn, and fabric.[17] However, there is a lack of a comprehensive review that covers the fabrication, classifications, and environmental impact of PCM-incorporated textiles.

This Review aims to provide a comprehensive overview of the current state of PCM-incorporated textiles, including their fabrication methods, classifications based on material selection and application domains, as well as their impact on the environment. Specifically, this article will focus on the environmental impact of PCM-incorporated textiles. We intend to sketch out a future outlook for these forward-thinking textiles by conducting an in-depth analysis of the benefits and drawbacks associated with PCM incorporation. In doing so, we hope to provide insights into the potential developments and opportunities that lie ahead in this ever-evolving field. The use of PCM in textile production has the potential to completely transform the textile industry and make a significant contribution to a more environmentally friendly and sustainable future.

2. INTRODUCTION TO PHASE CHANGE MATERIALS

Phase change materials (PCMs) are compounds that can store and release thermal energy during the phase change process.[18] The basics of incorporation of PCM in textiles have been illustrated in Figure 1. They may absorb heat during the transition from solid to liquid and release it during the transition back to solid. This characteristic enables PCMs to regulate temperature effectively, making them great candidates for incorporation into fabrics.

Incorporating PCM materials into the fabric structure or coating the fibers with PCM capsules constitutes PCM integration in textiles. The PCM changes phase when exposed to external heat or body temperature, absorbing excess heat and maintaining a steady microclimate between the fabric and the skin. When the temperature drops, the PCM freezes and releases the heat back to the user. By using this fundamental, many types of advanced functional clothing have been developed including thermal insulating items of clothing, cooling gears and so on.

The timeline of the developments of PCM and its propagation has been illustrated in Figure 2. Since the 1800s when scientists such as Sir James Dewar and Thomas Andrews laid the groundwork for understanding phase transitions, PCMs have a lengthy history of development.[19,20] In the 1930s, paraffin waxes became viable materials for thermal energy storage. Since the 1960s and 1970s, researchers have investigated the potential of PCMs for thermal energy storage and management by analyzing eutectic mixes and unique phase transition temperatures.[21,22] In the 1980s and 1990s, technological advances led to the discovery of several organic and inorganic PCMs with customized characteristics, resulting in the commercialization of PCM technology and the introduction of temperature-regulating textiles.[23] PCM research evolved to cover energy-efficient buildings, electronic cooling, and intelligent fabrics in the 2000s and beyond. PCM applications are continually enhanced in terms of scalability, cost-effectiveness, and longevity as a result of continuous work.[17,24−26] A bright future scope of PCM-incorporated textiles in terms of nanoencapsulation, cutting-edge applications, and environmentally friendly manufacturing.

3. CLASSIFICATION OF PCM

A large quantity of PCM is accessible at any temperature range desired. Based on how they are made, PCM can be categorized as organic, inorganic, or eutectic mixes, as shown in Figure 3.

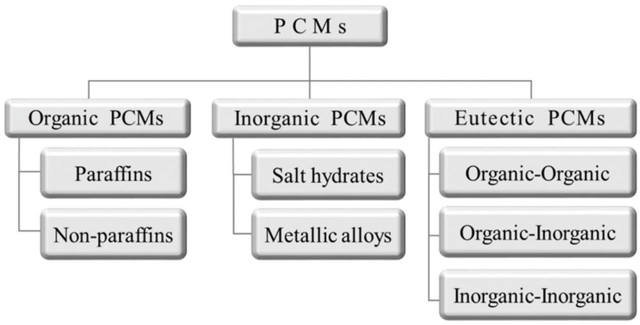

Figure 3. Classifications of PCMs

Those depend on the kind of PCM. Salt hydrates, paraffin waxes, fatty acids, and eutectic organic/inorganic compounds have been the types of materials that have seen the most widespread application over the past 30 years. Melting temperatures (Tm) for both inorganic and organic PCMs range from 8.1 to 130 °C. PCMs have a density of less than 10^3 kg/m^3 in most cases, making them smaller than inorganic materials such as salt hydrates and water. The paraffin-based PCMs like exadecane, heptadecane, octadecane, nonadecane, and hexane are the most often utilized PCMs for textile applications.[27,28] Their Tm ranges from 36 to 18 °C.[29] Hexasane also falls into this category. As the amount of carbons in their structures increases, they have various phase change temperatures, such as the Tm.[30]

3.1. Organic PCMs.

3.1.1. Paraffins. The most frequent PCMs are paraffins. To prevent repetition, the properties and structure of paraffin are briefly described in this section, while they will be explained in depth for PCMs.

