Application of Mineral-Based Materials in Electromagnetic Interference Shielding

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Abstract

electromagnetic radiation, raising critical concerns about health, data security, and device reliability. Consequently, electromagnetic interference (EMI) shielding has become indispensable in sectors ranging from aerospace and healthcare to consumer electronics and wearable technology. While metals like copper and aluminum remain benchmarks for shielding effectiveness (SE), their high density, susceptibility to corrosion, and inherent rigidity severely limit their suitability for next-generation flexible and lightweight applications. In response, mineral-based materials—including layered silicates, transition metal oxides, magnetic ferrites, and conductive mineral hybrids—have surfaced as sustainable, low-cost, and multifunctional alternatives. This comprehensive review examines the pivotal role of mineral-derived nanomaterials in enhancing EMI shielding within polymer matrices and textile architectures. Beyond a conventional survey, this work provides a novel synthesis by establishing a direct design pathway from mineralogical properties to textile-specific shielding performance. We uniquely dissect the shielding mechanisms (reflection, absorption, multiple internal reflections) and link them to the distinct electromagnetic signatures of specific minerals such as montmorillonite, hematite, magnetite, graphite, mica, and lapis lazuli derivatives. A significant innovative focus is placed on the critical translation of these materials into wearable textiles, where we analyze the unique set of requirements and challenges, including the conductivity-comfort trade-off, durability, and launderability. The review culminates in outlining future directions for developing eco-friendly, high-performance shielding textiles that are deeply rooted in natural mineral heritage.

Keywords: Electromagnetic interference (EMI) shielding, mineral nanoparticles, polymer nanocomposites, smart textiles, conductive fabrics, sustainable materials

1. Introduction

Electromagnetic interference (EMI) denotes the disruptive effect of external electromagnetic fields (EMFs) on the normal operation of electronic circuits, a phenomenon prevalent across frequencies from 30 MHz to 300 GHz. The rapid deployment of 5G/6G networks, the Internet of Things (IoT), and pervasive wearable electronics has led to a significant surge in ambient EMF levels, creating an urgent demand for effective, adaptable shielding solutions. Traditional EMI shields, predominantly metals like copper, aluminum, and steel, offer excellent shielding effectiveness often exceeding 60 dB but are burdened by high density, poor corrosion resistance, mechanical inflexibility, and an inherent incompatibility with modern flexible or wearable applications [1]. This landscape has catalyzed a global shift toward developing lightweight, flexible, and environmentally sustainable shielding materials. Research has increasingly focused on polymer- and textile-based composites enhanced with functional nanofillers. Among these, mineral-based materials are particularly compelling due to their natural abundance, low cost, environmental benignity, and rich spectrum of intrinsic electromagnetic properties [2]. Minerals such as magnetite (Fe_3O_4), hematite (α-Fe_2O_3), montmorillonite, graphite, and even complex rocks like lapis lazuli (composed of lazurite, pyrite, and calcite) possess elemental constituents (e.g., Fe, S, Al, Si) that can attenuate electromagnetic waves through mechanisms like polarization, electrical conduction, or resonant absorption. When engineered into nanoscale particles and integrated into polymeric hosts or textile fibers, these minerals give rise to multifunctional composites. Such composites can synergistically combine EMI shielding with other desirable attributes, including flame retardancy, UV protection, antimicrobial activity, and even cultural aesthetic value [3].

This review focuses on the strategic use of mineral-derived materials for EMI shielding within polymer composites and textile structures. We systematically analyze the relationships between mineral structure and electromagnetic properties, elucidate governing shielding mechanisms, evaluate hybridization strategies, and survey relevant processing techniques [4]. Finally, we address the practical challenges of translating these materials into viable polymeric products and outline future research trajectories.

2. Fundamentals of EMI Shielding Mechanisms and Material-Driven Attenuation Pathways

The effectiveness of an EMI shield is quantified in decibels (dB), representing its capacity to attenuate incident electromagnetic energy. The total shielding effectiveness (SE) arises from three co-existing physical mechanisms such as reflection (SER), absorption (SEA), and multiple internal reflections (SEM), as summarized by the fundamental equation: SE = SER + SEA + SEM [5].

-Reflection (SER): is the dominant mechanism in highly conductive materials like metals. It occurs at the interface between the shield and the surrounding air due to a pronounced mismatch in wave impedance. Effective reflection requires a high concentration of mobile charge carriers, establishing high electrical conductivity at the shield's surface [6].

