CONDUCTIVE TEXTILES FOR ELECTROMAGNETIC SHIELDING: A SHORT REVIEW

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ABSTRACT. The increasing use of electronic devices and wireless communications has generated growing demand for efficient electromagnetic interference (EMI) shielding materials. Traditional metallic enclosures, while effective, are heavy and rigid, limiting their use in modern wearable and flexible applications. Functionalized textiles have emerged as a versatile alternative, combining flexibility, low weight, and adaptability to complex geometries with effective EMI attenuation. This review provides a comprehensive, up-to-date analysis of conductive textile systems for EMI shielding, with explicit treatment of the underlying shielding mechanisms – reflection loss (SE_r), absorption loss (SE_a), and multiple internal reflections (SE_{MIR}). Major material categories are systematically discussed: metallic fiber fabrics, metal-coated textiles, intrinsically conducting polymer coatings, carbon-based nanomaterial systems, MXenes, and hybrid multi-layer architectures. Consolidated comparative tables of material performance and fabrication methods are provided as practical references. Practical challenges of washability, scalable manufacturing, standardization, and biocompatibility are discussed. Reported shielding effectiveness (SE) values range from ~5 dB for simple conductive-polymer coatings to over 100 dB for advanced hybrid multi-layer composites.

KEYWORDS: conductive polymers, metal-coated fabrics, flexible shielding, nanomaterials, MXene, EMI shielding effectiveness, wearable textiles

TEXTILE CONDUCTOARE PENTRU ECRANARE ELECTROMAGNETICĂ: O SCURTĂ ANALIZĂ

REZUMAT. Utilizarea tot mai frecventă a dispozitivelor electronice și a comunicațiilor fără fir a generat o cerere din ce în ce mai mare de materiale eficiente pentru ecranarea împotriva interferențelor electromagnetice (EMI). Carcasele metalice tradiționale, deși eficiente, sunt grele și rigide, ceea ce le limitează utilizarea în aplicații moderne, flexibile sau de tip dispozitiv purtabil. Textilele funcționalizate au apărut ca o alternativă versatilă, combinând flexibilitatea, greutatea redusă și adaptabilitatea la geometrii complexe cu o atenuare eficientă a interferențelor electromagnetice. Sinteza de față oferă o analiză cuprinzătoare și actualizată a sistemelor textile conductoare destinate ecranării EMI, abordând în mod explicit mecanismele fundamentale de ecranare: pierderile prin reflexie (SE_r), pierderile prin absorbție (SE_a) și reflexiile interne multiple (SE_{MIR}). Sunt analizate sistematic principalele categorii de materiale: țesături din fibre metalice, textile acoperite cu metal, straturi din polimeri intrinsec conductori, sisteme bazate pe nanomateriale pe bază de carbon, MXene și arhitecturi hibride multistrat. Sunt incluse tabele comparative sintetice privind performanța materialelor și metodele de fabricație, servind drept referințe practice. De asemenea, sunt discutate provocările practice legate de lavabilitate, producția la scară largă, standardizare și biocompatibilitate. Valorile raportate pentru eficacitatea ecranării (SE) variază de la aproximativ 5 dB, în cazul straturilor simple de polimeri conductori, până la peste 100 dB, în cazul compozitelor hibride multistrat avansate.

CUVINTE CHEIE: polimeri conductori, țesături acoperite cu metal, ecranare flexibilă, nanomateriale, MXene, eficacitatea ecranării EMI, textile purtabile

TEXTILES CONDUCTEURS POUR LE BLINDAGE ÉLECTROMAGNÉTIQUE : UNE BRÈVE SYNTHÈSE

RÉSUMÉ. L'utilisation croissante des appareils électroniques et des communications sans fil a engendré une demande accrue pour des matériaux efficaces de blindage contre les interférences électromagnétiques (IEM). Les enceintes métalliques traditionnelles, bien qu'efficaces, sont lourdes et rigides, ce qui limite leur usage dans les applications modernes, notamment les dispositifs souples et portables. Les textiles fonctionnalisés s'imposent comme une alternative polyvalente, alliant flexibilité, légèreté et adaptabilité à des géométries complexes, tout en assurant une atténuation efficace des IEM. Cette synthèse propose une analyse complète et actualisée des systèmes textiles conducteurs destinés au blindage électromagnétique, en examinant en détail les mécanismes sous-jacents : les pertes par réflexion (SE_r), les pertes par absorption (SE_a) et les réflexions internes multiples (SE_{MIR}). Les principales catégories de matériaux sont passées en revue : tissus à base de fibres métalliques, textiles revêtus de métal, revêtements en polymères intrinsèquement conducteurs, systèmes à base de nanomatériaux carbonés, MXènes et architectures hybrides multicouches. Des tableaux comparatifs synthétiques, portant sur les performances des matériaux et les méthodes de fabrication, sont fournis en guise de référence pratique. Les défis concrets — tels que la lavabilité, la montée en échelle de la production, la normalisation et la biocompatibilité — sont également abordés. Les valeurs d'efficacité de blindage (SE) rapportées dans la littérature s'échelonnent d'environ 5 dB pour des revêtements simples en polymères conducteurs à plus de 100 dB pour des composites hybrides multicouches avancés.