3.1.2. Nonparaffins. Organic PCMs that are nonparaffinic are referred to be the most extensively applied. They have relatively comparable qualities to one other, despite their differences when compared to paraffin. As thermal energy storage materials, scholars have used various forms of alcohol, ether, glycol, and fatty acid. These materials are commonly combustible and oxidation-resistant. Despite their high latent heat capacity, nonparaffin organic PCMs have flaws such as limited thermal conductivity, flammability, low combustion temperatures, and transitory toxicity. Fatty acids, glycols, poly alcohols, and sugar alcohols are the most important non-paraffinic PCMs.

3.2. Inorganic PCMs.

Inorganic PCMs are characterized by a large capacity about double the increased thermal conductivity of organic PCMs used for thermal energy storage. PCM-incorporated textiles are employed in sports, military, and medical applications. Further study is needed to optimize

Table 1. An Overview of the Advantages and Disadvantages of Different Types of PCM

Entry	PCM Types	Advantages	Disadvantages	ref
1	Organic	• Supercooling is negligible, which indicates that they undergo predictable and consistent temperature changes from solid to liquid (and vice versa). For fabrics to sustain thermal comfort, this dependability is essential.	• Thermal conductivity is quite low (only about 0.2 W/mK).	32,33
		• Stable in the laboratory that leads to maintaining long-term functionality	• Significant volume shifts on phase transition	
		• Reduced vapor pressure	• Flammability is detrimental to firefighting clothes.	
		• Inert to corrosion leads to keep good quality		
		• Excessive amounts of latent heat per gramme		
		• Able to work with standard construction supplies		
2	Inorganic	• Extremely high latent heat capacity per liter	• Supercooling	31,34
		• Excellent heat conduction (around 0.5 W/mK)	• Corrosion	
		• Not combustible	• Because of breakdown (phase separation), a thickening and nucleating agent is required.	
		• Very inexpensive		
3	Eutectics	• Intensive heat storage in a small volume	• Insufficient thermo-physical property test data is currently available.	31,35
		• The high point of melting		

inorganic PCMs in PCM-incorporated fabrics and evaluate their performance in various applications.[31] Salt hydrates and metals are two terms that are frequently used to describe them.

3.2.1. Hydrated Inorganic Salt. A significant group of PCMs is salt hydrates. Hydrogenated salts, hydrated salts, or inorganic salt hydrates are all examples of ionic substances that contain a large number of water molecules that have been tempted by the ions. MxNy.nH_2O is the most common formula for a hydrated salt, where M and N represent cations and anions, respectively, and n represents the number of water molecules per salt formula unit. Cations, the positively charged ions of salt, are bound to water molecules in the crystals of hydrates via hydrogen bonds and covalent bonds, respectively. The water of hydration and water of crystallization are two names for these water molecules. During heating, the enthalpy of dehydration (ΔH_{dehyd}) absorbs a certain amount of energy, which causes the hydrated salt to lose its water of crystallization. Hydrated salts include, for example, sodium sulfate decahydrate ($NaSO_4.10H_2O$), magnesium sulfate pentahydrate ($MgSO_4.5H_2O$), and others.

3.3. Eutectic PCMs. There are at least two types of PCMs in the eutectic system. Eutectics possess exceptional characteristics. Due to their lower melting and solidification temperatures, eutectics do not detach at the moment of the phase transition. As a result, there is no evidence of phase separation or super cooling in these materials. Comparative analysis of their basis types of PCM has been tabulated in Table 1. In comparison to salt hydrates, eutectics have a longer thermal cycle. The most common type is inorganic–inorganic eutectics. However, organic–inorganic and organic–organic variations have garnered increasing attention in recent studies. The commercialization of eutectics is a serious issue. It is common for them to cost two to three times as much as commercial PCMs.

4. MECHANISM TO THE FUNCTIONING OF PCM IN TEXTILE

PCMs would be encapsulated in very little spheres before being applied to textile structures to keep them contained in the state of a liquid. It is estimated that the diameter of these microcapsules ranges from 1 to 30 μm.[36] The microcapsules are thermal and mechanically robust and have a wide range of substances. They respond to changes in temperature variations in the following manner.[37] Heat is absorbed by the microcapsules in response to an increase in ambient temperature. The PCMs dissolve inside the microcapsules. They store the excess energy they gain from the surroundings via heat absorption. The temperature drops: Initially stored heat is lost as the temperature falls due to a decrease in the surrounding ambient temperature.

Different PCM effects contribute to their heat regulation capabilities. First, they produce a cooling effect by absorbing ambient heat. Second, they produce a heating effect by expelling stored heat when the surrounding temperature drops. Third, keeping a comfortable microclimate, in garment applications, PCM microcapsules or coatings interact with the wearer's body heat. When the body temperature rises owing to physical activity or environmental circumstances, the PCM absorbs and stores the surplus heat. When the body temperature lowers or when the external temperature rises, the PCM releases the stored heat, providing a steady and comfortable microclimate surrounding the body.

This helps minimize overheating and excessive sweating while the body is active or exposed to various environmental conditions. PCMs are advantageous for temperature control applications in several sectors because of their varied impacts.

