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Sustainable Thermal Management of Textiles

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Abstract

Phase change materials (PCMs) are an important part of textile thermal management because they can absorb and release heat in a temperature-responsive manner, enabling adaptive temperature regulation in biomedical textiles, protective clothing, and personal comfort. Polyethene glycol (PEG) is a particularly appealing PCM candidate due to its tunable temperature transition behaviour, low toxicity, high biocompatibility, and favourable environmental profile. Low-molecular-weight PEGs, such as PEG 100, PEG 400, and PEG 1000, are particularly helpful because their melting and crystallisation properties can be tailored to certain comfort or physiological temperature ranges. Molecular weight, crystallinity, latent heat storage, and transition temperature are discussed in connection with the thermal behaviour of low-molecular-weight PEGs. With a focus on enhancing loading stability and longevity, coating, padding, encapsulating, electrospinning, and fibre-filling techniques are also investigated. Recent developments in form-stabilisation and composite design are emphasised, as PEG-based PCMs may exhibit minimal intrinsic thermal conductivity and leakage.

Keywords: Energy efficiency; Encapsulation technology; Functional Textiles; Grafting methods; Thermal conductivity

Areviations: PCMs: Phase Change Materials; PEG: Polyethene Glycol; CNTs: Carbon Nanotubes; LCAs: Life Cycle Assessments

Introduction

The development of functional textiles for flexible and energy-efficient heat management is on the rise. Because they absorb and release latent heat during phase transitions, phase change materials (PCMs) are particularly effective at buffering temperature fluctuations and enhancing wearer comfort in textile substrates. Salt hydrates and paraffins make up the majority of traditional textile PCMs. Paraffins are petroleum-derived, flammable, and prone to leaking despite having good latent heat and stability. Although salt hydrates have a high thermal storage density, phase separation, supercooling, and corrosivity prevent their use in wearables.

Polyethylene glycol (PEG) has emerged as a possible alternative due to its molecular weight control, low toxicity, biocompatibility, and compatibility with greener manufacturing processes. Low-molecular-weight PEGs, such as PEG 100, PEG 400, and PEG 1000, are especially appealing for textile applications because their phase transition temperatures can be adjusted to human comfort levels. However, PEG-based PCMs continue to encounter issues such as leakage during melting and limited heat conductivity. To improve stability and heat transfer, recent research has concentrated on encapsulation, form-stabilisation, green electrospinning, coating, padding, and bio-based hosts such as biochar and lignin-derived carbon. This review examines low-molecular-weight PEGs as ecologically acceptable PCMs for long-term textile thermal management, focusing on thermal behaviour, safety, application procedures, and comparisons with traditional PCM systems (Figure 1) [1].

Polyethylene Glycol as a Phase Change Material

Molecular Weight and Thermal Properties

Polyethylene glycol (PEG) is a polyether whose thermal characteristics are significantly dependent on molecular weight. As the MW increases, PEG transitions from low-melting liquids to waxy solids with increasing melting temperatures and latent heat. PEG 100 is primarily used as a plasticiser or additive because its melting point is below 0°C, making it unsuitable as a standalone PCM. PEG 400 melts at 4-8°C and is useful for cold-storage applications, but it typically requires encapsulation or form stabilisation in textiles. PEG 1000 is one of the most studied textiles PCMs due to its melting range of 35-40°C, which is similar to skin temperature. Its latent heat ranges from 120 to 160 J/g, depending on purity and composite structure, making it appropriate for wearable thermal regulation. Higher-MW PEGs, such as PEG 2000, 4000, and 6000, have higher melting and latent heat, but they are more difficult to manufacture into textiles due to increased viscosity and decreased solubility [2].