MOTS-CLÉS : polymères conducteurs, tissus revêtus de métal, blindage souple, nanomatériaux, MXène, efficacité de blindage électromagnétique, textiles portables

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INTRODUCTION

Electromagnetic pollution has become a major global concern with the proliferation of electronic devices, recognized as the fourth environmental pollutant after noise, water, and air. Excessive exposure to electromagnetic fields can negatively impact human health, with documented biological effects on the nervous system, reproductive function, and sleep quality, while sensitive electronic equipment can malfunction due to electromagnetic interference (EMI) [1]. The rapid expansion of 5G telecommunications, the Internet of Things (IoT), autonomous vehicles, and wearable health-monitoring devices has dramatically increased both the density of EMI sources and the stringency of electromagnetic compatibility (EMC) requirements in critical sectors [2]. International directives such as the EU EMC Directive (2014/30/EU) and FCC regulations in the United States impose increasingly strict limits on electromagnetic emissions, driving demand for efficient, lightweight, and cost-effective shielding solutions.

Traditional EMI shielding is achieved through rigid metallic enclosures of aluminum, copper, or steel, which, despite excellent conductivity and shielding performance, present well-documented drawbacks: high density, mechanical rigidity, susceptibility to corrosion, and high fabrication cost [3]. These limitations are especially problematic in the context of modern portable, miniaturized, or body-worn devices, where metal enclosures are impractical and incompatible with ergonomic requirements. Conductive polymer-matrix composites have emerged as a partial alternative, but they too cannot replicate the flexibility of a textile substrate [3, 4]. Textile substrates offer a compelling alternative: flexible, breathable, lightweight, and moldable into complex three-dimensional shapes, with well-established industrial manufacturing processes. However, conventional textile fibers are dielectric insulators; the electrical conductivity necessary for EMI shielding must be imparted through a subsequent functionalization process [4].

The concept of electrically conductive textiles is not new, metallic threads have been woven into fabrics for centuries, but the rigorous exploitation of their electromagnetic properties is a more recent development, gaining momentum in the 1980s and accelerating dramatically with nanotechnology and surface engineering advances in the 2000-2020s [5-7]. The global market for electronic and smart textiles was valued at over $1.5 billion in 2022 and is estimated to exceed $5 billion by 2030, with EMI shielding as one of the principal application segments [2].

THEORETICAL BACKGROUND OF EMI SHIELDING

Shielding Effectiveness (SE)

Shielding effectiveness (SE) is the fundamental figure of merit for EMI shielding materials, defined as the ratio of the incident electromagnetic field intensity to the transmitted field intensity, expressed in decibels (dB) [8]:

$$SE\ (dB) = 20\ \log_{10}(E_0/E_1) = 20\ \log_{10}(H_0/H_1) = 10\ \log_{10}(P_0/P_1) \quad (1)$$

where E, H, and P are the electric field strength, magnetic field strength, and power of the electromagnetic wave, respectively; subscripts 0 and 1 denote values before and after the shield. SE of 0 dB corresponds to complete transmission; 20 dB means only 10% of the incident field is transmitted; 40 dB means 1%; 80 dB means 0.01%. Values above 20 dB are considered commercially adequate for civilian electronics; 40-60 dB are required for sensitive computing and communications equipment; critical military and medical applications typically demand SE > 80 dB [9]. SE is a frequency-dependent quantity and material performance can vary significantly across different frequency bands, making full-band characterization essential [8, 9].

Shielding Mechanisms

The total shielding effectiveness (SE_t) of an EMI shielding material is the sum of three components: shielding effectiveness due to absorption (SE_a), reflection (SE_r), and multiple internal reflections (SE_{Mir}), as illustrated in Figure 1:

$$SET = SE_r + SE_a + SE_{mir} \quad (2)$$

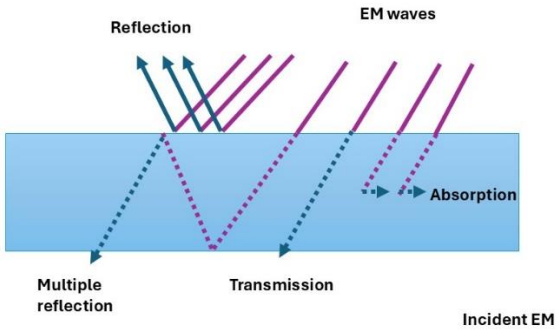


Figure 1. Schematic representation of the fundamental mechanisms in EMI shielding materials