The treated fabric containing 22.9% more microcapsules may absorb 4.44 J/g of heat if the microspheres on the fabric disintegrate. Due to their high heat absorption rates, microspheres prevent an overheated clothing environment. This reduces the risk of heat stress and increases thermophysiological comfort.[29] Wang et al.[30] looked into the influence of phase-change materials (PCM) on smart thermal-protective garments. During the heating process, the PCM layer melts when the temperature reaches or exceeds its melting point (28.0 °C), and the PCM is dissolved and becomes a liquid. Throughout this procedure, thermal energy is taken in and stored. After the PCM melts, the temperature keeps climbing. As soon as the PCM layer hits 29.0 °C, the conductive textiles were disabled. The PCM layer cools down quickly. Once the PCM layer's temperature falls below 27.0 °C, the liquid PCM freezes, releasing heat energy. Here, the PCM acts as a thermal buffer, expelling any excess heat.

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5. PCM IN THERMAL PROTECTION CLOTHING

Due to their ability to absorb and get free heat as needed, PCMs are commonly used in thermoregulating apparel. The outer layer of protection is an aerogel, with PCM acting as a supporting layer next to the human body's skin surface. The combination can protect the body from extreme heat while also absorbing metabolic heat. A bench scale device is constructed to measure the radiative heat protection of multiple layers of FPC at a time in a multilayer structure, and by housing PCM in aerogel nanopores, an easy-to-apply coating additive is prepared. One of the most crucial characteristics of PCM is that to prevent temperature rise over a specified period, it has a sufficient measure of latent heat. The basic mechanism of thermal protection apparel is illustrated in Figure 4. PCMs are utilized in textiles to either store body heat to keep the human body hot or to absorb which are high heat fluxes to make cool the body down.

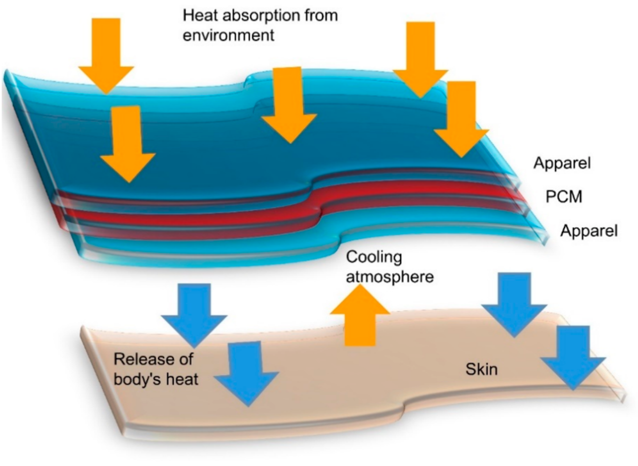

Figure 4. Basic mechanism of thermal protection apparel

The most traditional application of PCM's heat-storage capabilities is in very cold adversity gear, where phase change material absorbs and body heat stores before releasing it when needed.[38−40] PCM can be utilized to guard against heat as a passive technique. In this instance, PCM absorbs high heat fluxes from the outside to protect the human body to some extent. PCM-incorporated textiles for making thermal protective cloth for safe firefighting apparel applications developed by Su and his team.[41]

6. THE IDEA OF THERMAL COMFORT

The thermal condition of the human body is influenced by heat exchange with the surroundings. Thermal comfortability is a way of thinking that shows how happy someone is with the temperature of their surroundings. Particularly dissatisfying, as determined by the anticipated mean vote (PMV) and the making more accurate dissatisfied (PPD) indices, are hot or cold temperatures that cause physical discomfort. However, unpleasant warmth or cooling of one portion of the body can also induce thermal discontent (local discomfort). Warm and cool discomfort is expressed by the PMV and PPD indices for the entire body. PCM's coating on cotton fabrics is widely using to ensure thermal comfort.[42,43] Due to individual variances, it is hard to create thermal surroundings that will please everyone. A certain fraction of the population will continuously be unhappy. Nonetheless, it may be conceivable to establish surroundings that a certain percentage of the inhabitants will find acceptable. The new standard specifies comfort parameters that are expected to satisfy at least 80% of the passengers. Even when existing criteria are satisfied, the interior air quality in many air-conditioned or humidified buildings is relatively poor. The goal should be to be pleasant, deliver fresh, and stimulating indoor air with minimal negative health consequences, as well as a tolerable temperature environment for practically all inhabitants. The influence of enthalpy upon acceptability as well as the perceived quality of air, represented as a proportion of unsatisfied people, is significant. Humans enjoy the sensation of their respiratory system cooling as they breathe air. This produces a nice feeling of freshness. The air might feel stale, oppressive, and unpleasant if sufficient cooling is not provided. A high enthalpy indicates that the breathed air has poor cooling power, resulting in insufficient convection and evaporation chilling the moist mucous films of the breathing system, particularly the nose. Because breathing only accounts for around 10% of total heat loss, the effects of exhaled air temperature and humidity are rather minor. As a result, clothes will play a significant role in terms of user comfort. Conduction, convection, and radiation are all used in the movement of dry heat throughout a cloth. It is significantly more difficult to transport sensible heat transfer from a clothed subject's skin to such a colder environment. The heat balance formula may be used to compute the dry heat loss, H_{dry}, from the skin