-Absorption (SEA): involves the conversion of electromagnetic energy into heat within the shield's bulk material. This process is governed by dielectric loss (related to the imaginary part of the complex permittivity, ε'') and/or magnetic loss (related to the imaginary part of the complex permeability, μ''). Materials optimized for absorption typically possess moderate conductivity coupled with high dielectric or magnetic loss tangents. For wearable technologies, absorption-dominant shielding is often preferred, as it minimizes secondary pollution caused by reflected waves [7].

-Multiple Internal Reflections (SEM): represent a secondary attenuation mechanism where waves reflected between internal interfaces or surfaces undergo further dissipation before exiting the material. This effect is markedly enhanced in materials with porous, foam-like, or hierarchically structured architectures containing numerous internal boundaries and interconnected networks [8].

Mineral materials, based on their unique properties, are capable of generating protective states against electromagnetic wave radiation through various mechanisms, as mentioned below.

-Conduction Loss Pathway: Minerals with intrinsic or engineered electrical conductivity, such as exfoliated graphite, interconnected magnetite networks, or mineral hybrids with carbonaceous materials, establish percolating conductive pathways. This facilitates ohmic losses (enhancing SEA) and simultaneously improves surface reflectivity (increasing SER) by boosting the composite's overall conductivity [9].

-Dielectric Polarization Loss Pathway: Minerals characterized by high electronic or ionic polarizability, including many transition metal oxides (e.g., hematite, TiO_2) and layered silicates (e.g., montmorillonite), are potent contributors to absorption. Under an alternating electromagnetic field, these materials exhibit various polarization phenomena—electronic, ionic, dipolar, and particularly interfacial (Maxwell-Wagner-Sillars) polarization at the boundaries between mineral fillers and the polymer matrix. These processes efficiently convert electromagnetic energy into thermal energy [10].

-Magnetic Loss Pathway: Ferrimagnetic minerals, most notably spinel ferrites (e.g., Fe_3O_4, $CoFe_2O_4$), attenuate waves through magnetic resonance, natural resonance, and eddy current losses. Their characteristically high electrical resistivity suppresses detrimental eddy currents, rendering them exceptionally effective as microwave absorbers. They are frequently combined with dielectric fillers to achieve synergistic shielding effects [11].

-Structural and Geometric Enhancement: The physical morphology of the mineral filler plays a decisive role. Two-dimensional nanomaterials with high aspect ratios, such as graphene derivatives, nano-clays, and mica sheets, create extended, tortuous paths for propagating waves. This geometry promotes multiple internal reflections and scattering, effectively lengthening the wave's travel path within the composite and thereby increasing its interaction time and subsequent attenuation [12]

Therefore, the rational selection and combination of mineral fillers—orchestrating conductive, dielectric, and magnetic phases—enables the precise engineering of composite materials. This approach allows researchers to fine-tune the shielding profile, optimally balancing reflection and absorption for targeted applications [13]. In the context of textiles, these mechanisms operate across different scales of the fabric structure, from nano-scale fillers to macro-scale weave, as detailed in Figure 1.

