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Functional Composite Materials

REVIEW

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Progress in polymer nonwoven textile materials in electromagnetic interference shielding applications

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Abstract

Multifunctional flexible conductive materials have generated significant interest in developing future portable electronic systems, including wearable electronics, implantable devices, and many more. Producing wearable electronics materials that are dependable in all-weather situations and provide high-performance electromagnetic interference (EMI) shielding remains challenging. "electromagnetic textile materials" refers to these wearable EMI shielding garments. One key material that can address the EMI problem facing systems such as wearable/flexible circuit working environments and human health is conductive polymeric nonwoven (NW) textile materials. In this review, our focus is primarily limited to the polymeric NW textile and their composites family as effective EMI shielding materials. The study provides the fundamentals of NW-based EMI shielding mechanisms, mechanisms to mitigate EM reflection, and fabrication techniques of EMI shielding NW materials. Also, the standard for future researchers to select the ideal material combination for effectively mitigating EMI waves as shields/filters is presented. Review articles exist on EMI shielding textiles in general, but no single article is dedicated to NW textile-based EMI shields. Again, no review article exists presenting the approaches employed towards mitigating EM wave reflection in NW -based EMI shield design and fabrication. In addition, the challenges encountered with the fabrication and/or application of NW-based EMI shielding materials are presented in this paper. The question of why NW selection is the primary structure for EMI shield fabrication is presented herewith for the first time in this article.

Keywords Nonwoven textiles, Electromagnetic interference shielding, Fibers, Nonwoven technology, Needle punching

Introduction

The increasing concern for the prevention of ecocide from high-frequency EM radiation has caused growing attention towards the development of conductive polymeric NW textile materials and their composites. It is easy for one to be exposed to EM radiation and get affected since the EM radiation spectrum covers a whole range of wave sources and applications, as shown in Fig. 1 [1, 2]. Most, if not all, electronic devices generate EM radiation waves, which could be transmitted through the air, space, and any other substance from one electronic device to another, thus EMI [3, 4]. The advancement of technology and day-to-day wireless communication usage has increased the highest degree of EMI or electromagnetic (EM) pollution. In certain industries and applications, the flow of EM waves and interference can affect the running of electronic devices, creating unwanted responses and operational breakdown, and pose a safety and health risk [5, 6]. Industries that are more vulnerable to EMI include the automotive, consumer electronics,

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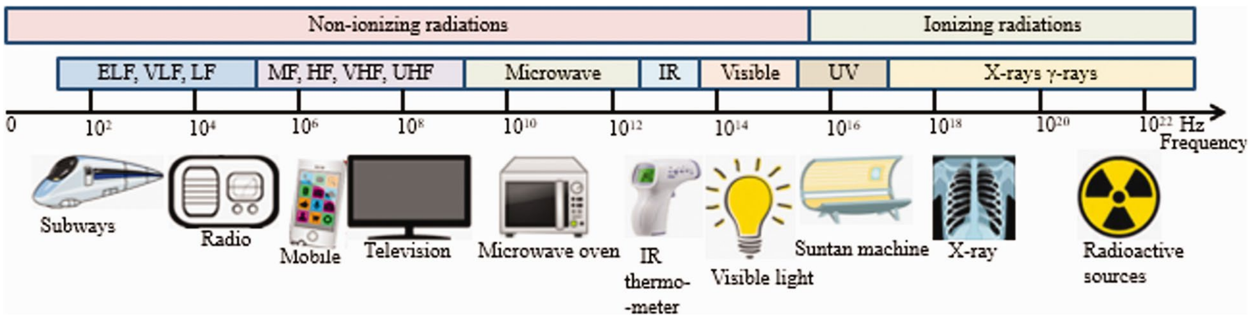

Fig. 1 Electromagnetic spectrum, sources, and applications.

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military and security, aerospace, 5G telecommunication, large medical equipment, wearable electronics, and intelligent packaging applications [7]. Security sectors store the confidential data which is being transmitted through computer appliances. EMI shielding active polymeric NW textile materials can be placed on this article to prevent the possible skimming of the data. Interesting applications are also in wearable electronics for human health information monitoring, such as heart rate, body temperature, and blood glucose. Such characteristics can be used in innovative packaging applications as an indicator.

Hence, future portable electronic systems such as wearable electronics, implantable devices, and many more have drawn much interest thanks to multifunctional, flexible, conductive materials. However, producing durable wearable electronics materials with high-performance electromagnetic interference (EMI) shielding and dependable exploitation in all weather conditions is still difficult. These wearable EMI shielding clothing's are referred to as EM textile materials (ETMs). A novel class of functional textile materials known as ETMs are made from fibers or yarns that have good electrical and magnetic properties by the use of textile processing techniques or by fusing functional micro/nanoparticles such as inorganic, organic, and/or metallic materials with conventional textile materials. In the meantime, EM textile materials combine a distinctive textile material structure with EM metal material capabilities. Traditional textiles are crucial electrical insulation materials because they are primarily dielectric. Electrical conductivity, electrostatic, dielectric, and magnetic properties are only a few examples of the expected textile's EM characteristics.

