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Application of Mineral-Based Materials in Thermal Protective Textiles

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Abstract

The rapid expansion of advanced technologies and industrial processes has heightened human exposure to fire hazards and thermal risks, underscoring the urgent need for enhanced thermal protective textiles. Firefighter turnout gear and protective clothing for high-risk mining workers such as those in sulfur and coal mines serve as critical defensive barriers, delivering robust flame resistance while preserving optimal weight and wearability. Layered silicate nanoparticles, including mica, montmorillonite, and vermiculite, alongside lightweight minerals like perlite and dolomite, exhibit distinctive flame-retardant properties, thermal stability, and barrier effects, positioning them as promising additives for advanced protective textiles. This review systematically evaluates the physicochemical characteristics of key fire-resistant minerals, explores methodological strategies for incorporating their nanoparticles into polymeric matrices and textile structures, and identifies primary technical challenges hindering commercial viability. Integrating insights from mineralogy, nanotechnology, and textile engineering, this study delineates pathways for developing next-generation lightweight, flame-retardant, multifunctional protective textiles optimized for operational safety, wearer comfort, and concurrent EMI shielding in firefighter and mining personnel apparel.

Keywords: flame retardancy; mineral nanoparticles; layered silicates; polymeric nanocomposites; protective textiles

1. Introduction

Workers in high-risk industries, such as firefighters and mining personnel engaged in sulfur and coal operations, face frequent exposure to intense fire hazards marked by extreme temperatures and direct flame impingement. Flame-resistant protective textiles must seamlessly combine flame retardancy with thermal insulation, wearer mobility, and moisture management to safeguard both safety and comfort. While current solutions like aramid fabrics for example Nomex, Kevlar and fiberglass composites in firefighter turnout gear and mining apparel offer vital flame resistance, they often contend with excessive weight, diminished flexibility, and curtailed durability amid extended thermal stress and mechanical wear. Emerging nanotechnology breakthroughs introduce viable alternatives through the integration of mineral nanoparticles as versatile flame-retardant agents into polymeric matrices and textile architectures. Layered silicates, including mica, montmorillonite, and vermiculite, paired with lightweight minerals such as perlite and

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dolomite, deliver superior thermal stability, barrier functionality, and inherent fire-resistant behavior, establishing them as compelling enhancers for protective textiles in these rigorous settings [1].

2. Overview of Minerals with Flame-Retardant Properties

Minerals exhibit exceptional thermal and flame-retardant properties owing to their ordered crystalline structures and distinctive chemical compositions, rendering them ideal candidates for thermal protective and flame-resistant textiles. Layered silicates such as mica, montmorillonite, and vermiculite together with lightweight minerals like perlite and dolomite, exemplify these attributes: they endure extreme temperatures while serving as robust barriers to heat transfer and hot gas permeation. Through the formation of thin layers, dense structures, or expanded porous matrices, these materials generate tortuous pathways that impede heat and flame propagation, thereby suppressing ignition rates and fire spread. Moreover, certain variants promote char formation or intumescent expansion under fire exposure, further augmenting protective efficacy. Consequently, integrating their nanoparticles or powders into protective textiles particularly for firefighter gear and apparel worn by mining personnel in sulfur and coal operations markedly enhances product safety and longevity [2].

2.1. Mica

Mica is one of the most important minerals in the phyllosilicate group. Its layered structure, favorable dielectric properties, and thermal stability grant it a prominent role in geoscience and materials engineering. Crystallographically, mica predominantly adopts a monoclinic system, characterized by a tetrahedral-octahedral-tetrahedral (T-O-T) layer sequence: two tetrahedral silica sheets flank a central octahedral sheet containing aluminum or magnesium, with these structural packets linked by interlayer cations such as potassium or sodium. The relatively weak interlayer bonding enables perfect basal cleavage, allowing mica to split into thin, flexible, and partially elastic sheets that bend readily and largely recover their original shape [3].