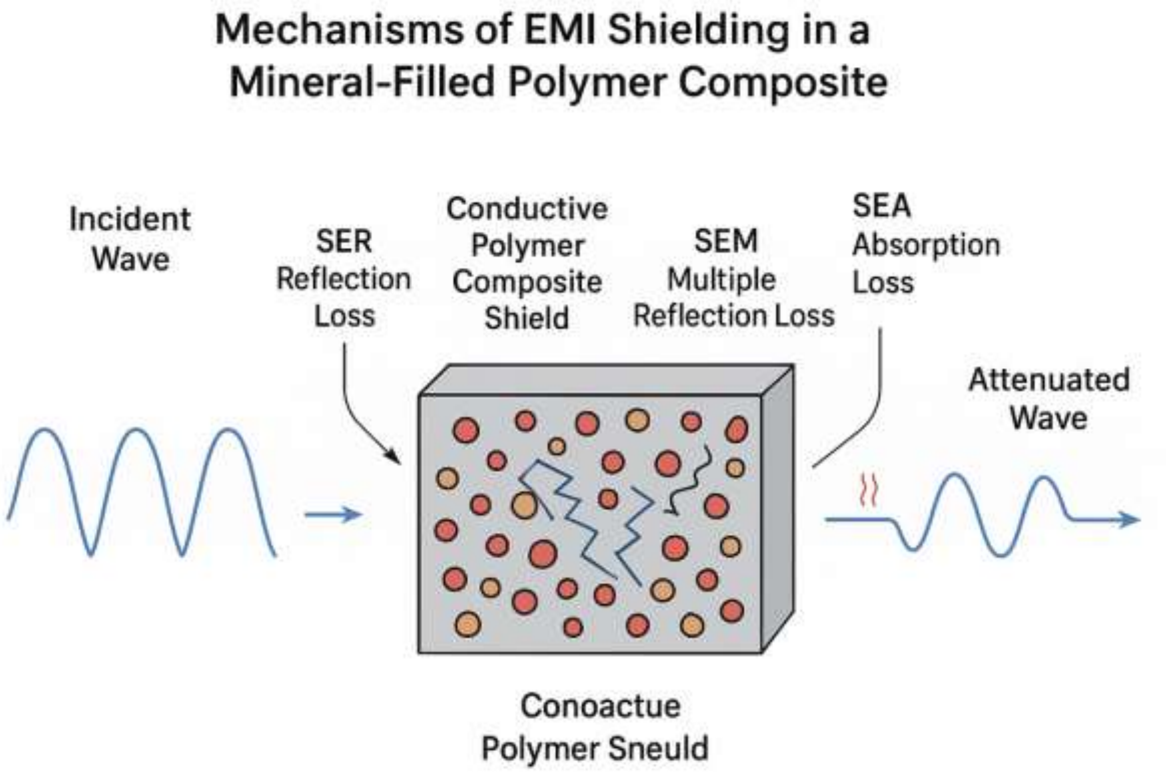

Figure 1. Schematic of EMI shielding mechanisms in a mineral-enhanced functional fabric structure.

3. Mineral based materials for EMI shielding

The diverse electromagnetic properties of minerals translate into a wide range of shielding capabilities [14]. A comparative analysis of key mineral-based materials, summarizing their primary mechanisms, typical performance, and inherent trade-offs, is provided as below.

3.1. Magnetic Ferrites (Fe_3O_4, γ-Fe_2O_3, $CoFe_2O_4$)

Magnetic ferrites are ceramic compounds primarily based on iron oxide (Fe_2O_3) combined with one or more transition metal oxides (e.g., MnO, ZnO, NiO). They are indispensable in modern electronics due to their unique combination of magnetic and electrical properties. Their high electrical resistivity is a key advantage, as it minimizes eddy current losses, enabling efficient performance at high frequencies—a trait crucial for transformers, inductors, antennas, and EMI shielding materials. Ferrites also exhibit tunable magnetic anisotropy, moderate saturation magnetization, and excellent chemical stability, all of which can be modulated through compositional variation or nano structuring. These properties, alongside their cost-effectiveness and ease of synthesis, cement their role as critical components in data storage, microwave devices, and advanced functional composites for EMI suppression [15].

For instance, magnetite (Fe_3O_4) nanoparticles are widely employed due to their strong saturation magnetization and chemical robustness. In polymer composites, such as those with polyaniline, magnetite fillers (below 15 wt%) can provide absorption-dominated shielding effectiveness greater than 20 dB in the 8–12 GHz (X-band) range. In textile applications, cotton fabrics coated with magnetite via dip-coating and cross-linking processes have demonstrated promising SE values between 15 and 25 dB, showcasing their potential for wearable shielding [16].

3.2. Layered Silicates (Montmorillonite, Bentonite)

Layered silicates like montmorillonite and bentonite belong to the smectite group of phyllosilicate minerals. Their structure consists of a central octahedral alumina sheet sandwiched between two tetrahedral silica sheets, forming a 2:1 layered architecture. Key features include a high cation exchange capacity (CEC) and the ability to swell by absorbing water and organic molecules between their layers. This swelling behavior, combined with a large surface area and tunable surface chemistry, makes them invaluable for applications ranging from nanocomposite reinforcement and rheology modification to environmental remediation [17].

Although electrically insulating in their pure form, montmorillonite nanoclay significantly enhances shielding when hybridized with conductive components. Its layered structure acts as a physical barrier, promoting multiple internal reflections and hindering electromagnetic wave propagation. For example, in ternary composites with epoxy and reduced graphene oxide, montmorillonite has contributed to achieving shielding effectiveness values as high as 35 dB, leveraging its ability to improve impedance matching and interfacial polarization [18].