One key material that can address the EMI problem facing the current circuit working environment and human health is conductive polymeric NW textile materials. These materials are fabrics commonly fabricated from a set of short and long fibers connected through physical entanglement, local thermal fusion, or chemical binders form of binding mechanism. Generally, the manufacturing techniques include well-known polymer processing methods such as melt blowing, melt spinning, and electrospinning [4, 8–10]. A typical application of this kind of material includes not only ballistic protection, thermal insulation, liquid-absorbing textiles, fireproof layers, and geotextiles for soil reinforcement but also EMI shielding application [10]. Conductive polymer composites and their NW textile materials show growing demand towards the field of EM shielding due to their low density, lightweight, corrosion resistance, tunable, excellent flexibility, cost-effective and easy processability [1, 11]. Moreover, materials with 2D, 3D, and porous structures, such as foamed polymer composites and NW textile surfaces, provide ultra-high shielding effectiveness due to their multiple internal reflection sites of EM radiations [1, 11]. However, natural conductive polymeric-based materials give less EMI shielding than carbon, graphene, Mxene, graphdiynes, and metals-based. Therefore, to achieve effective or ideal EMI shielding properties (more than 30 dB), polymeric materials are filled with high loading (~5 to 30 wt.%) of functional conductive/magnetic fillers until the percolation threshold is achieved [3, 4, 9, 11–13].

The above-stated has driven many researchers to examine the impacts of the morphology structure, size, and filler loading on the polymer composites and their NW textile materials towards EMI shielding application. For instance, Zhang et al. [13] fabricated (~5wt.%) 1.8 vol% graphene-filled polymethyl methacrylate nanocomposite foamed by subcritical carbon dioxide, which exhibited an EMI shielding of 13–19 dB at a density of 0.79 g/cm^3 and frequencies of 8–12 GHz. There are new developments in EMI shielding studies.

More importantly, an EMI active polymeric NW materials composed of nylon spacer fabric/carbon-fiber/low-melting-point polyester NW fabric and carbon-fiber/low-melting-point polyester/nylon spacer fabric respectively demonstrated EMI shielding of -45 and -65 dB with variations in stacking layers [14]. In summary, the polymeric composite or their NW -based materials used for EMI shielding are commonly made out of the following: a combination of metallic materials, laminated carbon fiber (CF) materials, high-loading incorporation, and coating (dipping or spraying) a mixture of carbon-based and metallic ions over the polymeric composites' materials.

In this rational, we have focused majorly on polymeric NW textile and their composites family as efficient EMI shielding materials. The study provides the fundamentals of the EMI shielding mechanism, EM reflection mitigation mechanism, and production techniques of EMI shielding NW materials. Moreover, the standard for future researchers to choose the ideal combinational material for effectively mitigating EMI waves as shields is presented.

Key aspects of the review

Review articles exist on EMI shielding textiles in general [1, 15], but no single article is dedicated to NW textile-based EMI shields. Again, no review article exists presenting the approaches employed towards mitigating EM wave reflection in NW -based EMI shield design and fabrication. Also, the challenges encountered with the manufacture and/or use of NW -based EMI shielding materials are presented in this paper for the first time. The question of why NWs selection as the primary structure for EMI shield fabrication is presented herewith in this article for the first time. We focus in particular on (a)*Comprehensive coverage:* One key aspect of this review is its comprehensive coverage of the latest developments in NW textile materials adoption for EM wave shielding. Again, the review of existing research, recent breakthroughs, emerging materials, and innovative techniques in NW EMI shields is discussed; *(b)New and innovation materials:* Highlights of new and innovative NW materials (including materials with enhanced performance, durability, or versatility) that show promise in EMI shielding as novel contributions are also conversed as per available literature. The vital aspects of textile-based EMI shields are also discussed for the first time in a dedicated review paper; *(c)Multi-frequency band shielding:* A few instances of materials that provide effective shielding across a wide range of EM frequencies are discussed. This is particularly important as the use of different frequency bands for communication and technology continues to expand; *(d) The Need for* NW *EMI shields:* The daring need to adopt NW EMI shield is for the first time elaborated in a dedicated review article; *(e) Integration with wearable technology:* As wearable technology and intelligent textiles gain prominence, instances involving novel materials suitable for integrating NW EMI shields into clothing or accessories for personal EMI shielding discussed; *(f) Cross-disciplinary insights:* This article has presented information capable of drawing insights from other fields, such as materials science, nanotechnology, or electronics, and applying them to the development of functional NW textiles for EMI shielding. Also, the approaches adopted towards the development of novel NW EMI shields, especially the mitigation of EM wave reflection, are discussed; *(g) Applications:* Diverse instances of NW EMI shield applications beyond traditional uses, such as in aerospace, healthcare, and military contexts, are discussed for the first time; and (h) *Challenges and future directions:* The challenges faced by researchers within the niche of NW EMI shield fabrication and application are presented. Also, speculations on future trends in this field and potential research directions, which are valuable for researchers, policymakers, and industrialists, are discussed for the first time in a dedicated review paper.

By offering a comprehensive review of the fundamental principles of the development of conductive polymer NW textile materials and the complexities of related research, this paper is expected to pave the way for future advances in the development of innovative functional polymer NW textile materials and their EMI shielding applications.

Why nonwovens and their composites/hybrids as EMI shields

Traditionally, EMI shielding applications require materials with excellent electrical and magnetic conductive properties; for this reason, EMI shielding materials are majorly known to be metals, conductive polymers, EM materials, and carbon-based materials. Under this background, the metallic materials have inherent excellent electrical conductivity and some drawbacks of being rigid, easily oxidized and corroded, poor absorption of EM waves, and having a heavyweight and high cost [14, 16]. Furthermore, metals demonstrate EMI shielding effectively, primarily by reflection mechanism which is not desirable in advanced EMI shielding systems. At the same time, the pristine conductive polymers are not favorable due to their poor conductivity relative to metals and poor mechanical properties, which are equally crucial as electrical conductivity towards EMI shielding application at large [16]. The EMI shielding properties of conductive polymers make them nothing compared to their metals-based counterparts. The intrinsically non-EMI shielding behavior of polymers informs that textiles-based materials are not naturally designed for EMI application. However, the development of NW material systems as EMI shielding material is drawing much attention owing to their merits of facile processability, lightweight, low cost, softness, breathability, ultra-high compressibility phenomenon or structural manipulation and multifunction compatibility for EMI shielding application [17–20]. To further reduce the weight and improve the EMI efficiency to meet the ultra-low-density and high EMI shielding requirement for some particular fields, novel porous structure networks (holes) or foam's structure and incorporation of conducting filler material have been innovatively fabricated through different processes. The increasing EMI pollution and concern about health associated with radiation exposure makes textile-based materials highly considered for EM shielding applications since they can be integrated into wearable electronics devices.