Reflection Loss (SE_r)

Reflection at the shield surface arises from the impedance mismatch between the incident wave in free space (impedance $\eta_0 \approx 377\ \Omega$) and the much lower intrinsic impedance of a conductive material. For a conductor with conductivity σ (S/m), relative permeability μ_r, at frequency f (Hz), the reflection loss is [8, 10]:

$$SE_r\ (dB) \approx 168 + 10 \log_{10}(\sigma / (f \times \mu_r)) \quad (3)$$

High-conductivity, low-permeability materials provide very large reflection losses even at relatively low frequencies. Copper (σ ≈ 5.8x107 S/m) and silver (σ ≈ 6.3x107 S/m) offer SE_r of 100-150 dB at GHz frequencies, while stainless steel (σ ≈ 1.4x106 S/m) offers somewhat lower values, partially offset by its higher magnetic permeability. Reflection is a surface phenomenon, essentially independent of shield thickness, which is why even extremely thin metallic layers (a few nm) can provide significant reflection [10, 11].

Absorption (SE_a)

The second primary EMI shielding mechanism is absorption (SE_a), which depends entirely on the intrinsic physical properties of the shielding material and is not influenced by the nature of the electromagnetic field source. Unlike reflection, which occurs at the material's surface, absorption involves the propagation of the electromagnetic wave into the bulk of the material, where its amplitude progressively decreases following an exponential decay law. This attenuation arises from induction currents generated within the material, which lead to energy dissipation through the Joule effect and its subsequent conversion into thermal energy. The main factors governing the magnitude of these losses are the ohmic resistance encountered by the induced currents and the dissipation associated with cyclic electric and magnetic polarization phenomena within the material's structure. To achieve effective absorption across the frequency range of interest, a shielding material must simultaneously exhibit high electrical conductivity, significant magnetic permeability, and adequate thickness.

Multiple Internal Reflections (SE_{MIR})

When the shield is thinner than the skin depth, electromagnetic energy reaching the second surface is not completely absorbed and a significant fraction is reflected back toward the first surface. These multiple internal reflections reduce the effective SE below the simple sum $SE_r + SE_a$. This correction term is negative and is given by [8]:

$$SE_{mir}\ (dB) = 20 \log_{10}|1 - e^{-2t}/\delta| \quad (4)$$

For thick shields (t >> δ), the exponential term approaches zero and $SE_{MIR} \approx 0$, so it is neglected in practice. However, the condition t < δ is frequently encountered for thin coatings of moderately conductive materials: graphene or rGO films, MXene layers, conducting polymer coatings, and vapor-deposited metals – where typical thickness is 1-100 µm. In these cases, the SE_{MIR} correction can reduce total SE by 5-15 dB compared to the simple $SE_r + SE_a$ estimate, especially at lower frequencies where δ is larger [11, 12]. Porous or multilayer textile architectures are engineered to exploit internal interfaces as additional absorption mechanisms, converting SE_{MIR} from a negative penalty into a structural advantage [12].

Key Material Parameters

The primary intrinsic material parameters governing SE are: electrical conductivity (σ), magnetic permeability (µ), and dielectric permittivity (ε). High σ enhances both reflection (SE_r) and absorption (SE_a); high µ increases SE_a and reduces δ but contributes negatively to SE_r by reducing input impedance;

high ε broadens dielectric loss mechanisms. At the textile structural level, weave or knit pattern, yarn twist, fabric porosity, and layer count control the effective conductivity of the composite and the electromagnetic transparency of open apertures. Theoretical studies based on equivalent electrical network modeling of textile structures have shown that the critical aperture size below which electromagnetic leakage becomes negligible is approximately λ/100 at the frequency of interest [12, 7].

TYPES OF TEXTILE STRUCTURES

Woven Textiles

Woven textiles are produced by interlacing warp and weft yarns in perpendicular directions, yielding dimensionally stable structures with controllable aperture geometry, good mechanical strength, and uniformity of conductivity distribution. Conductive yarns – pure metallic wires or hybrid yarns blending metallic fibers with synthetic or natural fibers – can be incorporated directly into the fabric in the warp, weft, or both directions. Their spatial distribution determines the density of the conductive network and hence the SE. Wang *et al*. [13] developed a multifunctional stretchable woven fabric incorporating tri-component elastic-conductive composite yarns containing stainless steel wire. The fabric exhibited effective electromagnetic shielding in the X-band (8.2–12.4 GHz), with no degradation of shielding effectiveness after 15 stretching cycles at 20% extension, while maintaining excellent stretchability (>40% elongation) and structural stability.