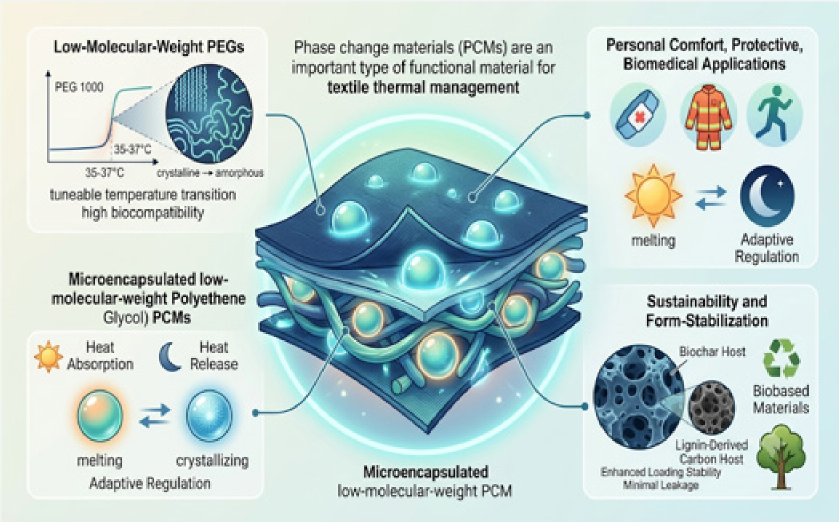

Figure 1: Low molecular-weight PEGs.

Phase Change Behaviour and Energy Storage Capacity

PEG-based PCMs store and release thermal energy via their latent heats of fusion and crystallisation, and their storage capacity increases when form-stabilised in polymer matrices or porous hosts, frequently exceeding 60 J/g. Ultra-flexible PEG/PVA membranes made by green electrospinning with melting and freezing latent heats of 60.1 J/g and 59.1 J/g at 55 % weight basis PEG, respectively, and a phase change range of 26.9-38.9°C, ideal for personal thermal control. Thermal conductivity can also be enhanced by adding fillers like carbon nanotubes (CNTs), expanded graphite, or boron nitride, while leakage during melting is controlled by encapsulation or form-stabilisation via capillary forces, hydrogen bonding, or cross-linking [3].

Eco-Friendly and Safety Advantages

PEG's proven nontoxicity and biocompatibility distinguish it from many traditional PCMs, making it suitable for human-contact applications such as protective apparel, biomedical dressings, and personal thermal management textiles. Unlike petroleum-derived paraffins, which may raise concerns about impurities or VOC emissions during thermal cycling, PEG is generally regarded as chemically inert and safer for skin contact; this safety profile is further supported by studies such as Kim et al., who highlighted PEG's advantages in direct-contact applications. For wearable use, PEG's safety is strengthened by form-stabilisation, encapsulation, and chemical grafting, which reduce the risk of liquid leakage onto the skin during phase change. From a sustainability perspective, PEG-based PCMs are also advancing through bio-based synthesis routes, solvent-free and catalyst-free processing, green electrospinning with water-based scaffolds, and the use of bio-based or waste-derived hosts such as lignin-based carbon and carbonised cotton fabric waste, all of which improve performance while supporting greener manufacturing and circular material flows.

Applications for Textiles

a) Green Electrospinning - Electrospinning is a promising technique for creating PEG-based nanofibers with a large surface area, superior breathability, and efficient temperature regulation. PEG is typically coupled with a structural polymer to improve form stability, and water-based processing can mitigate environmental problems associated with solvent use [4].

b) Coating and Padding -Coating and padding are easy and scalable methods for applying PEG to materials. These technologies are simple to apply, but leakage control is critical; form stabilisation or cross-linking is often required to maintain performance.

c) Encapsulation - Encapsulation increases durability and helps to prevent leaks during phase change. PEG can be encased in polymer shells, biopolymer systems, or porous hosts to maintain thermal performance during repeated heating and cooling processes [5].

d) Chemical Grafts - Chemical grafting enables a more durable attachment of PEG to textile substrates, thereby improving wash resistance. It is less adaptable than physical approaches, yet it is effective when long-term stability is required [6].