The reason that the fiber network has numerous interfaces capable of reflecting radiation multiple times; so NW fabrics are becoming attractive substrates to manufacture flexible and wearable high-performance EM shielding materials. For instance, considering the fact that cotton fibers' low density as a matrix overcomes the lack of heavy metal, metal-wrapping of cotton fiber networks with high dielectric loss can receive more attention and be used more extensively instead of bulk metal [21]. It has been suggested that employing Ag wet electroless depositing on the surface of NW cotton fibers can produce flexible, high-performance NW fabrics that are effective at EMI shielding. Because of the cell-like topologies, which are porous structures in the non-woven textiles and voids in Ag layers, the EMI shielding performance of the Ag-coated NW fabrics was claimed to be outstanding [21].

In this rationale, incorporating carbon-based material has enormous potential to channel the polymeric NW textile materials for EMI shielding application. Moreover, the carbon-filled polymer nanocomposites display good mechanical strength, excellent flexibility, and ultra-thin thickness, as well as remarkable electrical properties, which are critical for the EMI shielding application [22]. Hence, carbon-filled polymer nanocomposites hold great promise for future EMI shielding materials. However, the main drawback lies with the high filler loading strategy to achieve the ideal electrical conductivity threshold required for the intrinsic EMI shielding domain, thus hampering the processability [16]. For instance, a NW composite based on 40 wt.% carbon fibers-filled propylene/polyethylene composition exhibited EMI shielding as high as 30.29 dB [22]. Contextually, the porous structure of NW materials or foamed materials has a few advantages, including critical lower density, critical higher flexibility, and compressibility effects. The stronger microwave-absorbing ability is ideal for eliminating the secondary pollution brought by EM reflection, thus a complex EMI shielding mechanism which adds value to the efficiency.

Furthermore, the critical lower density can reduce the weight and cost of EMI shielding materials. At the same time, the critically higher flexibility can widen their application in electronic packing compared to their solid-based materials. Therefore, to develop a topnotch neat polymers and their composites NW textiles as EMI shielding materials, conductivity, free-moving electrons, or holes are the prerequisites for the shielding material efficiency [23]. Thus, the polymers and their composites NW textiles are emerging as EMI shielding materials.

Current status of nonwovens utilized as EMI shields

EMI shielding is a rapidly growing technology; the novel strategy involved in the design and fabrication of these systems is the use of carbon-based materials, especially graphene [19], Mxene [24], carbon black [25], discontinuous carbon fibers [4, 8, 9], CNTs [26, 27], and others. A unique aspect of carbon-based fibers or polymeric NW textile utilization as EMI shielding materials is their complex shielding mechanism, which includes reflection loss, multiple internal reflections, and absorption loss to accomplish high-quality EMI shielding properties. Conductive fillers such as carbon-based materials have paved the opportunity to integrate multiple functions into polymeric textiles to form electronic textiles for novel wearable electronics that can monitor human health and display EMI shielding properties. Kashi and co-workers [28] demonstrated that the composites containing CdS nanocrystals-CNTs can be efficient microwave absorbers at elevated temperatures or harsh environments. For high-quality EMI shielding properties, critical technical approaches have been extensively considered to modify the electrical conductivity of the plastic/polymer-based materials by applying three modification strategies. Applying conductive coating on plastics/polymers, incorporating conductive fillers through compounding, and utilizing intrinsically conductive polymers with a critical processing strategy (core–shell fiber construction and NW development) is an attractive approach [29]. Moreover, by taking advantage of polymers' remarkable compressibility, the shielding performance of the polymer-based foamed materials could be adjusted through a simple mechanical compression, showing promise for adjustable EMI shielding [30]. This rational, layer-by-layer construction of light-weight polymeric NW fabrics could demonstrate a similar compression mechanism to that of foamed material and display adjustable EMI shielding properties.

To date, polymeric, NW textile materials containing conductive particles such as carbon-based particles have been explored intensively as potential EMI shielding materials. The incorporation or coating of rGO [19], Mxene [24], carbon black [25], carbon fiber (CF) [14, 26] and CNTs [26, 27] into different polymeric-based matrices have exhibited suitable EMI shielding performance. Within recent decades, graphene and its derivatives have also been demonstrated to be effective fillers for preparing conductive polymeric composite materials with good EMI shielding performance [19, 31]. Pakdel et al. [32] developed carbon fiber/polyamide 6 (CF/PA6) NW fabric with outstanding EMI shielding performances from 80% waste material. The 80%CF/20%PA6 NW s provided an outstanding EMI shielding performance of about 85 dB, attributed to the high content of CF and the thickness of NW fabric. The lightweight and flexible polymeric NW textile materials also have potential EMI shielding applications in the power electronic industry due to the electronic industry equipment expansion towards space and their extensive use in communication [33].

For this reason, a sophisticated technique is needed to tailor polymeric NW textiles for EMI shielding application between the electronic receiving device on the ground and the novel space-based energy generation. If this is not taken care of in the initial research & development of space-based energy generation system, humans health and wireless communication will be compromised at large. Further advances in the field of EMI shielding by polymeric NW textile materials are required whereby a fundamental understanding of the necessary steps involved is gained.