3.3. Graphite and Related 2D Materials

Graphite and graphene-like minerals form a class of layered materials renowned for exceptional electrical conductivity, thermal stability, and mechanical strength, stemming from their anisotropic two-dimensional (2D) crystal structures. Natural graphite comprises stacks of graphene layers held together by weak van der Waals forces, allowing for easy exfoliation a property exploited in lubricants, batteries, and refractory materials. Beyond graphite, interest has expanded to isostructural 2D minerals like molybdenum disulfide (MoS_2) and hexagonal boron nitride (h-BN), which offer complementary properties such as tunable bandgaps and chemical inertness [19].

When exfoliated, natural graphite provides high electrical conductivity (~10^4 S m^{-1}). Graphite/polymer composites, for instance with polyurethane, can achieve SE values exceeding 40 dB at filler contents around 20 vol%. In textiles, coatings based on graphite applied to polyester fabrics have demonstrated SE of approximately 30 dB while maintaining essential fabric flexibility, pointing toward practical applications in smart clothing [20].

3.4. Sulfide-Containing Minerals: Pyrite and Lapis Lazuli

Sulfide-based minerals, particularly pyrite (FeS_2) and the lazurite component of lapis lazuli, have recently garnered attention for their potential in EMI shielding, primarily due to unique electrical properties and polarizable anionic structures. Pyrite is a naturally occurring semiconductor with a bandgap around 0.95 eV, a high density of free charge carriers, and moderate electrical conductivity. These attributes allow it to contribute to electromagnetic attenuation via absorption mechanisms, especially in the microwave region, through dielectric loss and interfacial polarization when embedded in polymer matrices [21].

Lapis lazuli itself is not a conductor; however, its vibrant blue color originates from the Tri sulfur radical anion (S_3^-) trapped within the aluminosilicate cage of lazurite. This chromophore exhibits strong optical absorption and electronic polarizability. When used as a functional pigment alongside conductive additives in composite coatings, lapis lazuli can enhance the scattering and multiple internal reflections of electromagnetic waves. While not traditional shielding materials like ferrites, these sulfide minerals present a novel, mineral-based route for creating hybrid shielding systems, especially when processed at the nanoscale or functionalized to yield synergistic effects in multifunctional composites [22] as detailed in Figure 2.

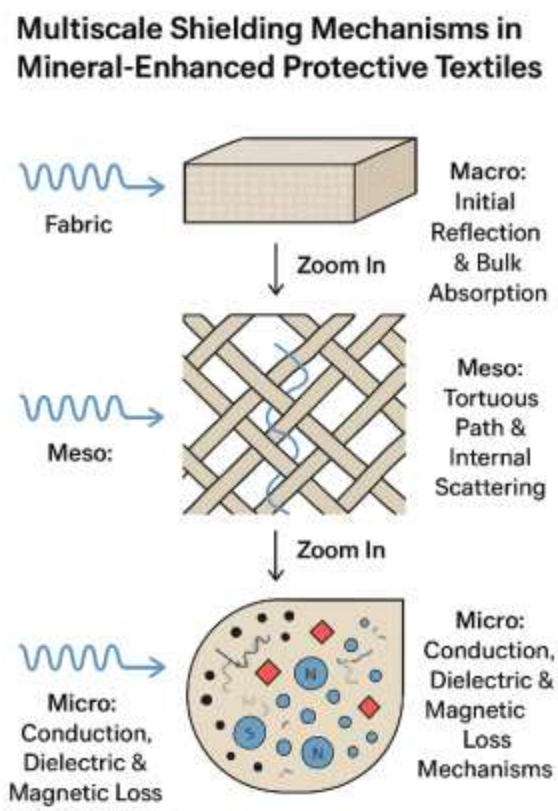

Figure 2. Multiscale shielding mechanisms in mineral-enhanced protective textiles.

In addition, Table1 summarized mineral based materials properties for EMI shielding application.