Knitted Textiles

Knitted fabrics are produced by forming interconnected loops of yarn, yielding highly elastic and three-dimensionally conformable structures particularly suited for body-worn applications where the shape and motion of the human body must be accommodated without loss of functional performance. Their inherently higher porosity compared to woven structures reduces SE for a given metal content; however, superior flexibility and higher body coverage compensate in many practical applications. Mikolajczyk *et al*. [14] investigated ten knitted fabric variants differing in stitch pattern, structural parameters, and conductive yarn type. The results demonstrated that electromagnetic shielding effectiveness depends strongly on the fabric structure, stitch pattern, and yarn composition, with measurements performed in the 2–4 GHz and 4–7 GHz frequency ranges. Perumalraj and Dasaradan [15] investigated the electromagnetic shielding effectiveness of knitted fabrics incorporating copper core yarns in the 20 MHz–18 GHz frequency range. The study demonstrated that shielding effectiveness increased with the fabric tightness factor, wale density, and course density. Furthermore, interlock knitted fabrics exhibited superior shielding performance compared with rib and plain knitted structures, while increasing the copper wire diameter resulted in reduced shielding effectiveness.

Nonwoven Textiles

Nonwoven fabrics – including electrospun fiber mats, needle-felted batts, wet-laid sheets, and thermally or chemically bonded materials – are assembled from individual fibers bonded together without weaving or knitting processes. Their high porosity, large specific surface area, and controllable thickness make them excellent substrates for coating techniques, as conductive solutions can penetrate through the material thickness and form a continuous three-dimensional conductive network. Electrospun nonwovens, composed of fibers with diameters of 100 nm-10 µm, offer particularly large specific surface areas (tens of m^2/g), facilitating highly uniform coating with minimal conductive material quantities. Duan *et al*. [16] fabricated a $Ti_3C_2T_x$ MXene/carbon fiber fabric/ thermoplastic polyurethane (TPU) composite through electrohydrodynamic atomization deposition, layer-by-layer stacking, and hot pressing. The composite achieved an EMI shielding effectiveness of up to 40.4 dB, while exhibiting excellent mechanical strength, flexibility, durability, and stable shielding performance after repeated bending cycles. The enhanced shielding was attributed to the

dielectric loss provided by the conductive MXene fillers and the increased absorption within the sandwich structure. Liang *et al*. [17] fabricated porous $Ti_3C_2T_x$ MXene nanosheets sandwiched between electrospun polyimide fiber mats, achieving an EMI shielding effectiveness of 48.8 dB in the X-band (8.2–12.4 GHz). The porous nonwoven architecture provided high flexibility, low weight, and enhanced electromagnetic wave attenuation through multiple internal reflections.

CONDUCTIVE MATERIALS AND FABRICATION METHODS

Metallic Fiber Integration

The most direct and industrially mature route to conductive textiles involves mechanically integrating metallic fibers or wires into the textile structure at the yarn spinning or fabric formation stage. Stainless steel fibers with diameters of 4-12 µm, known in industry as ultra-fine stainless steel fibers, are the most commonly used material, produced by intimate blending with polyester or polyamide fibers at concentrations of 10-30 wt%. The electrical conductivity of the resulting hybrid yarn follows the percolation of the metallic network and reaches values sufficient for shielding at concentrations above ~15 wt%. Gupta *et al*. [18] demonstrated that the electromagnetic shielding performance of hybrid woven fabrics strongly depends on the conductive yarn content and fabric structure. A cell-structured fabric containing 32.58 wt% stainless steel achieved shielding effectiveness of approximately 31–35 dB in the 8.2–18 GHz frequency range while maintaining good breathability. Copper and silver fibers confer higher conductivity than stainless steel but are more expensive and more prone to corrosion; they are used in niche applications where maximum conductivity is a priority [7, 18]. The primary trade-off is between metal content – which increases SE but adds weight and stiffness – and textile comfort characteristics: bending stiffness, air permeability, and long-term skin compatibility.