The current research informs the use of polymeric NW textile and their composites/hybrids as high-quality EMI shielding materials. Hence, it is acceptable and novel to set carbon-based filled polymeric NW textile materials as a benchmark for future EMI shielding research [28]. The strong push is mainly driven by good mechanical, superior electrical conductivity, lightweight, large specific areas, and thermal properties of carbon-based material and their ability to follow complex shielding mechanisms in NW EMI shields [19, 28]. In addition, the potential of extensively using polymeric NW textile materials is supported by numerous advantages such as processability, flexibility, lightweight, porosity and compressibility and complex morphology structure. The critical surface functionalization of porous polymeric NW textile materials by conducting fillers such as carbon-based material (CNTs, graphene and its derivatives) have shown the potential for high EMI shielding efficiency.

As per science direct search results (as depicted in Fig. 2) using the keywords "NW Electromagnetic Interference Shielding," we found out that there is a comparatively progressive growth in the utilization of NW textiles materials as EMI shields either as prepared or accompanied with additional post-treatments processing aimed at achieving excellent EMI shielding performance.

There are challenges facing this technology, such as the large-scale manufacture of smart wearable textiles with EMI shielding properties, fabrication of low-density, compressible polymeric-based material and the problem of conductivity percolation threshold towards the shielding mechanism, still faces significant hurdles [22, 30, 34].

Conclusively, NW EMI shielding materials are currently known to combine conductive and non-conductive fibers or coatings. The conductive elements, such as metal particles or fibers, help reflect or absorb EM radiation. NW EMI shields can be found in various applications, including electronic devices, automotive components, aerospace equipment, and medical devices. They protect sensitive electronic components from interference and ensure compliance with EM compatibility (EMC) standards. These materials offer several advantages, including flexibility, ease of customization, and cost-effectiveness compared to traditional metal enclosures. They can be designed to meet specific shielding requirements while minimizing weight and bulk. EMI shielding technology continues to evolve, and new materials and methods are being developed to address emerging challenges related to higher frequencies and the miniaturization of electronic devices. Researchers are exploring novel materials and manufacturing techniques to improve the performance of EMI shields. However, it is vital to note that NW EMI shields aimed at effective EMI shields must comply with industry-specific standards and regulations, such as those set by the Federal Communications Commission (FCC) in the United States or the European Union's EMC Directive. Compliance testing ensures that devices meet EMI emissions and immunity requirements.

Shielding mechanism of EMI shields in textile materials

It is expected that a textile-based EMI filter designated, for instance, to be used in clothing material must be simple to wear, along with electronic stability under all usage conditions, and conformal for its implementation in other textiles. In addition, it needs to also adhere to hygiene standards related to wearable clothing. The initial prerequisite for EMI filter textile (EMIFT) is flexibility so that it can sufficiently accept human motion and different formats of deformation like finger, wrist, and elbow bending. Its ability to adapt to various environmental situations comes second. For instance, it is crucial to understand how different temperatures and chemicals might affect it. Thirdly, it must be comfortable to wearer, which means it must be soft and breathable. The final aspect is its washability, which is one of