The general chemical formula for the mica group is:

XY2−3(Si,Al)4O10(OH,F)2XY2−3(Si,Al)4O10(OH,F)2

where X is typically K, Na, or Ca, and Y represents Al, Mg, Fe, or Li. Thus, mica can be viewed as a hydrated aluminosilicate incorporating alkali and alkaline-earth cations, along with variable amounts of magnesium, iron, lithium, and sometimes fluorine. This compositional variability yields several principal species. Muscovite, a potassium-rich aluminous mica with the approximate formula:

KAl2(AlSi3O10)(OH)2KAl2(AlSi3O10)(OH)2

appears colorless, silvery white, or pale green and displays high transparency in thin sheets. Biotite, a Mg-Fe-bearing mica approximated by

K(Mg,Fe)3Al(Si3O10)(OH)2K(Mg,Fe)3Al(Si3O10)(OH)2

ranges from dark brown to black and abounds in igneous and metamorphic rocks. Phlogopite, a magnesium-rich, iron-poor variant with formula

KMg3Al(Si3O10)(OH)2KMg3Al(Si3O10)(OH)2

exhibits yellow, light-brown, or bronze hues and often associates with ultramafic rocks. Lepidolite, a lithium-bearing mica represented by:

K(Li,Al)1−2(Al,Si)3O10(OH,F)2K(Li,Al)1−2(Al,Si)3O10(OH,F)2

occurs in pink, purple, or light gray tones and serves as a key lithium source in pegmatites [4].

Physically, mica shows a Mohs hardness of 2.5–4 and a specific gravity of roughly 2.7–3.1 g cm^{-3}, with iron-rich varieties denser. Basal surfaces display vitreous to pearly luster; thin flakes especially muscovite are transparent to translucent, while biotite appears darker and opaquer due to its iron content. Physicochemically, mica excels as an electrical insulator, featuring a relatively high dielectric constant, low dielectric loss, and high-volume resistivity. These traits suit it for capacitor dielectrics, insulating plates in high-voltage gear, and electronic substrates. Its thermal stability and shock resistance further promote mica sheets and mica paper in thermal insulation, heating elements, and refractories [5].
In summary, mica's unique blend of layered crystallography, sheet-like cleavage, electrical insulation, thermal endurance, and chemical resistance coupled with compositional and color diversity from light muscovite and dark biotite to bronze phlogopite and pink-purple lepidolite positions it as a cornerstone for advanced functional materials. Notably, it acts as an effective filler and reinforcer in polymers, paints, coatings, and high-performance composites, enhancing mechanical strength, dimensional and thermal stability, and electrical performance alike [6].

Figure 1. Macroscopic image of the layered crystalline structure of mica, illustrating its platelet-like morphology, which underpins its high thermal stability and effectiveness as a physical barrier in heat-resistant applications [7].

2.2. Montmorillonite
Montmorillonite ranks as a prominent member of the smectite subgroup within phyllosilicates, renowned for its highly layered structure, expansive specific surface area, and remarkable swelling capacity. These attributes position it as a vital functional mineral in advanced composite systems. Crystallographically, it features a 2:1 layer arrangement where an octahedral sheet chiefly occupied by aluminum or magnesium lies sandwiched between two tetrahedral silica sheets. Isomorphic substitutions, such as Mg^{2+} replacing Al^{3+} in the octahedral layer or Al^{3+} for Si^{4+} in the tetrahedral sheets, impart a net negative charge to the layers. This charge is counterbalanced by exchangeable interlayer cations (typically Na^{+} or Ca^{2+}) and water molecules [8]. The feeble bonding between these charged layers and hydrated cations facilitates extensive intercalation and swelling, often culminating in full exfoliation under appropriate chemical or mechanical conditions. The idealized chemical formula approximates

(Na, Ca)0.33(Al, Mg)2Si4O10(OH)2·nH2O(Na,Ca)0.33(Al,Mg)2Si4O10(OH)2·nH2O

underscoring its nature as a hydrated aluminosilicate with variable magnesium, sodium, and calcium contents. Such flexibility drives its high cation-exchange capacity and enables customized surface chemistry via ion exchange or organomodification. Physically,