Table1: Comparative Analysis of Key Mineral-Based materials for EMI shielding

Mineral based Material	Primary Shielding Mechanism(s)	Typical SE Range (Reported in Composites)	Key Advantages	Main Challenges/Limitations
Magnetite (Fe_3O_4)/Ferrites	Magnetic Loss (dominant) via natural/resonance & eddy current; Supplementary dielectric loss	15–40 dB (X-band, 8-12 GHz) with 5-20 wt% loading	High magnetic loss, excellent high-frequency absorber; Natural abundance; Good chemical stability; Enables lightweight composites	Moderate electrical conductivity limits conduction loss; High density (~5 g/cm³); Susceptibility to oxidation
Exfoliated Graphite/Graphene	Conduction Loss (dominant) via ohmic dissipation; High reflection; Structural multiple reflections	30–50+ dB (X-band) with 5-20 vol% loading	Exceptional electrical conductivity; Very high SE at low thickness; Excellent mechanical & thermal properties	Tendency to agglomerate; High cost; Processing complexity; Increases stiffness
Montmorillonite/Layered Silicates	Dielectric Loss via interfacial (Maxwell-Wagner-Sillars) polarization; Structural barrier	5–35 dB (hybridized with conductive fillers in X-band)	Excellent dispersion & exfoliation; Improves mechanical/barrier properties at low loadings (1-5 wt%); Low cost, eco-friendly	Electrically insulating alone; Requires hybridization; SE dependent on design
Hematite (α-Fe_2O_3)	Dielectric Loss via electron hopping & dipole polarization	10–25 dB (X-band) as part of hybrid systems	High chemical/thermal stability; Abundant, low-cost, non-toxic; Good dielectric loss filler	Lower intrinsic loss vs ferrites; Requires conductive/magnetic partners

Pyrite (FeS_2)	Dielectric & Semiconductor Loss via polarization and charge carrier mobility	Preliminary data suggests measurable loss in X-band	Natural semiconductor; Earth-abundant; Synergistic potential in hybrids	Underexplored for EMI; Properties sensitive to stoichiometry/defects; Stability needs study
Lapis Lazuli (Lazurite-based)	Dielectric Loss via polarizable S_3^- anions; Structural scattering	Not yet quantitatively reported for EMI	Unique cultural/aesthetic value; Multifunctional (color, UV protection); Sustainable	Very low conductivity; Functional/aesthetic co-filler; Requires conductive matrix
Mica	Dielectric Loss; Structural barrier creating tortuous path	20–35 dB (optimized polymer/textile composites)	Excellent thermal stability; High aspect ratio platelets; Enhances mechanical properties	Electrically insulating; Must combine with conductive phases

4. Mineral–Polymer Composites for EMI Shielding

Mineral-polymer composites have firmly established themselves as a leading class of materials for EMI shielding, prized for their light weight, corrosion resistance, and highly tunable electrical properties. The strategy involves dispersing conductive or high-permittivity mineral fillers such as graphite, carbon nanotubes, MXenes, or metal oxides into an insulating polymer matrix (e.g., polyvinylidene fluoride, polyaniline, epoxy). This creates a material capable of attenuating electromagnetic waves through a combination of dielectric loss, conduction loss, and multiple internal reflections. Notably, even relatively low filler loadings can dramatically improve SE, with some composite systems surpassing 30 dB in the X-band a level sufficient for many commercial applications. The inclusion of layered silicates like montmorillonite further enhances these composites by not only improving mechanical and thermal stability but also aiding in impedance matching, a crucial factor for minimizing surface reflection and promoting absorption-dominant shielding [42].

The design of high-performance composites revolves around several key strategies. Controlling the percolation threshold is fundamental; by using nanostructured fillers with high aspect ratios, electrical conductivity can be achieved at minimal loadings, preserving the polymer's inherent flexibility and processability. Interfacial engineering, frequently accomplished using silane coupling agents, is critical for strengthening the adhesion between the inorganic mineral fillers and the organic polymer matrix. This leads to improved filler dispersion, reduced agglomeration, and ultimately, higher and more stable SE. Perhaps most powerfully, hybrid filler systems that combine minerals with complementary loss mechanisms can create synergistic shielding effects. A prime example is a polyaniline nanocomposite containing both magnetite (for magnetic loss) and montmorillonite (for dielectric loss via interfacial polarization). This ternary system achieved a remarkable SE of 42 dB at 12 GHz with only 10 wt% total filler, substantially outperforming its individual components by capitalizing on a combined magnetic-dielectric-conductive attenuation mechanism [43] as shown in Figure 3.