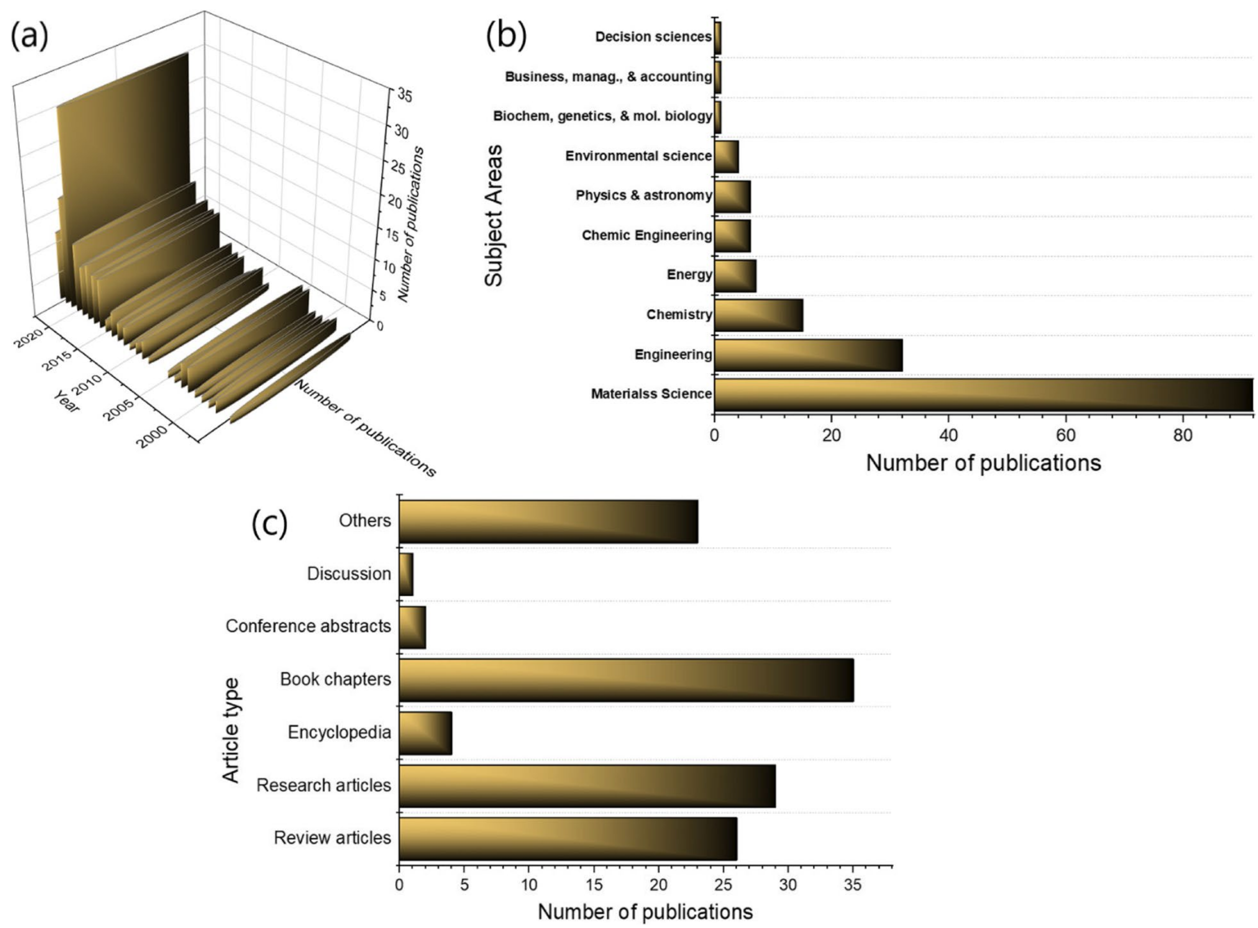

Fig. 2 Progress in the utilization of nonwoven textile materials as EMI shields either as prepared or accompanied with additional post-treatments processing aimed at achieving excellent EMI shielding performance, date: 21.04.2023, Time: 10:02. **a** Number of publications per year, (**b**) Number of publications per subject area, and (**c**) Number of publications with regards to article type

the main difficulties in constructing wearable EMIFTs. Due to the requirement for conformal contact with human cells, the EMIFT is susceptible to contamination by human cells, sweat, oil, and germs. However, washable EMIFT allows for a large cost reduction while improving hygienic conditions for those utilizing protective textiles [35].

Textile materials, such as woven, non-woven, or knitted fabrics, are suitable for shielding due to their capacity to take on the shape of the human body, compatibility, flexibility, and their ability to have a custom-designed structure [36]. Particularly, soft, lightweight, and highly effective EM shielding materials are in considerable demand. Due to its qualities like softness and breathability, cotton fabric is one of the most well-known raw textile materials. Additionally, because of its affordability, adaptability, and tailorability [37], it can be used as a substrate for EM shielding. Figure 3 illustrates the various material characteristics for EMI shielding materials adoption in/as technical textiles.

The natural source of EM waves that we encounter in everyday life is from the sun. Meanwhile, EM waves also come from satellites and other electronic devices. The interference of EM waves from different sources generally leads to EM pollution(s), which can hamper the performance of electronic devices and human health stability. Hence, it is important to understand the sources of EM waves, the EMI shielding mechanism, and the materials' total EMI shielding effectiveness (EMSE). According to Schelkunoff's theory, the total EMSE is controlled by the amount of EM waves being reflected (SE_R), multiple reflected (SE_M), and absorbed (SE_A) (equations i and ii). Therefore, the EMSE is the sum of $SE_R + SE_A + SE_M$ [1, 4, 9, 12]. However, when the SE_T reaches 15 dB the multiple reflection mode is normally ignored [1]. EMI shielding materials ordinarily reflect or absorb a portion of EM waves and transmit the remaining amount of EM waves [1, 4, 9, 12]. The ideal EMI shielding materials exhibit a single reflection mode, secondary multi-reflection mode, and absorption of a more significant portion of EM waves

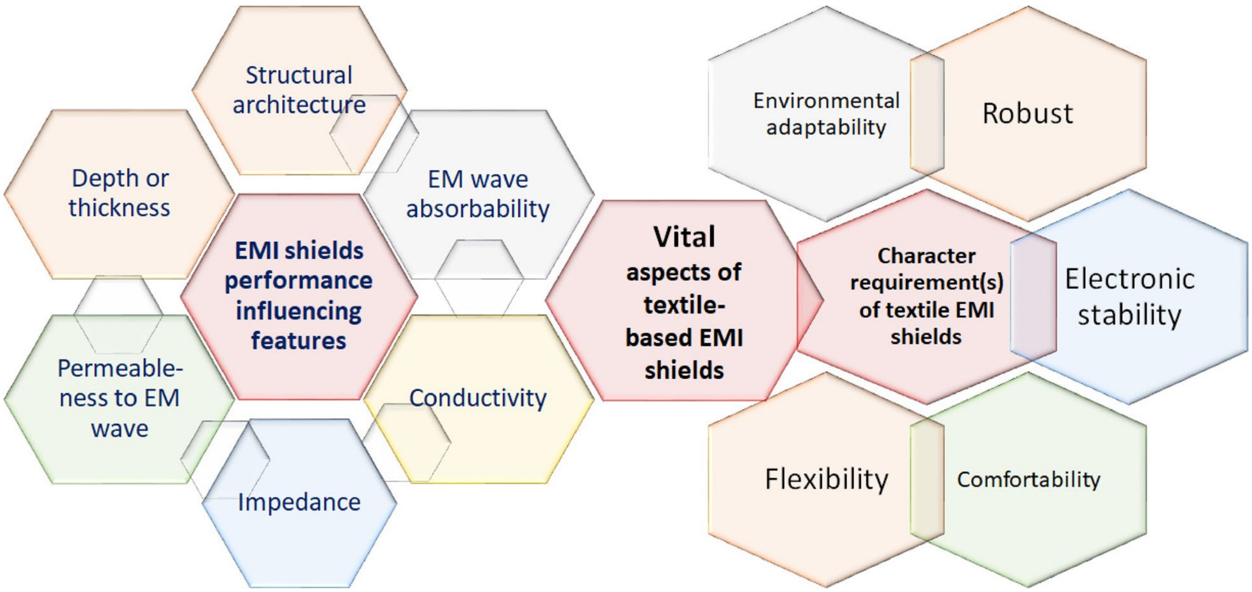

Fig. 3 Vital aspects of textile-based EMI shields

as well as transmitting a very small amount of EM waves (Fig. 4) [16]. Materials with ideal electrical conductivity employ a reflection mechanism, while materials with ideal magnetic properties normally employ an absorption mechanism [14]. According to specific application scenarios, textile technology-based materials or foamed polymer composites are described by the complex EM wave mechanisms such as normal reflection, absorption, and multi-internal reflection mechanisms due to their sophisticated morphology structure.