montmorillonite forms ultrafine grains, with platelets mere nanometers thick and lateral spans from tens of nanometers to several micrometers. In bulk, it presents as soft, earthy to clay-like aggregates in cream, gray, or pale green shades. Its Mohs hardness spans 1–2, with specific gravity around 2.3–2.6 g cm^{-3}. Unlike mica's robust flakes, montmorillonite platelets lack standalone mechanical strength but excel as reinforcements due to their extreme aspect ratio and surface area when adequately dispersed [9].
Physicochemically, pristine montmorillonite acts as an electrical insulator, yet its heterogeneous makeup fosters strong dielectric polarization at interfaces. In alternating electromagnetic fields, permittivity and conductivity mismatches between aluminosilicate layers, interlayer cations, and the host matrix induce Maxwell–Wagner–Sillars polarization, boosting dielectric loss in polymer nanocomposites. Interlayer accessibility supports organic cation, polymer, or metal ion intercalation, yielding organophilic clays and hybrids with enhanced affinity for hydrophobic matrices. This intercalation-exfoliation mechanism underpins polymer-clay nanocomposites, where dispersed platelets form tortuous paths to improve mechanical integrity, barrier properties, thermal stability, and flame resistance [10].
In polymers, modest loadings often just a few weights percent yield marked gains in modulus, dimensional stability, and gas impermeability, alongside flame retardancy via char reinforcement and heat-shielding layers. Though inherently nonconductive, pairing montmorillonite with fillers like carbon nanotubes, graphene, or metals creates hybrids that enhance dispersion, adhesion, and impedance matching for absorption-dominant EMI shielding. Its abundance, affordability, and eco-friendliness further commend it for sustainable composites. Ultimately, montmorillonite's expandable 2:1 layers, adaptable chemistry, high aspect ratio, and interfacial polarization make it an ideal platform for multifunctional nanocomposites targeting reinforcement, barriers, fire safety, and electromagnetic shielding [11].

Figure 2. Macroscopic view of dolomite mineral, showing its massive texture and mineral structure, which serve as a source of endothermic reactions and refractory phase formation in heat-resistant systems [12].

2.3. Vermiculite

A layered phyllosilicate mineral akin to smectites and hydrated micas, draws keen interest for thermal insulation and advanced engineered materials due to its unique exfoliation at elevated temperatures. It features a 2:1 layer structure: an octahedral sheet primarily aluminum and magnesium sandwiched between two tetrahedral silica sheets. Isomorphic substitutions in these layers yield a net negative charge, offset by interlayer cations like magnesium, iron, potassium, and notably water molecules. The weak interlayer bonding and hydrated species drive dramatic thermal expansion; rapid heating causes grains [13].
Chemically, vermiculite acts as a magnesium-iron aluminosilicate with exchangeable interlayer cations and variable hydration, its stoichiometry varying by geological origin and weathering. It boasts high cation-exchange capacity and modifiable surfaces through ion exchange or organophilization. Macroscopically, raw vermiculite forms shiny, mica-

like flakes in golden to bronze-brown hues; post-exfoliation, it yields lightweight, porous granules. Mohs hardness is low to moderate, true density ~2.5–2.7 g cm^{-3}, while exfoliated bulk density plummets from extensive porosity [14].
Physicochemically, natural vermiculite serves as both electrical and thermal insulator. Its layers, laced with water and mobile cations, enable dielectric polarization and moisture absorption. In alternating electromagnetic fields especially microwaves it fosters loss via interfacial polarization and ionic mobility, despite negligible conductivity. Yet its engineering appeal centers on thermal traits: heating-induced expansion, high porosity, and low conductivity suit it for lightweight insulators, low-density refractories, and flame/heat barriers [15].
In polymer and composite systems, exfoliated vermiculite functions as a lightweight filler boosting thermal stability at reduced density. Porous particles create tortuous heat and gas paths, curbing conductivity and permeability; during fire, the refractory structure builds an insulating char layer to hinder spread and transfer. Lacking inherent conductivity for EMI shielding, it pairs effectively with conductive or magnetic fillers as a stable, low-density ceramic phase. Here, vermiculite adds porosity, wave reflection/scattering paths, and thermal resilience, enabling multifunctional insulator-shielder hybrids. This blend of expandable layers, refractory expansion, low weight, and tunable surfaces positions vermiculite as a prime candidate for lightweight functional materials like thermal insulators, fire retardants, and advanced composites [16].

Figure 3. Macroscopic view of vermiculite mineral with a layered structure and platelet-like appearance, highlighting its high thermal expansion capability and its ability to form porous insulating layers at elevated temperatures [17].