$$H_{dry} = M - W - C_{res} - E_{res} - E - S$$

In this equation, M is the metabolic rate, W is the amount of work done outside the body, C_{res} is the convective respiratory heat loss, E_{res} is the evaporative respiration heat loss, E is the amount of heat lost through perspiration, and S is the impact on the body's heat storage capacity. All figures are shown in watts/m^2. Maintaining a steady body temperature is necessary, but not sufficient, for experiencing thermal comfort. Also, no one must experience any kind of localized heat or cold pain, which might be brought on by asymmetry in radiation. When compared to mixed ventilation, a personalized ventilation system (PVS) can enhance users' thermal comfort and subjective air quality, as well as the severity of sick building syndrome (SBS) indicators. The temperature differential between ambient and customized air, as well as the room air

Table 2. Factors to Define Perfect PCM

Entry	Factors	Description	ref
1	Physical requirements	A sufficient phase transition temperature, good thermal resistance, a high heat capacity, a substantial enthalpy change, and supercooling	44,45
2	Chemical factors	Low vapor pressure, nontoxicity, little volume changes, nonexplosivity, used chemical stability, compatibility and nonexplosivity with chemicals are all essential chemical properties for a successful PCM	46−48
3	Economic factors	it is preferable if the approved PCM is abundant and inexpensive. It also must be nonflammable to be used in textile applications	16,49

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temperature, influence the increase in perceived air quality using PVS. When tailored air was cooler than ambient air, the biggest benefit was seen.

7. SELECTION CRITERIA OF A SUITABLE PCM AND COST COMPARISON

Factors to define a perfect PCM are physical, chemical, and economic as well. Table 2 reports an overview of those factors.

Physical requirements include a sufficient phase transition temperature, good thermal resistance, a high heat capacity, a substantial enthalpy change, and supercooling.[44,45] Higher latent heat confirms that even little amounts of material may retain enough energy. During phase transition the volume changes should be small, allowing for the employment of basic containment and heat-exchange design. Low vapor pressure, nontoxicity, little volume changes, nonexplosivity, used chemical stability, compatibility and nonexplosivity with chemicals are all essential chemical properties for a successful PCM.[46] From a pecuniary standpoint, it is preferable if the approved PCM is abundant and inexpensive. PCMs must also be nonflammable to be used in textile applications.[16] Another desirable quality is congruent melting, which assures the entire melting of the substance so that the solid and liquid conditions have similar compositions. If the substance does not entirely melt, the distinction in densities between solid and liquid creates dissociation, which causes changes in the material's composition of chemical.[46] However, finding a single PCM with all of these desirable characteristics is almost impossible. As a result, PCM should be chosen with as many advantageous qualities as feasible. Referring to that part, it may be quickly stated here that a temperature limit of 33 to 37 °C is required to ensure firefighters' comfort, while a temperature limit of less than 52 °C is important for upkeeping against irreparable second-degree burn. So, eicosane has been discovered to have excellent features for improving comfort in fire protective clothes due to its phase-transition limit of 31 to 37 °C, good compatibility, high heat capacity, and inexpensive cost.[50]

In Table 3, the price comparison PCM-incorporated fabrics with flame retardant and waterproof fabric have been compared. Overall, it is found that PCM-incorporated special fabrics exhibit higher prices.

Table 3. Price Range of PCM Incorporated Fabric, Flame Retardant Fabric, and Waterproof Fabric

Types	Description of fabrics	Price range/m^2	ref
PCM fabric	PCM microcapsule special function nonwoven fabric	\$3.80-\$4.50	51
	Cooling fabric sportswear PCM	\$5.00-\$12.00	
	Cooling textile polyester PCM functional fabric	\$5.00-\$7.00	
	PCM microencapsulated fabrics in textiles for temperature control	\$10.00-\$13.00	
	Cooling fabric polyester PCM	\$5.00-\$7.50	
	Functional thermal insulation PCM microcapsule material fabric	\$8.00-\$11.00	
Flame retardant fabric	100% cotton flame-retardant fabric	\$2.50-\$4.00	
	100% polyester waterproof oxford flame retardant fabrics	\$0.65-\$1.5	
	Lightweight full blackout flame retardant fabric	\$1.91-\$2.50	
Waterproof fabric	High-quality camouflage 600 × 300d oxford fabric waterproof	\$0.52-\$1.5	
	Oxford 100% polyester waterproof tent fabric	\$1.09-\$2.0	