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Comparative Analysis: PEG vs. Conventional PCMs

PEG vs. Paraffin-Based PCMs

While paraffins are widely utilised for their high latent heat, Polyethene Glycol (PEG) offers a safer, more sustainable alternative, specifically optimised for textile applications (Table 1).

Table 1: Comparison between PEG and Paraffin-based PCMs.

Feature	Paraffin-Based PCMs	PEG-Based PCMs
Environmental	Petroleum-based; requires organic solvents.	Bio-based potential; water-soluble for green processing.
Safety	May emit VOCs; contains impurities.	Non-toxic, biocompatible, and skin-safe.
Leakage & Stability	Nonpolar; strict encapsulation required.	Polar; enables efficient physical confinement via hydrogen bonding.
Flammability	High volatility; lower ignition temperature.	Low volatility; higher ignition temperature (lower fire risk).

Table 2: Comparison between PEG and Inorganic salt PCMs.

Feature	Inorganic Salt Hydrates	PEG-Based PCMs
Corrosivity	Degrades textile fibers and corrodes metals.	Chemically inert; non-corrosive to textile substrates.
Thermal Reliability	Highly prone to supercooling and phase separation.	Consistent phase transitions with minimal supercooling.
Skin Safety	Caustic and hygroscopic; risks irritation or burns.	Intrinsically safe; widely approved for cosmetics and pharmaceuticals.
Environmental Fate	Disposal risks land and water salinization.	Biodegradable under standard conditions; low environmental persistence.

PEG vs. Inorganic Salt Hydrates

Inorganic salt hydrates offer cost-effectiveness and high latent heat, but their chemical reactivity severely limits their viability in wearable textiles (Table 2).

Form Stabilisation and Leakage Prevention

Preventing liquid-phase PCM migration is crucial for fabric breathability and comfort. Because PEG is polar, it has strong chemical interactions with cellulosic and protein-based fibres, providing enhanced leakage resistance through four basic mechanisms:

I. Microencapsulation is the process of encapsulating PEG within protective micro- or nano-shells.

II. PEG is impregnated into highly porous materials, such as expanded graphite and carbonised biomass. Capillary forces and hydrogen bonding ensure high loading capacities (up to 70% by weight).

III. Polymer Matrix Blending is the process of physically restricting PEG within structural polymer networks (e.g., PVA, polyurethane) by electrospinning or melt mixing, which is often strengthened by crosslinking [7].

IV. Chemical grafting is the process of covalently attaching PEG to the textile substrate. While this ensures permanent prevention of leakage, the limited molecular mobility may result in a minor loss of latent heat capacity [8].

Emerging Trends and Research Gaps

To achieve broad commercialisation, future research must address three essential areas:

i. Technical Optimisation and Scaling: Focus on optimising low-molecular-weight formulations (PEG 100 and 400) for cold storage. Transition from lab-scale testing to continuous industrial production with proven long-term wash durability.

ii. True sustainability entails developing a 100% bio-based PEG synthesis to eliminate reliance on petroleum. Conduct comprehensive Life Cycle Assessments (LCAs) and prioritise biodegradable encapsulation to integrate these textiles into a circular economy.

iii. Multifunctionality: Combine thermal features with secondary characteristics (e.g., antibacterial, UV protection,

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conductivity) to produce high-value smart wearables and biomedical textiles.

Summary

For textile thermoregulation, low-molecular-weight PEGs outperform volatile paraffins and corrosive salt hydrates in terms of environmental sustainability. Recent advances in green encapsulation and waste-derived host materials have effectively addressed prior leakage difficulties. To fully realise their commercial potential, the industry must now prioritise increasing bio-based production and ensuring long-term durability. Finally, PEG-based PCMs provide a compelling pathway to next-generation smart textiles that strike an ideal balance between thermal performance, human safety, and environmental responsibility.

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