2.4. Perlite

A siliceous volcanic glass, has emerged as a vital mineral in lightweight insulation and engineered composites owing to its pronounced expansion upon heating and the resulting highly porous structure. Geologically, it originates from hydrated rhyolitic and dacitic glasses formed by rapid quenching of silica-rich magmas, followed by secondary hydration. Characteristic textures include concentric onion-skin fractures and arcuate cracks, stemming from contraction-expansion stresses during cooling and hydration. Mineralogically amorphous unlike crystalline phyllosilicates perlite may contain minor dispersed phases like feldspar, quartz, or clays within its glassy matrix [18].
Chemically, perlite mirrors other silica-rich volcanic glasses, dominated by high SiO_2 content alongside Al_2O_3 and notable Na_2O and K_2O, with lesser CaO, MgO, and Fe oxides. Critically, it harbors several weight percent of molecular and hydroxyl water, which governs expansion. Rapid heating to 800–900 °C vaporizes this water into steam, building internal pressure that foams the glass into low-density, vesicular granules. Raw perlite's true density spans 2.2–2.4 g cm^{-3}; expanded forms drop below 0.1 g cm^{-3} due to extreme

porosity.

Physicochemically, perlite excels as an electrical and thermal insulator with low conductivity and fair thermal stability. Its glassy composition confers resistance to many chemicals, though strong alkalis or weathering may induce devitrification and clay formation. The closed-cell foam structure of expanded perlite disrupts conductive and convective heat paths, yielding exceptionally low effective thermal conductivity ideal for insulating mortars, lightweight concrete, refractory boards, and fire-protective coatings. Incombustible and inorganic, it remains stable under fire, forming a heat-blocking layer to curb transfer and spread [19].

In polymer composites, expanded perlite serves as an ultra-lightweight filler that cuts density, boosts insulation, and elevates fire performance. Hollow cellular particles lower specific weight while creating porous microstructures and interfaces that tortuously hinder heat and gas flow, reducing conductivity and permeability. Lacking inherent conductivity for standalone EMI shielding, it pairs with conductive or magnetic fillers as a stable, low-density scaffold. Here, perlite delivers insulation, weight savings, fire resilience, and a robust framework for functional phases. This suite of glassy heritage, thermal expansion, ultralow density, porosity, insulation, and nonflammability establishes perlite as a cornerstone for lightweight construction, insulators, and multifunctional composites [20].

Figure 4. Macroscopic view of expanded perlite, showing its porous granular structure and low density, which make it an effective material for thermal insulation and heat transfer reduction [21].

2.5. Dolomite

A carbonate mineral, serves prominently as both a rock-forming phase and functional filler in engineered materials, thanks to its tunable reactivity, thermal behavior, and mechanical attributes. Crystallographically, it crystallizes in the trigonal system with a rhombohedral structure akin to calcite. The lattice features alternating Ca^{2+} and Mg^{2+} cation layers coordinated by CO_3^{2-} anions, yielding a distinctive ordered Ca–Mg–Ca–Mg sequence along the c-axis. This cation ordering sets dolomite apart from calcite-magnesite solid solutions, influencing lattice parameters, cleavage, and stability. Crystals often display rhombohedral habits with curved or saddle-like faces; in sedimentary rocks, it appears as fine- to medium-grained mosaics or replacement textures in limestones and dolostones [22].

Chemically, dolomite is an anhydrous calcium-magnesium carbonate, ideally

$$\mathrm{CaMg(CO3)2}CaMg(CO3)2$$

Though natural variants incorporate Fe^{2+}, Mn^{2+}, or other divalent cations substituting for Mg^{2+} or Ca^{2+}—imparting pink, brown, or gray tones versus the white-to-colorless pure form. Mohs hardness falls between calcite and quartz at 3.5–4, with specific gravity ~2.8–2.9 g cm^{-3}. It shows perfect rhombohedral cleavage and reacts sluggishly with cold dilute HCl (unlike effervescent calcite), though powdering or heating intensifies the response. Fresh surfaces gleam with vitreous luster and transparency to translucency [23].