8. BASIC TECHNIQUES TO INCORPORATE PCM IN TEXTILES

The PCMs would be remarkable for use in textiles if they changed conditions at temperatures just above and below human body temperature. The intriguing characteristic of PCMs would be valuable to produce all-season human body protective textiles. PCMs in fabric, fiber, and foam would store the heat generated by the body and then get it free when needed. Because phase transition is a dynamic process, materials are certainly shifting from one condition to another depending on outside temperature and the intensity of physical activity. The addition of PCMs microcapsules to a mixed polymer solution before fiber extrusion allows the manmade fiber to have a thermo-regulating property. PCM microcapsules are strung within the fiber throughout the procedure. PCMs must be incorporated into the textile matrix through the coating, laminating, melt spinning, finishing, fiber extrusion, bicomponent synthetic, injection molding, and foaming methods. Three major methods have been successfully used in the textile industry to incorporate PCM into fiber, yarn, and fabric, as tabulated in Table 4.

Table 4. Methods to Incorporate PCM in Textiles with Key Features

Entry	Methods	Key features	ref
1	Fiber technology	PCMs are sealed in the structure of the fiber. In the stage of polymerization, it could be integrated through doping.	52,53
2	Coating	PCMs are spread over in the used binder. The coating could be applied to the fabric by using various machines.	54
3	Lamination	It proceeds as a form of thin laminating film. The foam mixing is applied to the fabric.	55

PCMs incorporated into textiles have been intensively investigated in garments as a technique of body-heat management and comfort enhancement.[16,56,57] Several procedures have been documented in which pure PCM or microencapsulated PCM (MPCM) has been used for textile substrates at various stages of manufacture, from fiber generation through final garments.[58−60] However, Alay et al.[61] stated that there are four general approaches for incorporating PCM into textiles: Filling a hollow fiber with PCM,[62−64] adding PCM during fiber spinning,[65] coating with a cross-linking agent PCM on textiles,[60,66,67] and laminating are the four methods. The PCM is first integrated into a thin film, which is laminated onto the surface of the textile during lamination.[16] Figure 5 illustrates the three ways to incorporate PCM in textiles.

According to our findings, the reference where Vigo and Frost submerged hollow fiber in PCM solution is the first attempt to prepare a phase-change fiber (inorganic salt solution). Zhang et al. used melt spinning[68] and wet spinning[69] to introduce microencapsulated PCM into fiber. Fiber packed with PCM, on the other hand, does not contain enough PCM in heating or cooling to be useful.[70] The use of PCM in coating processes has been broadly researched. Kwon et al.[71] used a waterborne binder to dip-coat nylon fabric with polyurethane−urea micro capsulated PCMs for 1 h at room temperature.

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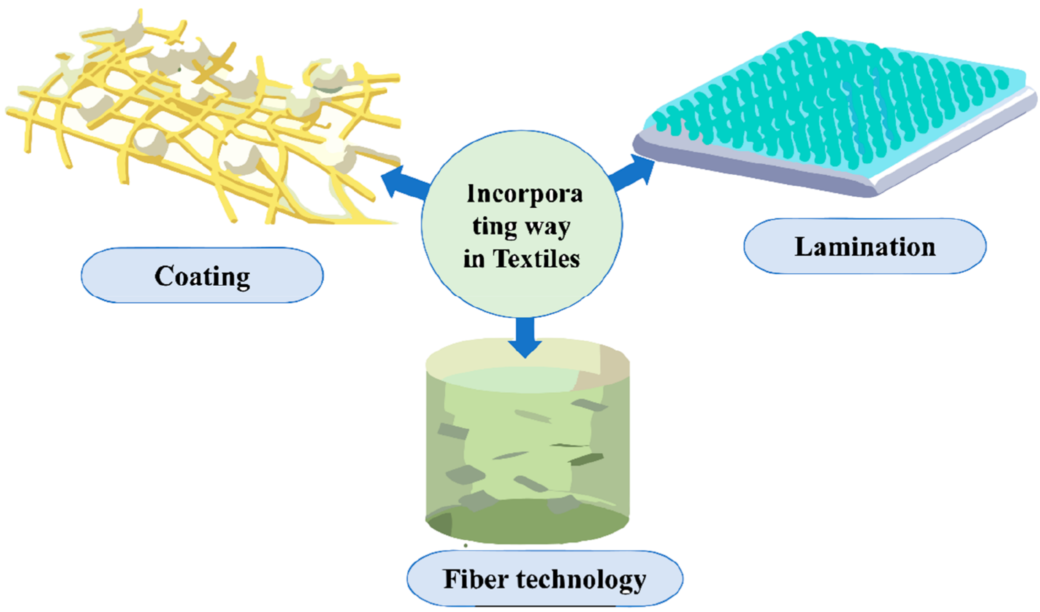

Figure 5. Schematic illustration regarding the way to incorporate PCM in textiles.