Metallic Coatings

Applying a continuous and conformal metallic layer on the surface or through the bulk of the textile is among the most effective strategies for achieving high SE while preserving substrate flexibility and low weight. Electroless plating deposits a metal (typically copper, nickel, or silver) through chemical reduction onto a catalytically activated textile surface without external current. The method provides conformal coverage of complex fiber geometries, scalable batch processing, and good adhesion. Hu *et al*. [19] investigated copper-coated nonwoven textile materials (MEFTEX) fabricated via electroless copper plating for electromagnetic interference shielding applications. The results showed that shielding effectiveness increases with the areal density of the material, reaching values of approximately 56–63 dB in the frequency range of 30 MHz–1.5 GHz for single-layer samples. Furthermore, multilayer structures significantly improved shielding performance due to increased thickness and reduced electrical resistivity, with up to 83% enhancement compared to single-layer configurations [19]. Electroplating enables the formation of relatively thick metallic coatings on textile substrates, resulting in high electrical conductivity and enhanced electromagnetic shielding effectiveness. However, the process often leads to increased fabric stiffness and reduced breathability due to the continuous metallic layer covering the textile structure. Magnetron sputtering enables the deposition of thin metallic coatings onto textile substrates to improve their electrical conductivity and electromagnetic shielding properties. Surdu *et al*. [21] investigated copper coatings with thicknesses of 200, 400, 800, and 1200 nm deposited on woven textile structures, including cotton, polyester, and fabrics containing conductive yarns. The authors reported electromagnetic attenuation values of 20–34 dB for copper-coated fabrics incorporating conductive yarns, while fabrics coated with copper on one side exhibited lower attenuation values of 3–8.5 dB. These findings highlight the potential of magnetron sputtering for developing textile-based electromagnetic shielding materials.

Conductive ink printing with silver nanoparticles or carbon-based inks enables spatially patterned conductive structures on textile surfaces, opening the way to integrating shielding with antennas and electrodes in multifunctional smart garments [22].

Conducting Polymer Coatings

Intrinsically conducting polymers (ICPs) – polypyrrole (PPy), polyaniline (PANI), polythiophene (PTh), and poly(3,4-ethylenedioxythiophene) (PEDOT) – can be chemically synthesized directly on textile fiber surfaces through in-situ oxidative polymerization, providing a conformal conductive coating without metallic components. *In-situ* polymerization involves immersing the textile in a monomer solution followed by addition of an oxidizing agent, initiating polymerization preferentially at fiber surfaces. Rybicki *et al*. [23] investigated conductive polymer coatings on polyacrylonitrile (PAN) fabrics using reactive inkjet printing of polyaniline (PANI) and polypyrrole (PPy). The electromagnetic shielding effectiveness was evaluated in the frequency range of 2.5–18 GHz using the waveguide method. The results showed that both PAN/PANI and PAN/PPy composites exhibit good EMI shielding performance, with PAN/PANI demonstrating higher effectiveness. This difference was attributed to the higher electrical conductivity of doped polyaniline compared to polypyrrole. Bashir *et al*. [24] synthesized and characterized conductive fibers based on PEDOT and polypyrrole (PPy) for smart textile applications. The study focused on the preparation and evaluation of electrically conductive polymer-based fibers, highlighting their potential for wearable electronic and textile applications.

Zou *et al*. [25] developed a durable EMI shielding fabric based on a polypyrrole (PPy)-modified textile coated with a hydrophobic 1H,1H,2H,2H-perfluorooctyltriethoxysilane (POTS) layer. The system exhibited strong resistance to water, salt, and corrosive environments. Additionally, the protective layer could be rapidly self-healed via microwave-induced heating within approximately 4 seconds, due to the thermal response of PPy under electromagnetic irradiation. The self-healing process was repeatable even after severe damage, demonstrating high potential for durable EMI shielding applications.

Carbon-Based Nanomaterials

Carbon nanomaterials – single-walled (SWCNT) and multi-walled carbon nanotubes (MWCNT), graphene, reduced graphene oxide (rGO), and carbon black – are widely used in EMI shielding textiles due to their unique combination of high electrical conductivity (σ up to 104-105 S/m for MWCNT networks), low density, very high aspect ratio (>103 for MWCNT), chemical stability, and processability from aqueous suspension. MWCNT-coated fabrics show SE of 15-40 dB in the GHz range, with superior values obtained for covalently functionalized MWCNTs that form denser networks due to improved dispersion [26]. Pande *et al*. [26] demonstrated that multilayer MWCNT/PMMA structures prepared by stacking thin composite films exhibit significantly improved electromagnetic interference shielding effectiveness compared to bulk composites. Shielding effectiveness up to ~40 dB was achieved for a seven-layer configuration, compared to ~30 dB for thicker multilayer structures. The results highlight that multilayer architecture enhances shielding performance, primarily through absorption-dominated mechanisms. Song *et al*. [27] fabricated multilayer graphene/polymer sandwich composite films and investigated their electromagnetic interference shielding performance. The results showed that shielding effectiveness is strongly influenced by the electrical conductivity of the composites. Both experimental and theoretical analyses indicated that reflection is the dominant shielding mechanism, while absorption can be enhanced by optimizing thickness and electrical properties. An optimized shielding effectiveness of up to approximately 27 dB was reported for the fabricated structures.