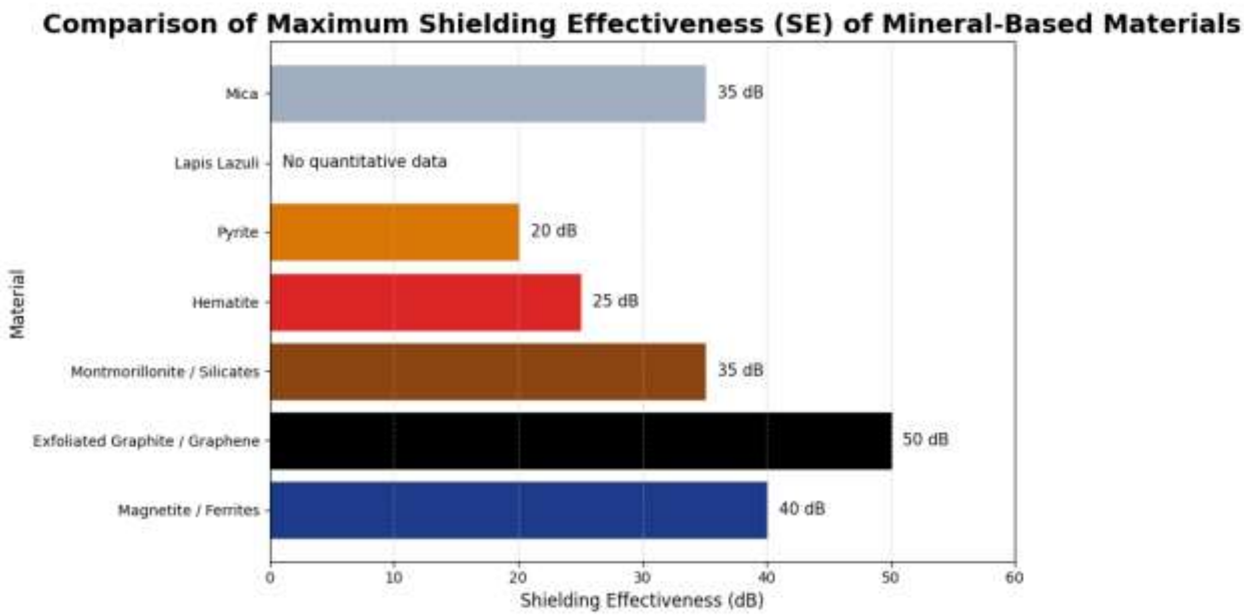

Figure 3. Comparative chart of SE values in key Mineral based Material.

The relatively limited industrial adoption of mineral based polymer composites for EMI shielding, despite the promising laboratory results, arises from a combination of performance, processing, economic, and regulatory constraints. Achieving high shielding effectiveness often requires substantial mineral loadings, which increase density, stiffness, and brittleness and thus erode the intrinsic advantages of polymers such as low weight and flexibility. Many minerals are purely dielectric or purely magnetic and must therefore be combined with additional conductive or magnetic phases in carefully designed hybrid systems, which complicates formulation and optimization. At the microstructural level, uniform dispersion of mineral nanoparticles within polymer matrices is difficult; particle agglomeration and poor interfacial adhesion degrade both electrical pathways and mechanical integrity, particularly under repeated bending, abrasion, or laundering in textile applications. From an industrial perspective, long-standing reliance on metals and carbonaceous fillers is reinforced by their extensive data, standards, and processing know-how, whereas mineral based systems still lack comprehensive design guidelines, standardized test protocols, and long-term reliability data at scale. Furthermore, the scalable production of surface-engineered mineral nanoparticles with consistent size, morphology, and surface chemistry remains costly and technically demanding, limiting competitive cost–performance ratios. In wearable and textile formats, additional challenges arise from the need to balance conductivity with comfort, breathability, and drape, as high filler contents tend to block pores and increase fabric weight. Finally, environmental and toxicological uncertainties associated with certain transition-metal oxides and ferrites, together with incomplete life-cycle assessments for many mineral nanoparticle systems, contribute to industrial caution. Overall, the gap between laboratory-scale demonstrations and robust, economical, and regulation-compliant products explains why mineral based polymer EMI shielding materials have so far seen restricted practical deployment compared with more established metallic and carbon based solutions.

5. Requirements and Challenges for EMI Shielding Textiles

Translating EMI shielding functionality from bulk composite materials into practical, flexible polymers and textiles introduces a complex set of performance demands and technical hurdles that extend far beyond merely achieving a high SE value in a laboratory setting [30].