Physicochemically, dolomite remains stable to moderate temperatures before undergoing stepwise thermal decomposition. The $MgCO_3$ moiety breaks down at lower temperatures than $CaCO_3$, liberating CO_2 and forming mixed oxides or carbonate-oxide phases. This endothermic process aids flame retardancy and smoke suppression in polymers or cementitious systems by absorbing heat and diluting combustibles. The resultant MgO–CaO residues build refractory, ceramic-like frameworks that bolster high-temperature integrity. In composites, finely milled dolomite acts as a versatile filler and extender in polymers, rubber, paints, and coatings enhancing dimensional stability, stiffness, abrasion resistance, and economy. Its moderate refractive index and whiteness allow partial substitution for costlier pigments, while carbonate chemistry tunes fire and thermal response. In cement and concrete, dolomite modifies hydration, early strength, and durability via controlled dissolution-reprecipitation. Electrically insulating and unsuited for direct EMI shielding, it provides a stable, robust, low-cost matrix for hybrids with conductive or magnetic additives. Ultimately, dolomite's ordered rhombohedral architecture, managed decomposition, mechanical reinforcement, and chemical adaptability make it a cornerstone for multifunctional composites and construction materials [24].

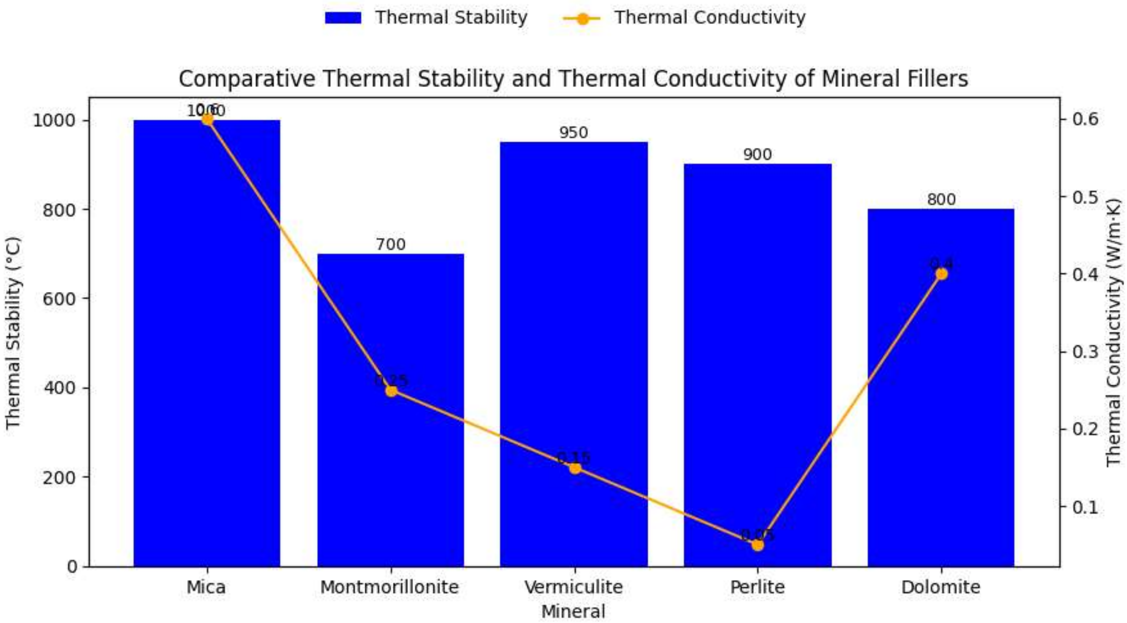

Figure 5. Macroscopic view of dolomite crystals, illustrating their crystalline morphology and mineral structure, which are of interest in heat-resistant applications as a source of endothermic reactions and refractory phase formation [25].

Figure 6. Comparison of thermal stability (°C) and thermal conductivity (W/m·K) of different mineral fillers, including mica, montmorillonite, vermiculite, perlite, and dolomite.