MXenes and 2D Nanomaterials

MXenes – a large and expanding class of two-dimensional nanomaterials comprising

transition metal carbides, nitrides, and carbonitrides, with the general formula:

$$M_{n+1}X_nT_x \quad (5)$$

where M is an early transition metal such as Ti, V, Nb, Mo, or Cr; X is C and/or N; n = 1, 2, or 3; and T_x represents surface functional groups -OH, =O, -F, which have emerged since 2016 as the most promising class of two-dimensional nanomaterials for EMI shielding, becoming one of the fastest-growing areas in conductive textile literature [29]. MXene synthesis involves selective etching of the A layers (typically Al) from MAX phase precursors (Mn+1AXn) in hydrofluoric acid solutions or inorganic fluoride mixtures, followed by delamination and exfoliation into mono- or few-layer nanosheets. $Ti_3C_2T_x$, the most extensively studied MXene, exhibits metallic electrical conductivity in films (σ up to 10,000 S/cm), excellent processability from stable aqueous colloidal dispersions, and rich surface chemistry that promotes adhesion to cellulosic fiber surfaces through electrostatic interactions and hydrogen bonding [29, 30]. Shahzad *et al*. [29] first reported SE of freestanding MXene of 92 dB in the X-band for a 45 µm thick film, establishing MXene as the most efficient shielding material per unit thickness among all reported materials at that time. Duan *et al*. [16] fabricated a MXene/carbon fiber fabric/TPU nonwoven composite achieving ~38 dB SE in the X-band with a density below 0.5 g/cm³. Yin *et al*. [30] fabricated a lightweight and flexible PANI/MXene/carbon fiber fabric using a layer-by-layer assembly approach, in which MXene nanosheets and polyaniline were alternately deposited onto carbon fiber substrates. The resulting composite (0.55 mm thickness, five cycles) achieved an EMI shielding effectiveness of 26.0 dB in the X-band (8–12 GHz), together with good electrical conductivity and a high specific shielding effectiveness of 135.5 dB·cm³/g. The material also exhibited excellent Joule heating performance, air permeability, and structural stability. The shielding mechanism was reported to be absorption-dominated. Han *et al*. [31] investigated the EMI shielding performance of 16 different MXenes, including single-metal, ordered double-metal, and solid-solution compositions. Thin films prepared via spin coating, spray coating, and vacuum filtration exhibited effective EMI shielding above 20 dB. Ultrathin $Ti_3C_2T_x$ films (~40 nm) achieved about 21 dB, and the study showed that shielding performance can be tuned through elemental composition and structure, highlighting the potential of MXenes for ultrathin and flexible EMI shielding applications [31].

Hybrid and Multilayer Architectures

The highest SE values reported in conductive textile literature are achieved by hybrid architectures that synergistically combine multiple conductive components, exploiting the complementarity of physical mechanisms: metallic components with high conductivity maximize reflection (SE_r), while magnetic or carbon-based inclusions enhance absorption (SE_a), and hierarchical interface structuring increases the effective path length of the wave through the material. Jia *et al*. [32] demonstrated a robust superhydrophobic electromagnetic interference (EMI) shielding textile based on a silver nanowire (AgNW) network deposited onto a commercial cotton fabric, combined with a surface modification strategy to achieve both water repellency and electromagnetic shielding performance. The resulting textile exhibited a high water contact angle of 160.8° and a low sliding angle of 2.9°, confirming excellent superhydrophobic behavior.

In terms of electromagnetic performance, the developed material achieved a shielding effectiveness of approximately 51.5 dB in the X-band (8–12 GHz). Importantly, the multifunctional textile maintained both its superhydrophobic properties and a significant EMI shielding effectiveness of 42.6 dB even after 5000 stretching–releasing cycles, demonstrating outstanding mechanical durability.

Additional tests confirmed strong resistance to harsh environmental conditions, including ultrasonic treatment, repeated peeling cycles, acidic and alkaline solutions, and exposure to various organic solvents. This exceptional durability is attributed to the synergistic effect of the AgNW conductive network together with carbon nanotubes, polytetrafluoroethylene (PTFE) nanoparticles,

and a fluoroacrylic polymer coating, which together provide robust mechanical stability, chemical resistance, and sustained electrical conductivity [30, 32].

COMPARATIVE PERFORMANCE

Table 1 consolidates representative performance metric values for the main categories of conductive textile EMI shielding systems based on peer-reviewed literature data.