$$SE_T = SE_R + SE_A + SE_M \tag{1}$$

$$SE_T = SE_R + SE_A (\text{When} SE_T > 15\text{dB}) \tag{2}$$

The EMI shielding of a particular electronic device is influenced by several factors, including operating frequency range, shielding filter/enclosure thickness, as well as the expanse betwixt the transmitter and the receiver. Other factors include the magnetic, electrical, and material qualities of the shield/filter. An exponential decrease in

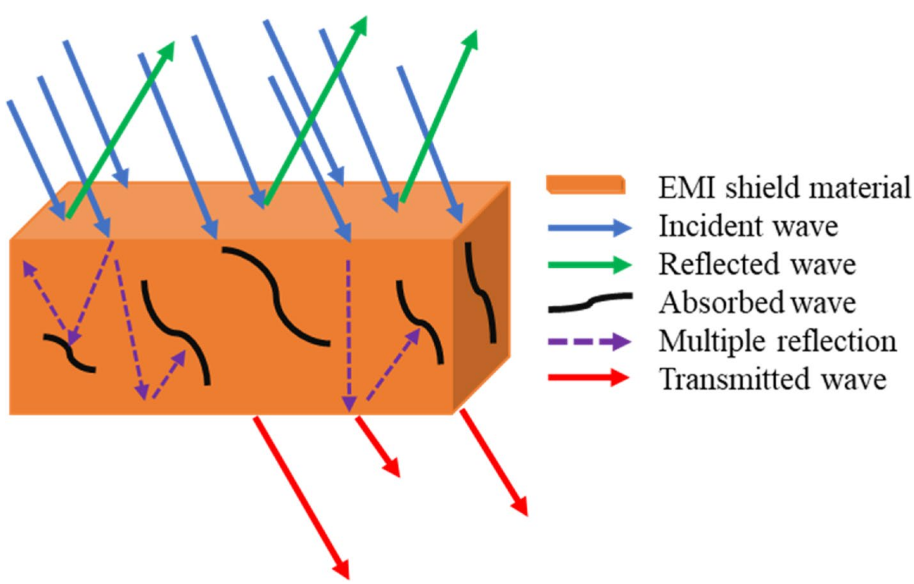

Fig. 4 Typical EM wave transmission mechanism on shielding material

the amplitude of EM radiation is observed when it travels through the shield. An absorbing process frequently causes such exponential degradation: Ohmic losses are caused by the induced current within the medium. The EM wave's ability to penetrate a surface depends on how magnetic and electric dipoles interact. The absorption rate/contribution of an EM wave can be calculated using Eq. (3):

$$A = 8.686t_n\sqrt{\pi f \mu_r \sigma_r} \tag{3}$$

Herewith, t_n denotes the EMI filter thickness, f represents the frequency of operation, σ_r stands for the shield electrical conductivity, while μ_r denotes the shield relative permeability. The formula shown above shows that the effectiveness of shielding via the absorption mechanism is proportional to $\sqrt{\pi f \mu_r \sigma_r}$, where the loss of absorption rises with frequency. A material's ability to successfully absorb EM waves (EMW) depends on its ability to conduct electricity well and have a high permeability. Additionally, adequate thickness is needed for appropriate skin depth penetration. The absorption loss is influenced by the shielding filters' thickness [36].

It is important to note that the definition of EMW impedance is "the amplitude ratio of the electric to magnetic field." The characteristic EM wave impedance in space is 377 Ω, but the impedance of a conductive shield is substantially lower. This impedance mismatch at the shield/air interface causes a strong reflection of EM waves. Therefore, impedance matching requirements at the shield/air contact must be met for the shield to achieve dominant absorption and minimized reflection [38]. A shielding material's ability to provide efficient shielding is also influenced by reflection. Reflection generally results from a mismatch between the incident wave and the substance (non-woven textile material) acting as a shield.

Reflection loss (SE_R)

Once an incident EM wave encounters the surface of a shielding material, a part of the EM wave is reflected because of the impedance mismatch that the EM wave experiences at the interface of any two media of different impedances [5, 39]. It is well-known that materials with inherent electrical conductivity demonstrate a reflection mechanism; this reflection loss (SE_R) is inversely proportional to frequency and directly proportional to the electrical conductivity of the shielding material (as in Eq. 4) [1, 4, 8, 9, 12].

$$SE_R = -10log\left(\frac{\sigma}{16f\varepsilon\mu_r}\right) \tag{4}$$

The EMI shielding through the reflection mechanism is practically based on the efficiency of mobile charge carriers (electrons or holes) when interacting with the EM fields in the radiation space. Thus, electrically conducting martials are the most favorable candidates due to their inherent free electrons phenomenon [40]. Hence, the reflection mechanism is mostly demonstrated by metals due to their excellent electrical conductivity properties. In this regard, Wang et al. [40] fabricated a single layer of 7.97 wt.% and 18.87 wt.% Mxene-coated NW fabric for wearable heater materials and found that the 7.97 wt.% Mxene-coated fabric could reach average SE_T, SE_A, and SE_R values of 27.3, 20.0, and 7.3 dB, respectively. While the 18.87 wt.% Mxene-coated NW fabric reached average SE_T, SE_A, and SE_R values of 35.7, 27.1, and 8.6 dB), respectively. The improved SE_T and SE_A values were attributed to the increased loading and electrical conductivity of Mxene. Based on the reflection coefficient (R) and absorption coefficient (A) of 18.87 wt.% Mxene-coated NW fabric, the R was reportedly nearly 0.86, indicating that the EMI shielding mechanism was primarily a reflection. More importantly, a high reflection mechanism can trigger other problems by reflecting waves to the generation source itself and cause undesirable electric noise [41].