Table1: Comparative Table of Specifications and Flame-Retardant Properties of Key Minerals

Feature	**Mica**	**Montmorillonite**	**Vermiculite**	**Perlite**	**Dolomite**
Mineral Group	Phyllosilicates	Phyllosilicates	Phyllosilicates	Siliceous volcanic glass	Carbonate
Thermal Stability	Up to ~1000°C	Up to ~700°C	Up to ~950°C	Up to ~900°C	Up to ~800°C
Structure	Layered sheets	Layered sheets with interlayer expansion	Expandable layered sheets	Closed-cell porous	Rhombohedral crystals
Thermal Conductivity	0.5-0.7 W/m·K	0.15-0.3 W/m·K	0.1-0.2 W/m·K	0.04-0.07 W/m·K	0.3-0.5 W/m·K
Flame-Retardant Mechanism	Barrier formation and char promotion	Intercalation and char barrier	Heat absorption and barrier effect	Thermal insulation via porosity	Endothermic decomposition
Flame-Retardant Applications	Protective textiles, electrical insulation	Polymer nanocomposites, coatings	Fireproofing, insulation	Spray coatings, insulation boards	Spray mortars, intumescent coatings
Specific Surface Area	Low to moderate (micro)	High (nano-exfoliated)	Moderate to high (layer expandable)	Very high (expanded form)	Low (ground powder)

3. Investigation of High-Temperature Protection Mechanisms in Mineral-Based Textiles

Mineral-based thermal protective textiles function through multiple mechanisms, including physical barrier formation, heat absorption, and attenuation of heat transfer pathways [26].

3.1. Layered Barrier Formation and Tortuous Pathways

Layered silicates like mica and montmorillonite form thin, dense layers that elongate and complicate heat transfer routes, thereby delaying hot gas and flame penetration. Mica, in particular, preserves structural integrity up to ~1000°C owing to its exceptional thermal stability, establishing an impermeable physical barrier. These architectures concurrently reinforce char formation, serving as secondary insulation that curtails combustion rates [27].

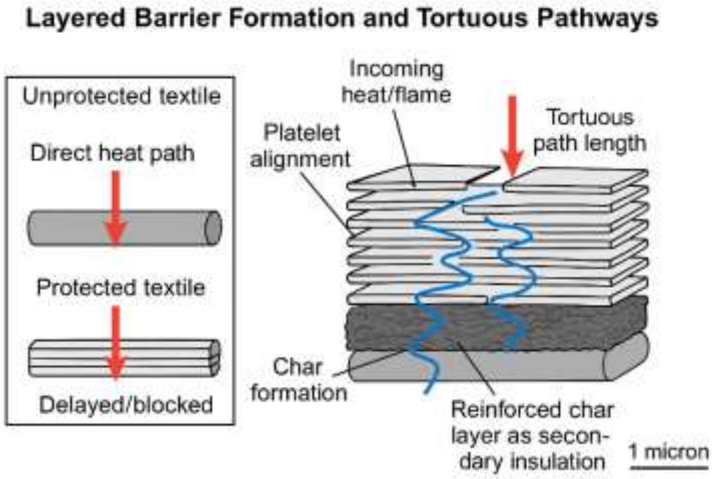

Figure 7. Protective mechanism of layered silicates (e.g., mica and montmorillonite) in textiles: the aligned platelet architecture creates tortuous pathways that hinder heat and hot-gas transport, delaying flame penetration. Owing to their high thermal stability, these layers act as an impermeable physical barrier while promoting reinforced char formation as a secondary insulating layer.

3.2. Thermal Expansion and Porous Morphology

Vermiculite and perlite exhibit dramatic expansion upon high-temperature exposure, yielding low-density porous structures with thermal conductivity below 0.1 W/m·K. This intumescent behavior generates a protective insulating layer that effectively disrupts convective and conductive heat transfer [28].

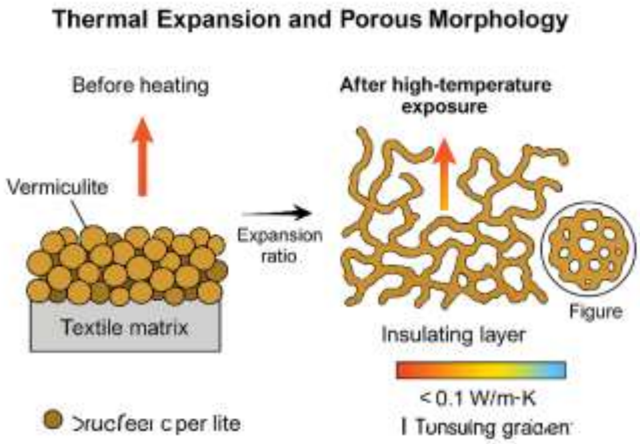

Figure 8. Thermal expansion and intumescent behavior of vermiculite and perlite under high-temperature exposure: rapid expansion forms a low-density porous insulating layer with ultralow thermal conductivity, effectively suppressing conductive and convective heat transfer.