Table 1: Comparative performance values of conductive textile EMI shielding materials

Material	Conductivity (S/m)	SE (dB)	Frequency Range	Flexibility	Wash Resistance	Ref.
Stainless steel fiber fabric	1.4×10^{6}	30–60	1–18 GHz	Moderate	Good	[7,17]
Silver-coated fabric (Ag)	4×10^{5}	40–70	30MHz–40 GHz	High	Moderate	[18]
Copper-coated fabric (Cu)	5×10^{7}	42–80	30 MHz–30 GHz	Moderate	Moderate	[18, 20]
Metal film fabric (Ag/Cu sputtering)	1×10^{7}	40–60	1–40 GHz	High	Low	[21]
Conductive polymer-coated fabric (PANI / PPy)	10^{2}–10^{3}	5–22	0.1–18 GHz	Very high	Low–Moderate	[23, 25]
Carbon nanotube-coated fabric (MWCNT)	10^{3}	15–40	0.1–18 GHz	Very high	Low–Moderate	[26, 28]
Graphene / reduced graphene oxide (rGO) coated fabric	5×10^{3}	20–65	1–18 GHz	Very high	Low–Moderate	[27]
MXene-coated fabric ($Ti_3C_2T_x$)	1×10^{4}	38–75	8–12 GHz	High	Moderate	[15, 30, 31]
Hybrid multilayer fabric AgNW + Fe_3O_4	~10^{6}	60–100	8–12 GHz	High	Good	[32]

Table 2 provides a fabrication-oriented comparative summary, designed as a practical tool for selecting material and fabrication method depending on the specific application requirements.

Table 2: Comparative overview of fabrication methods for conductive textile EMI shielding systems

Fabrication Method	Typical SE (dB)	Scalability	Cost	Key Advantages	Key Limitations
Metal fiber integration	20-45	High	Moderate	Durable; no post-processing	Reduced comfort; heavy
Electroless plating	40-70	High	Low-Moderate	Conformal; uniform	Wastewater treatment
Electroplating	60-80	Medium	Moderate	Thick coatings; high sigma	Stiff; less breathable
Magnetron sputtering	40-60	Low-Med.	High	Uniform thin films; pure	Vacuum equipment needed
Dip/spray (CNT, graphene, MXene)	20-75	High	Moderate	Flexible; solution process	Wash durability; aggregation
In-situ polymerization	5-25	High	Low	Biocompatible; low cost	Lower sigma; aging sensitivity
Conductive ink printing	10-40	High	Low-Moderate	Patternable; multifunctional	Crack formation on flex
Layer-by-layer assembly	40-100	Medium	Moderate	Nanoscale control; high SE	Time-consuming

PRACTICAL APPLICATIONS

Conductive textiles for EMI shielding have found practical applications across diverse sectors with distinct performance and comfort requirements. In the sector of personal protection and occupational safety, military uniforms and technical coveralls for operators working in proximity to intense EMI sources (radar stations, high-power transmitters, industrial electrical installations) have incorporated stainless steel or copper wire fabrics to reduce operator exposure below the

limits recommended by ICNIRP (International Commission on Non-Ionizing Radiation Protection) [1, 5]. European standard EN 50490-1 specifies minimum SE requirements for EMF protective clothing, mandating SE > 20 dB across relevant frequency bands.

In the medical sector, conductive textiles are used in: (i) isolation garments for patients with sensitive electronic implants (cardiac pacemakers, neurostimulators) that must be protected from ambient EM fields; (ii) shielding blankets and curtains for magnetic resonance imaging (MRI) and electroencephalography (EEG) enclosures, where external radiofrequency fields degrade image quality; and (iii) wearable devices for monitoring bioelectric signals (ECG, EMG, EEG) in high-EMI environments, where shielding integrated into the garment suppresses interference without requiring rigid external cabling [4, 5]. Biocompatibility requirements are strict in these applications, limiting materials to silver (used clinically as an antimicrobial agent) and to conducting polymers with documented biocompatibility.

The consumer electronics industry employs conductive textiles as flexible shields integrated into laptop, tablet, and smartphone cases – replacing rigid metallic shields with lightweight flexible textile foils. The aerospace and aeronautics industry has adopted conductive textile materials for shielding cabling and electronic modules in civil and military aircraft, where weight reduction compared to conventional metallic shields generates direct fuel savings [3].

CHALLENGES AND FUTURE DIRECTIONS

Performance-Comfort Trade-Off

There is a fundamental trade-off between electromagnetic shielding performance and textile comfort properties: higher SE and conductivity generally come at the cost of reduced breathability (lower air and water vapor permeability), increased weight, and higher bending stiffness. Engineering solutions that partially decouple these properties include: (i) patterned metal meshes that maintain significant open area for air permeability; (ii) auxetic textile geometries with negative Poisson's ratio that distribute strain more uniformly; (iii) ultra-thin MXene or graphene coatings (~10-100 nm) applied only to critical garment regions, minimizing mass addition; and (iv) integration of micro-structured conductors (micro-grids, micro-coils) that are nearly invisible and do not disturb the textile texture [32]. Multidisciplinary research integrating materials science, textile engineering, and applied ergonomics is essential for achieving the optimal performance-comfort trade-off in commercial products.