Multiple reflections

Herein, non-absorbed and non-reflected incident EM wave from the first shielding cycle encounters the internal surface of a shielding material, then a part of the EM wave is re-reflected (multiple reflection). However, multiple reflections can be ignored when the SE reaches 15 dB; thus, SE is determined by reflection and absorption [1, 4, 9, 12]. The fundamental requirement for multiple reflections includes large specific surface area, large interfacial areas, and ultra-high porous or foamed material to be in contact with the EM waves. The other vital requirements are polymeric phase separation morphology with a critical network structure and the incorporation of different kinds of conducting fillers, such as carbon materials and metal nanostructures. Finally, the processibility and conversion of this kind of EMI shielding material into polymeric NW textile material for critical morphology structure and compressibility effects can further improve the EMI shielding performance. The requirements mentioned above are important since a highly (3D) porous/foam composite material affords a large specific surface area as well as a large interfacial area. While the different kinds of conductive fillers can also offer large surface and interfacial areas, electrical conductivity, and magnetic permeability for improved EMI shielding [23]. This suggests that carbon-based material with critical morphology network structures like graphene-filled composites can afford complex shielding mechanisms due to conductive pathways and surface area effects. Tan and co-workers [11] demonstrated that the use of

10wt.%PCL/90wt.%PLA/CNTs with sea-island morphology exhibited higher EMI shielding relative to the same components with co-continuous morphology. The high EMI shielding in the sea-island morphology material was due to the highly efficient multiple reflection mechanism due to the confined distribution of CNTs in the PCL phase. The inherent low viscosity of PCL promotes strong interaction between PCL and CNTs as well as the confined CNTs distribution into the PCL phase; hence multiple reflection is noted. Moreover, the small size of the PCL/CNT particles distribution in the PLA matrix promotes high-efficient microwave scattering at the PCL/CNT particles; again, this signifies the role of incorporating relatively high conductive filters. The above findings suggest that for polymeric NW textile material, porous or foamed material can be integrated inside the core–shell structure of the individual fibers that make the NW textile material (Fig. 5).

Absorption loss (SE_A)

The term "shielding effectiveness" or "total shielding effectiveness (SE_T)." refers to the power loss caused by shielding, which is represented in decibels (dB) This loss's absorption component is referred to as the absorption loss (SE_A). This loss's reflection-related portion is referred to as the reflection loss (SE_R). The following definitions of these numbers are mathematical. The scattering parameters, often known as S-parameters, define how a network with N ports responds to signals that are incident on one or more ports. The first number in the subscript of the S-parameters abbreviation designates the responding port, whereas the second designates the incident port. Consequently, the output at port 2 as a result of a signal at port 1 is referred to as S_{21}. Through the equations, the variables SE_T, SE_R, as well as SE_A are derived from the S-parameters thus [42].

$$SE_T = -log(T) = -log|S_{21}|^2 \tag{5}$$

$$SE_R = -log(1-R) = -10log(1-|S_{11}|^2) \tag{6}$$

$$SE_A = SE_T - SE_R - SE_M \tag{7}$$

The terms T (transmission coefficient) and R (reflection coefficient) in these equations denote the proportions of the input power transmitted into and reflected from the sample interior, respectively. T and R must be reported as fractions or percentages rather than in decibels (dB). SE_M is used in Eq. (7) to describe the shielding caused by multiple reflections inside the sample.

If the total shielding SE_T reaches 15 dB, SE_M is often insignificant in real-world applications. Equation (7) changes in this scenario.

$$SE_A = SE_T - SE_R = -\log(\frac{T}{(1-R)}) \tag{8}$$

The ratio of SE_A to SE_T is referred to as the absorption contribution (A). According to the equation(s) below, EM theory predicts that the SE_A rises with increasing frequency. [42];

$$SE_A = 131.4t\sqrt{\sigma_r \mu_r f} \tag{9}$$

$$SE_A = 131.4t\sqrt{\frac{f\mu\sigma}{(\mu_0\sigma_{Cu})}} \tag{10}$$

$$SE_A = 8.68t\sqrt{\pi f \mu\sigma} \tag{11}$$

where t is the specimen's thickness in meters, f is the frequency in hertz, μ_r is the material's relative magnetic permeability in relation to copper, σ_r is its electrical conductivity in relation to copper, σ is its electrical conductivity, and μ is its magnetic permeability, with $\mu = \mu_r\mu_0, \mu_0 = 4\pi \times 10^{-7} H/m$. Equations (9, 10, and 11) are applicable in the context of conductive materials. In the event that μ_r and σ_r do not decrease with increased frequency, it suggests that SE_A grows. Furthermore, it shows that SE_A at a particular frequency rises with both permeability but also conductivity.