5.1. Multifunctional Performance Requirements

An effective EMI shielding textile for real-world wearable or technical applications must satisfy a multifaceted profile:

-Effective Shielding Performance: Deliver sufficient SE (typically >20 dB for consumer applications, >30 dB for sensitive environments) across relevant communication frequency bands (e.g., 2.4 GHz WiFi, 3-6 GHz 5G) [31].

-Mechanical Durability and Flexibility: Withstand the repeated bending, stretching, folding, and abrasion inherent in textile use without suffering from coating cracks, filler delamination, or a significant decline in shielding performance [32].

-Wearer Comfort: Preserve essential comfort properties, most critically breathability (for moisture vapor transmission) and air permeability, while maintaining an acceptable hand feel (softness and drape). A dense, impermeable metallic coating is impractical for prolonged wear [33].

-Environmental and Operational Stability: Retain shielding functionality after exposure to environmental stressors such as humidity, temperature cycles, UV radiation, and perspiration [34].

-Launderability: Demonstrate robust resistance to degradation including loss of conductive filler, coating delamination, or reduction in conductivity over multiple standard industrial or domestic washing and drying cycles. This is a critical benchmark for commercial viability [35].

-Lightweight and Low Bulk: Avoid adding excessive weight or stiffness that would impair user mobility and comfort, a key consideration for wearable electronics and protective garments [36].

5.2. Pervasive Technical Challenges

Meeting this comprehensive set of requirements while successfully integrating mineral-based fillers presents several significant, interconnected challenges which needs more attention to obtain EMI shielding.

The Conductivity-Comfort Trade-off: High loadings of conductive fillers (often >10-15 wt%) are typically necessary to establish a percolating network for effective shielding. However, such high loadings can clog the pores of the textile substrate, severely degrading breathability and altering the fabric's hand feel. The central challenge is to achieve a low electrical percolation threshold through optimal filler morphology, dispersion, and distribution, thereby minimizing the required filler content [37].

Interfacial Adhesion and Durability: For the shield to survive mechanical stress and laundering, a strong, durable bond must exist between the mineral filler surface and the polymer matrix or textile fiber. Weak interfaces become failure points, leading to filler detachment, the formation of microcracks, and consequent degradation of SE over time [38].

Uniform and Durable Coating/Integration: Applying a uniform, adherent, and crack-free functional coating onto the complex, porous architecture of a textile (yarns, woven or knitted structures) is highly challenging. The coating must remain intact and functional as the fabric flexes and stretches [39].

Scalability and Cost-Effectiveness: Many promising lab-scale synthesis and application techniques (e.g., in-situ polymerization, vacuum filtration) are difficult or expensive to adapt to high-throughput, low-cost textile manufacturing processes like padding, continuous dip-coating, or screen printing. Bridging this lab-to-fab gap is essential for commercialization [40].

Multifunctional Integration Without Compromise: While mineral fillers often offer additional functionalities like UV blocking or flame retardancy, integrating these properties without negatively impacting the primary shielding performance or other essential textile qualities requires careful and holistic system design [41].

Addressing these intertwined challenges represents the forefront of current research, driving innovation in filler surface engineering, composite formulation, and advanced textile integration techniques to realize the promise of high-performance, durable, and truly wearable EMI shields.

6. Environmental and Toxicity Concerns

The pursuit of sustainable EMI shielding solutions through mineral-based fillers must be tempered by a clear-eyed assessment of environmental and toxicological impacts. Not all inorganic materials are benign. Certain high-performance synthetic compounds, particularly some cobalt ferrites ($CoFe_2O_4$) and nickel-containing ferrites, raise significant concerns. These materials can pose toxicity risks through the potential leaching of Co^{2+} and Ni^{2+} ions, which are classified as possible human carcinogens and as persistent environmental pollutants. These ions may induce oxidative stress in biological systems and accumulate in ecosystems, especially under the acidic or humid conditions often encountered during a product's lifecycle or disposal [44].