Buhler et al.[38] examined the performance of flexible blister foils containing various PCMs. Choi et al.[58] used an acrylic binder to coat octadecane on polyester fabric, whereas Shin et al. padded in an aqueous solution fabric samples with a polyurethane binder of microencapsulated PCM (Snotex P11). When Sanchez et al.[40] coated microencapsulated PCM on textiles, they found a thermoregulating effect.

Coating microencapsulated PCM, on the other hand, can be challenging since they are tough to wet. In a U.S. patent, Zuckerman et al.[60] detailed a method for overcoming this difficulty and creating a coating formulation with micro-encapsulated PCM dry powder. Prior to being added to the binder polymer mixture, the microencapsulated PCMs are wetted in a mixture of water, surfactant, dispersant, and antifoaming agent. By utilizing microencapsulated PCM in a coating paste, the tendency to destabilize the binder polymer can be reduced.[72] PCMs can also be combined with foam and put into textiles. Rossi et al.[39] incorporated PCM into a foam and applied it on a firefighting gear liner. Shim et al.[73] cured a foam-like emulsion containing 60% microencapsulated PCM that was cast directly onto a foundation fabric.

To incorporate PCM in fiber, electrospinning is a relatively contemporary method of applying PCM to textiles. For the first time, McCann et al.[74,75] used molten coaxial electro-spinning to create nanofibers made of PCM in 2006. A fine capillary which is supported by an auxiliary syringe pump is introduced into the main metallic needle to inject nonpolar paraffin into the filament to be enclosed. The nonpolar substance was electrically spun as the core inside the polar polymer. This approach, however, necessitates a unique setup that differs from standard electrospinning. Chen et al.[76−78] used a simpler method to electro-spin PCM in containing fiber by combining PCM material solution with a fiber polymer solution. Electro-spun mats are another option for incorporating PCM into nanofiber. These fiber mats are highly porous and can hold a significant amount of PCM. Cai et al.[79] described a straightforward method for making PCM-loaded electrospinning mats. PAN fiber was acquired commercially, washed to remove oil in acetone, liquefied in DMF, and electrically spun into a nonwoven mat. PCM was melted in a beaker, and after that the nonwoven mat was dipped in the resolved PCM for 10 h. Then it was kept to dry. Even when the integrated PCM was molten, the resulting composite material maintained its overall shape.

In the lamination process, two textile layers or substrates are sandwiched with a layer of PCM material. Heat and pressure are frequently used to form this sandwiched structure, fusing the layers together.[80] Typically, the PCM layer has the shape of a thin sheet or film. Although lamination allows fine control, it can also be bulky and less flexible. Although fiber-based approaches easily incorporate PCM into textiles, PCM loading may be constrained. Since coating techniques are portable and flexible, their endurance may cause problems. Ultimately, the trade-offs between thermal performance, comfort, weight, and other criteria relevant to the intended application should be taken into account while choosing the best PCM application process.

9. THE ENVIRONMENTAL IMPACT OF PCM-INCORPORATED TEXTILES

The use of PCM in textiles has drawn attention as a cutting-edge method of enhancing the comfort and usefulness of garments. PCMs can enhance thermal insulation, control body temperature, and offer comfort under a variety of circumstances when they are included in fabrics. The positive and negative impact of PCM-incorporated textiles will be highlighted in this segment, as shown in Figure 6. In recent studies, found both positive and negative effects of PCM-incorporated textiles were found. In this section, both views will be discussed.

9.1. Positive Effect on the Environment. *9.1.1. Energy Savings.* Because PCM fabrics can absorb and release heat to maintain a comfortable temperature, they can lessen the demand for heating and cooling systems in temperature-controlled spaces (such as buildings). For instance, Rathore and his colleagues reported a review article on the energy-saving features of microencapsulated PCM in building applications.[81] The same phenomenon can happen for energy-saving textiles, as reported by Faruk et al.[82] They

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Figure 6. Positive and negative impact of PCM-incorporated textiles.

reported a review of the functional textiles and composite with many materials including PCM. PCM materials absorb and retain excess body heat in hot settings, keeping the user cool and comfortable. This lowered body heat may eliminate the need for air conditioning or other cooling devices, therefore conserving energy and decreasing electricity use. Similar data were found in an article by Peng et al.[83] Thus, PCM-incorporated floor mats and window covers can contribute to saving energy in this critical time of the global energy crisis.