3.3. Endothermic Decomposition and Gas Dilution

Mica delivers passive thermal protection via its exceptional stability (~1000°C) and low thermal conductivity (0.5–0.7 W/m·K), functioning as a non-reactive heat shield. Dolomite, meanwhile, liberates CO_2 through endothermic decomposition, diluting flammable gases and cooling surfaces, while yielding refractory MgO–CaO phases that form durable ceramic-like frameworks. Together, these mechanisms bolster thermal protection up to 900–1000°C [29].

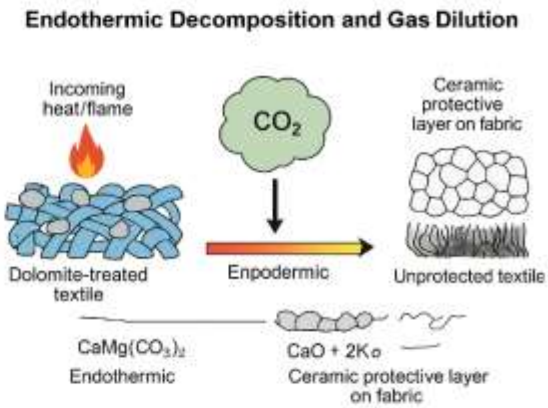

Figure 9. Endothermic decomposition–driven thermal protection mechanism: dolomite releases CO_2 upon heating, absorbing heat and diluting flammable gases, while forming refractory CaO–MgO ceramic phases that establish a stable protective layer and enhance high-temperature resistance.

4.Applications of Mineral–Polymer Composites for High-Temperature Protection in Textile Industry

The application of mineral-polymer composites in thermal protective textiles has gained momentum since the 2010s, with extensive research exploring nanoparticle incorporation into polymer matrices to boost flame retardancy, thermal stability, and durability under harsh conditions [30].

4.1. Mica

Mica nanoparticles feature prominently in commercial flame-retardant coatings for industrial textiles, especially where thermal insulation and dimensional stability converge. Studies show that 2–5 wt% mica in polyurethane or PVC matrices raises the limiting oxygen index from ~20% to over 30%, while fostering a dense, impermeable barrier stable to ~1000°C. European firefighter gear has adopted these mica nanocomposites in multilayer architectures [31].

4.2. Montmorillonite

Organically modified montmorillonite underpins commercial epoxy- and polyester-based nanocomposites for technical textiles. Around 2015, experiments revealed that 3 wt% organo-montmorillonite in cellulose acetate enhances thermal resistance by ~50% and roughly doubles ignition or after flame times. These nano clay systems now equip mass-produced protective garments for coal mining in China and the United States, prioritizing flame retardancy and barrier performance [32].

4.3. Vermiculite
Exfoliated vermiculite serves as a lightweight, thermally stable filler in insulating layers of firefighter turnout gear meeting NFPA standards. Fire tests akin to ASTM E84 demonstrate ~70% heat transfer reduction in vermiculite-polyamide composites versus neat polymers. Major manufacturers have integrated ~10 wt% vermiculite into insulation for sulfur mining and high-temperature industries [33].
4.4. Perlite
Expanded perlite appears in spray coatings for industrial textiles and insulation boards demanding ultralow thermal conductivity and density. Adding ~15 wt% nano- or micro-perlite to phenolic resins yields effective conductivities ~0.05 W/m·K with sound mechanical integrity. Commercialized in Europe for bus interiors and mining protective linings, these composites excel in transportation and harsh environments [34].
4.5. Dolomite
Finely ground dolomite functions as a filler in intumescent textile coatings and PVC composites for mining applications. Studies indicate ~20 wt% dolomite cuts smoke release by ~40% and shields to ~800°C via endothermic decomposition into CaO–MgO residues. In Iran and India, dolomite-laden coatings protect workers in sulfur mining and high-risk operations [35].