Scalable and Sustainable Manufacturing

The vast majority of high-performance conductive textile systems reported in the literature rely on laboratory-scale fabrication processes that cannot be directly transferred to continuous industrial processing (roll-to-roll, large batch). Key technical barriers include: (i) formulation of stable dispersions of nanomaterials at high concentrations without agglomeration, compatible with industrial coating machines; (ii) optimization of line speeds and drying/heat treatment conditions to achieve uniform coating thicknesses at scale; (iii) management of waste streams from metallic plating processes in compliance with environmental requirements; and (iv) quality control and inline SE inspection at production speed, where standard measurement methods cannot be applied inline [36]. The transition from laboratory to industry requires close collaboration between materials scientists, textile process engineers, and production engineers.

Biocompatibility and Safety

For textiles intended for direct prolonged skin contact or medical applications, systematic evaluation of the biocompatibility of conductive coatings is an essential and regulated requirement (EU MDR 2017/745, ISO 10993 standards). Silver nanoparticles have demonstrated useful antibacterial activity but also cytotoxicity at high concentrations for human skin cells; nanoparticle migration studies indicate that conventional silver-coated textiles can release significant amounts of Ag+ ions under normal use conditions [36]. High-aspect-ratio carbon nanotubes have been associated with asbestos-like biological effects at high doses, and long-term biocompatibility data for MXenes remain insufficient. Research

in the biocompatibility of conductive textiles represents a major barrier to the certification and commercialization of products for medical and personal protection applications.

CONCLUSIONS

This review has summarized the fundamental principles, materials, fabrication strategies, and application domains of conductive textile-based electromagnetic interference (EMI) shielding systems. The analysis shows that EMI shielding in textiles is governed primarily by a combination of reflection, absorption, and multiple internal reflection mechanisms, which are strongly dependent on intrinsic material properties such as electrical conductivity, magnetic permeability, and dielectric permittivity, as well as on textile architecture and structural design.

A clear hierarchy of material performance emerges across the reviewed systems. Metallic-based solutions, particularly silver- and copper-coated textiles, still provide the highest shielding effectiveness (SE), often exceeding 70–80 dB, due to their superior electrical conductivity. However, these materials suffer from limitations related to cost, rigidity, and reduced durability under mechanical deformation or washing cycles. Carbon-based materials, including carbon nanotubes and graphene derivatives, offer a favorable balance between flexibility and moderate-to-high SE (up to ~65 dB), while enabling lightweight and mechanically robust structures. MXenes, particularly $Ti_3C_2T_x$, represent the most promising emerging class of materials, combining metallic-level conductivity with solution processability and enabling SE values exceeding 70 dB in thin-film configurations. Conductive polymers, although limited in intrinsic conductivity, provide advantages in terms of low cost, lightweight nature, and potential biocompatibility, especially when combined with carbon nanostructures.

From a structural perspective, textile architecture plays a critical role in determining shielding performance. Woven structures generally provide higher SE due to lower porosity and more controlled conductive pathways, while knitted and nonwoven structures offer superior flexibility, breathability, and conformability, making them more suitable for wearable applications despite their lower baseline shielding performance. Hybrid and multilayer architectures consistently demonstrate superior performance by synergistically combining reflection-dominant metallic components with absorption-enhancing carbon- or magnetic-based materials, often achieving SE improvements beyond the additive contributions of individual components.

In terms of fabrication methods, no single approach is universally optimal. Metallic fiber integration remains the most industrially scalable solution, while electroless plating offers an effective compromise between performance, cost, and scalability. Advanced techniques such as magnetron sputtering, conductive ink printing, and layer-by-layer assembly enable high-performance or multifunctional systems but are currently limited by cost, complexity, or scalability constraints. Solution-based approaches, particularly dip-coating and spray-coating with nanomaterials, are attractive for large-scale production but require further improvements in dispersion stability and long-term wash durability.

Despite significant progress, several key challenges remain unresolved. The most critical issue is the intrinsic trade-off between electromagnetic shielding effectiveness and textile comfort properties, including breathability, flexibility, and weight. In addition, scalable and environmentally sustainable manufacturing routes are still under development, particularly for nanomaterial-based coatings. Biocompatibility and long-term safety also remain essential concerns, especially for applications involving direct skin contact or medical use, where potential cytotoxicity and nanoparticle migration must be carefully controlled.

Future research is expected to focus on the development of hierarchical hybrid systems, self-healing conductive networks, and stimuli-responsive or frequency-selective shielding textiles. Furthermore, the integration of artificial intelligence and data-driven materials design is likely to accelerate the optimization of textile architectures and compositions. Overall, conductive textile EMI shielding represents a rapidly evolving interdisciplinary field at the intersection of materials science, textile engineering, and applied electromagnetics, with

strong potential for scalable deployment in next-generation wearable electronics, healthcare systems, and advanced communication technologies.

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