To mitigate these hazards, research and development should prioritize naturally abundant, inherently low-toxicity minerals that offer a favorable balance of environmental compatibility and functional electromagnetic properties. Candidates include hematite (α-Fe_2O_3), a stable and abundant iron oxide with useful dielectric loss; montmorillonite, a naturally occurring clay that enhances polarization and acts as a barrier; and historical pigments like lapis lazuli-derived lazurite, whose sulfur-rich framework can contribute to dipole relaxation. These earth-abundant minerals typically require minimal chemical modification, reduce dependence on critical or toxic metals, and align with green engineering principles. Their integration into bio-based or readily recyclable polymer matrices can further lower the overall ecological footprint of the shielding composite. Shifting the focus from high-performance but potentially hazardous synthetic fillers toward functional, benign natural minerals is a vital step toward truly sustainable electromagnetic protection technologies [45].

7. Future Outlook: Toward High-Performance and Sustainable EMI Shielding

The future trajectory of EMI shielding research extends beyond optimizing a single metric. The next frontier embraces the development of intelligent, multifunctional, and sustainable material systems that are seamlessly integrable into polymers and textiles [46]. Therefore, key research directions are mentioned as below:

-Advanced Hybrid Nanocomposites: Designing next-generation composites with meticulously architected multi-mineral fillers. The goal is to create synergistic "triple-loss" materials that simultaneously exploit conductive, dielectric, and magnetic attenuation pathways across broad frequency ranges, all while maintaining low filler loadings for flexibility and comfort [47].

- Innovative Textile Integration Techniques: Moving beyond simple coatings to develop core-shell yarns, conductive inks for digital printing, and melt-spun hybrid fibers where mineral nanoparticles are encapsulated within the fiber itself. These methods promise better durability, wash fastness, and preservation of textile aesthetics and handle [48].

- Sustainability and Circular Design: Intensifying life-cycle assessments (LCA) of shielding textiles, from mineral sourcing to end-of-life. This will drive the adoption of recycled polymers, bio-based matrices, and designing composites for easier disassembly and material recovery, closing the loop in a circular economy [49].

-Smart and Adaptive Shielding: Exploring the integration of mineral-based composites with responsive polymers or 2D materials to create shields whose properties (e.g., SE, absorption/reflection ratio) can be dynamically tuned by external stimuli such as temperature, humidity, or an applied electrical field, enabling context-aware electromagnetic protection [50].

Realizing this vision will demand sustained, deep collaboration across disciplines materials science, chemistry, textile engineering, and environmental science. By anchoring innovation in the versatile properties of mineral nanomaterials and a steadfast commitment to sustainability, the path forward leads to a new generation of high-performance EMI shielding solutions that are not only effective but also adaptable, durable, and aligned with ecological stewardship [51].

8. Conclusion

The relentless expansion of wireless technologies has made effective EMI shielding a non-negotiable requirement across critical industries, with polymeric and smart textiles representing a rapidly growing frontier. While conventional metal-based shields are effective, their fundamental limitations in weight, flexibility, and environmental resistance have necessitated a search for advanced alternatives. Mineral-derived materials encompassing layered silicates like montmorillonite, oxides like hematite and magnetite, conductive carbon forms like graphite, and novel candidates like lapis lazuli derivatives offer a compelling and versatile pathway. By leveraging intrinsic mechanisms such as dielectric and magnetic loss, interfacial polarization, and multiple internal reflections, these materials can be engineered into polymer composites and integrated textiles that achieve competitive shielding effectiveness, often exceeding 20-30 dB in optimized systems.

This review has highlighted how strategic material design focusing on filler morphology, dispersion, and interfacial compatibility is crucial for enhancing absorption-dominant shielding, which is preferable for minimizing secondary electromagnetic pollution. Furthermore, many mineral fillers confer valuable secondary functionalities like UV resistance and antimicrobial properties, making them ideal for next-generation protective and smart textiles.

Nevertheless, significant challenges remain on the path to commercialization. These include the precise control of electrical properties, achieving uniform filler dispersion without agglomeration, ensuring long-term durability under mechanical stress and laundering, and scaling up production processes cost-effectively. Future efforts must prioritize green synthesis routes, comprehensive toxicity and lifecycle assessments, and the strategic valorization of regionally abundant minerals. By fusing technical innovation with sustainable design principles and a deep understanding of textile science, the development of EMI shielding textiles can progress. This convergence promises not only to safeguard electronic devices and protect human health but also to foster the growth of resilient, eco-conscious, and technologically sovereign industries. The journey forward is one of interdisciplinary partnership, where diverse fields unite to shape a safer and less cluttered electromagnetic future.

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