9.1.2. Extended Product Lifespan. PCM textiles can offer improved comfort, which could result in longer product lifespans since consumers might be happier with their clothes and use them for longer periods of time.[84,85] In addition, textiles using PCM can assist control body temperature and improve comfort. When the user is more comfortable, he or she is less prone to engage in unnecessary movements or garment alterations owing to discomfort. Consequently, the cloth ensures less wear and tear, resulting in a longer product lifespan.[86,87]

PCM fabrics may also assist maintain a more constant and pleasant temperature, which means the user may not need to launder the garment as often. By limiting the number of wash cycles, the structural integrity of the fabric may be maintained for an extended duration. As reported by Shin and co-workers, developed PCM-treated fabric needs fewer wash cycles. Thus, it could be longer lasting compared to conventional clothes.

9.1.3. Improved Insulation. PCM fabrics can make clothes more thermally insulating, allowing people to be comfortable

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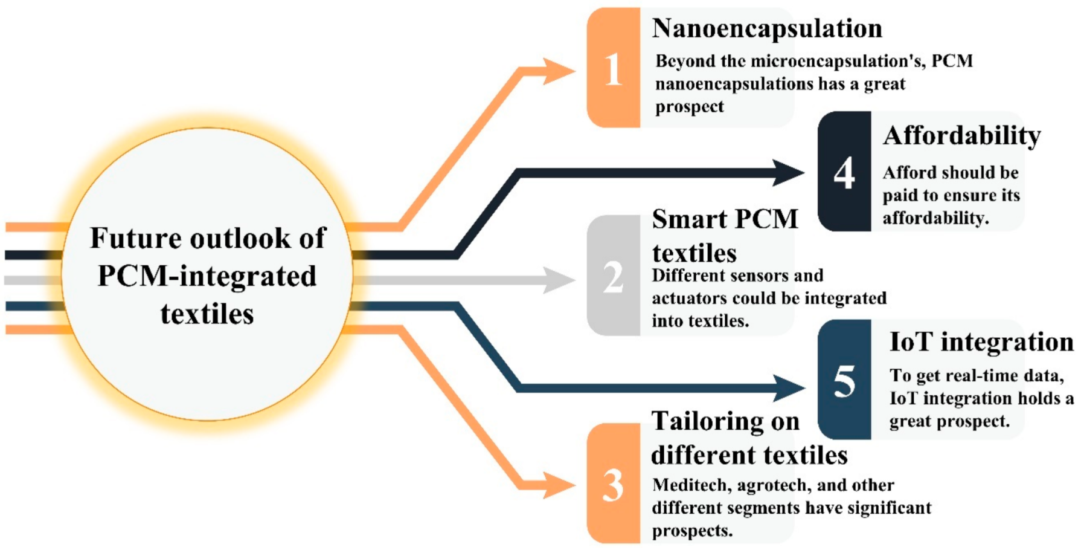

Figure 7. Future outlook of PCM-integrated textiles.

in colder interior climates while using less energy for heating. When the ambient temperature exceeds a specific threshold, the PCM absorbs excess heat from the wearer's body or the surrounding environment. This heat absorption acts as a barrier against heat gain by preventing external heat from accessing the material, as discussed by Arumugam et al. in their latest study.[88] This excellent property of PCM leads to making jackets with PCM coating to save from cold.[89]

9.2. Environmentally Harmful Effects. *9.2.1. Added Chemical Additives Tend to Negative Impact on the Environment.* Some PCM additives used in textiles may contain substances that, over the course of the product's lifespan, might potentially harm the environment through leaching or the buildup of additives in the environment.[90] For instance, flame retardants may use with PCM to ensure fire retardancy features of the PCM-incorporated textiles. However, a few types of flame retardants are not good for environments including polybrominated diphenyl ether, decabromodiphenyl, hexabromocyclododecane, and chlorinated phosphates.[91,92]

9.2.2. Less Disposal Features Textiles after Integration with PCM. Managing the end-of-life of PCM textiles can be difficult, depending on the type of PCM utilized. If the PCM additions are neither recyclable nor biodegradable, they can increase waste and perhaps harm the environment. Chandel and his colleagues reported the adverse effect of PCM in many applications including textiles. They highlighted the fewer disposal properties of the developed products lead to higher negative environmental impact.[93]

9.2.3. Source of Raw Materials of PCMs Which Have Environmental Effects. The extraction of particular raw materials, which may have environmental effects like habitat loss or increased resource consumption, may be necessary for the creation of PCMs. For example, organic PCMs generated from petroleum, a nonrenewable fossil resource, are paraffin waxes. The mining and processing of petroleum can cause environmental degradation, habitat loss, and greenhouse gas emissions.[94] In addition, as PCMs, certain chlorinated paraffins are utilized. Due to their toxicity, these chemicals can remain in the environment and pose threats to aquatic ecosystems and species.[95]

9.2.4. Lead Higher Energy Consumption in the Manufacturing Process. Compared to normal textiles, the production of PCM textiles requires additional stages like suitable PCM selection, microencapsulation, preparation of PCM solution, applying it by using the proper method, and the usage of certain PCM additives, which might lead to higher energy consumption and carbon emissions. Thus, PCM-incorporated textiles are more responsible for environmental harmful effects than conventional textiles. Mondal et al. discussed the additional PCM-incorporating process and its viability in the market.[16] Future improvements in PCM technology might result in less harmful solutions for the environment and more sustainable options. A thorough life cycle evaluation is necessary for each new material or technology to fully comprehend the environmental effects.