Table 2: summarizes the indicative commercialization status of the discussed minerals in textile-related flame-retardant systems:

Mineral	**Commercialization level**	**Main application**	**Approximate LOI improvement (%)**
Mica	High	Firefighter gear	~+15
Montmorillonite	High	Mining protective suits	~+20
Vermiculite	Medium	Insulation layers	~+25
Perlite	Medium	Spray-applied coatings	~+18
Dolomite	Low	Intumescent coatings	~+12

5. Challenges and Barriers to Widespread Adoption in the Textile Industry
Despite encouraging laboratory outcomes, technical and economic hurdles continue to hinder widespread industrial adoption of mineral-polymer composites in thermal protective textiles. Uniform dispersion of layered silicates like mica and montmorillonite in hydrophobic polymer matrices proves elusive, frequently causing agglomeration and mechanical degradation. Weak interfacial adhesion between hydrophilic nanoparticles and textile fibers triggers delamination during flexing or laundering, undermining durability silane coupling agents or organophilic modifications raise costs by 20–30% yet offer only partial compatibility gains. High-shear exfoliation demands exceed conventional textile coating equipment capacities, capping speeds at lab rates (1–5 m/min) versus industrial

norms (20–50 m/min); polymer thermal decomposition during mineral incorporation above 200°C introduces defects, while preserving nanoparticle alignment through fabric weaving remains daunting at scale. Mineral nanoparticles command 5–15 times the price of traditional flame retardants (e.g., phosphorus compounds), with mica nanoplatelets at $50–100/kg against $5–10/kg for micronized fillers; supply shortages of size-controlled, high-purity vermiculite and perlite limit mass production, and dolomite's compositional variability necessitates batch-by-batch quality checks [36].
Finally, lack of standardized protocols for mineral-enhanced textiles under combined thermal-mechanical-wear cycles impedes certification (NFPA 1971, EN 469), as existing standards fail to evaluate nanoparticle migration during laundering or skin irritation from dolomite decomposition products consistent limiting oxygen [37].

6. Future Prospects, Innovations, and Environmental Concerns

Polymeric mineral composites promise smart textiles blending fire resistance with electromagnetic interference (EMI) shielding, as technical hurdles yield to sustainable innovations [38].
Integration of nanomaterials like mica, montmorillonite, vermiculite, perlite, and dolomite into polymer matrices boosts thermal resistance and LOI by up to 25%, targeting firefighter gear, mining suits, and advanced insulation. The global technical textiles market eyes $15 billion by 2030. Key strengths lightweight design, flexibility with high tensile strength, superior fire retardancy and EMI shielding without sacrificing breathability signal strong commercialization potential, especially for mica and montmorillonite [39].
Uniform filler dispersion poses the chief challenge, now addressed via nanotechnology; future innovations pivot to graphene hybrids for multifunctional protection. Environmentally, vermiculite and perlite mining risks soil degradation and high-water use, while non-biodegradable composites hinder recycling. Remedies include recycled minerals, low-carbon processes, and biopolymer hybrids, slashing carbon footprints by up to 40% and extending lifecycle sustainability [40].

7. Conclusion

Mineral-polymer composites leveraging layered silicates (mica, montmorillonite, vermiculite) and lightweight minerals (perlite, dolomite) offer transformative potential for thermal protective textiles in high-risk applications like firefighting and sulfur/coal mining . These materials excel through multiple mechanisms—barrier formation, intumescent expansion, and endothermic decomposition—achieving superior flame retardancy (LOI gains 15–25%), ultralow thermal conductivity (~0.05 W/m·K), and multifunctionality including EMI shielding while maintaining breathability and flexibility.
Mica and montmorillonite demonstrate high commercialization readiness in firefighter gear and mining suits, while vermiculite/perlite provide NFPA-compliant insulation layers and dolomite enhances smoke suppression via refractory residues . Despite technical challenges like nanoparticle dispersion, high costs (20–30% premium), and certification gaps under NFPA 1971/EN 469 standards, nanotechnology solutions (graphene hybrids) and sustainability strategies (recycled fillers, biopolymers) reduce carbon footprints by up to 40%.
With the global technical textiles market projected at $15 billion by 2030, targeted R&D in uniform dispersion, scalable processing, and standardized protocols will drive widespread industrial adoption of these lightweight, multifunctional protective textiles, balancing operational safety, wearer comfort, and environmental sustainability.

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