10. FUTURE OUTLOOK

The future of PCM in textiles is hopeful, with continuous research and technological advances resolving the aforementioned difficulties. Researchers are creating eco-friendly and sustainable PCM materials to meet the rising demand for eco-friendly textiles. Some probable developments include nanoencapsulation, smart PCM textiles, tailoring features, affordability, and ensuring energy efficiency. This segment will focus on the future outlook by considering the above points, and a symmetric diagram in Figure 7 demonstrates those future outlooks.

10.1. Nanoencapsulation. Nanotechnology advancements may lead to improved PCM encapsulation, hence enhancing PCM's longevity and textile integration. Micro capsulations are widely used form to apply PCM in versatile applications including fashion and apparel. The use of nanoencapsulation has been already initiated, but there is a huge scope to propagate its features and applications. For instance, Nikpourian and his team reported the novel PCM textiles nanocapsulation's thermal performance, which is promising for versatile use.[96] Moreover, Maleki et al. presented the thermal performance and development of nanoencapsulation PCM/plaster wallboard for thermal energy storage in buildings.[97]

10.2. Smart PCM Textiles. Integration of PCM with smart textile technologies, such as sensors and actuators, might result in garments with more dynamic and responsive temperature management. Yang et al. reported an overview of organic PCMs integration on apparel and fashion cloths.[17] In addition, Cherif et al. reported ecofriendly PCM applications for advanced fields including smart textiles.[98] Moreover, Mondal and co-workers reported a comprehensive overview of the applications of PCM on smart textiles. This sector has huge potential and scope to expand it.

10.3. Tailoring on Different Textiles. PCM solutions that are tailored to specific applications, such as medical textiles or clothes designed for adverse climates, might give improved benefits. Yilmaz at al. reported the fabrication of PCM-incorporated polylactic acid (PLA)/cotton biocomposite yarn along with providing thermoregulation function. They proposed it for use in medical textiles.[99] In addition, Baptista-Silva and co-workers also agreed on the prospect of PCM loading on the textiles for its advanced medical textiles applications.[100]

10.4. Affordability. Continued research and scale-up of production processes may result in cost reductions, making PCM-enhanced fabrics more accessible and inexpensive to customers. Gholamibozanjani et al. reported an overview of PCM control strategies, especially in buildings. In Table 3, it is found that PCM-incorporated special fabrics exhibit higher prices. Since cost is a big factor, thus they also talked about the cost-reduction techniques like optimization of PCM type and loading, efficient PCM applications, etc.[32]

10.5. Internet of Things (IoT) Integration. The integration of PCM textiles with IoT devices enables real-time data monitoring and thermal property study of the textile. IoT-enabled PCM textiles may connect with external devices to enhance thermal regulation, assuring the comfort of the wearer in a variety of climatic circumstances. Manglani and his colleagues reported an overview of the IoT's applications in the textile industry, especially in the spinning industry.[101] Choi et al. reported the integration of IoT of the smart textile lighting/display system with multipurpose fiber devices for large-scale smart home and IoT applications.[102] So, there is a great prospect to integrate IoT in PCM-incorporated textiles for advanced applications.

PCM in textiles provides interesting opportunities for enhancing comfort and performance in a variety of applications. As research and technology evolve, it is expected that the obstacles associated with PCM integration will be solved, leading to a wider acceptance of PCM-enhanced textiles in daily life.

11. CONCLUSION

The PCM-incorporated fabrics' unique and adaptable qualities, such as thermal comfort, energy saving, comfort in harsh conditions, etc., have attracted substantial interest over the years since they solve key difficulties in a wide range of sectors. This Review discussed the preparation techniques and factors regarding this. Additionally, positive and negative impacts of PCM-incorporated textiles have been critically analyzed. Moreover, future research directions of this material like nanoencapsulation, progression of smart PCM-integrated textiles, making it affordable, and increasing energy efficiency have been discussed. In addition, a multidisciplinary process which includes textile academics, material scientists, chemical engineers, and other specialists' collective approach is essential to drive progress in the PCM-incorporated textile sector. Accelerating research and facilitating the smooth integration of PCM technology into textile applications may be accomplished through the merging of various skills. Prospects for PCM in textiles are optimistic since ongoing research and technical advancements are tackling the aforementioned challenges. This Review can be used as a credible source for the researcher and industrialist.

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Notes

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