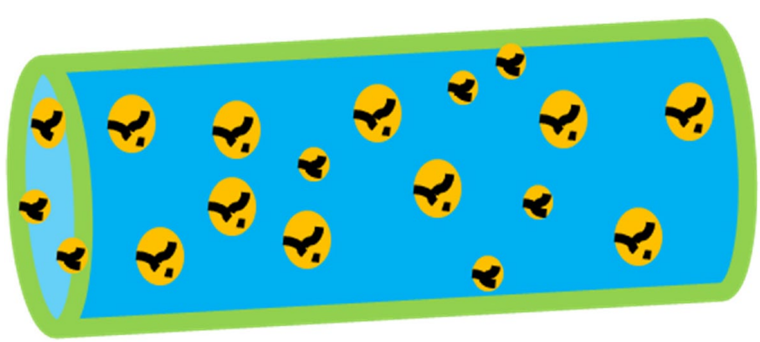

Fig. 5 Typical 3D-phase morphology or porous core–shell nano fibers morphology with possible multiple reflections mechanism index

Herein, once a non-reflected incident EM wave encounters the internal surface of a shielding material, a part of the wave is absorbed and dissipated in the form of heat. The rest is transmitted through the shielding medium [43]. Metals are excellent conductors of electricity; however, they can conduct both electricity as well as heat. Hence, metals can demonstrate the EMI shielding phenomenon through absorption but also reflection mechanism, as stated above [29]. Moreover, materials with magnetic conductivity or a carbon-based apply an absorption dissipation mechanism. Generally, materials with excellent absorption loss must own dipole characteristics; this absorption loss can further increase with increasing the EM wave frequency [1, 23]. For example, super-permalloy materials such as 20% iron and 80% nickel have a high magnetic permeability, so this material can demonstrate effective EMI shielding through an absorption mechanism [23]. Naeem and co-workers [44], developed a porous, NW material containing electrically conductive activated carbon from acrylic fibrous waste material. For this process, 1200 °C carbonization temperature was the optimum regarding surface area and charge transport mechanism (Fig. 6). They reported that EMI sheading performance increased with increasing frequency; 63.26 dB, 66.75 dB, and 75.44 dB were found for respective frequencies of 600 MHz, 1 GHz, and 1.5 GHz. This behavior was attributed to the increased multiple internal reflections and stronger absorption mechanism. Shen and coworkers [30], prepared PU/graphene (PUG) foams material with a density as low as ~ 0.027–0.030 g/cm^3 for EMI applications. It is worth noting that the PUG possessed good comprehensive EMI shielding performance through an absorption-dominant and multiple reflection mechanism. Sano and Akiba [41], developed a high porosity NW fabric coated with CNTs. The incorporation of CNTs with excellent electrical conductivity and pours structural network of NW fabric have been shown to demonstrate the potential for high performance EM absorbers. It is highly desirable to design multifunctional polymeric-based materials with integrated conductivity, ultra-low-density, flexible, and porous network structure for adjustable compressibility phenomenon. These combined characteristics could add value to the efficiency of EMI shielding material through the shielding mechanism and functionalities of the material. Moreover, the addition of 3D conductive-based filler (such as graphene) network could also enhance the efficiency of EMI shielding material, through loading and multi shielding mechanism.

Shielding effectiveness (SE)

To maximize the EMI shielding performance of polymeric NW textile materials, effective parameters such as the type of matrix polymer, density of fibers, thickness of the NW material, porous morphology structure, weight, and production process, as well as the fabric surface resistance must be controlled [40]. More porous morphology structure (up to the threshold porosity), high thickness, and excellent surface resistance are favorable. It is well known that the EMI shielding performance of the fabric material is directly proportional to its thickness [45]. Also, the electrical but also thermal conductive properties, active filler loading, filler alignment/distribution, dispersion and particle size of the reinforcement

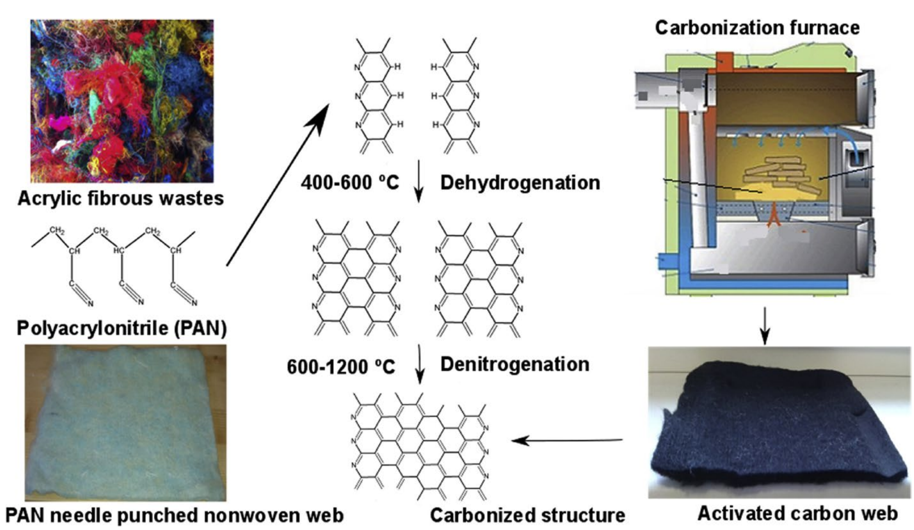

Fig. 6 Schematic of preparation of activated carbon from acrylic fibrous wastes.

Reproduced with permission from Naeem et al. [44], Copyright 2016, Elsevier Science Ltd material become crucial [46]. For instance, Wang et al. [40], fabricated a Mxene-Coated NW fabric for wearable heater materials, where EMI shielding properties are necessary—a single layer of 7.97 wt.% MXene-coated NW fabric with a sheet resistance of 30.21 Ω/sq (excellent electrical resistance) exhibited EMI shielding of about 27.3 dB. While single layers of 10.14 wt.%, and 18.87 wt.% MXene-coated NW fabric with decreased sheet resistance to about 15.07 Ω/sq and 4.36 Ω/sq exhibited the corresponding EMI shielding of 31.9 dB and 35.7 dB, respectively. On the other hand, the EMI shielding efficiency of a double layer of the 7.97 wt.% 1, 10.14wt.%, and 18.87 wt.% MXene-coated NW fabric is 46.3 dB, 51.7 dB, and 62.9 dB, respectively. Liu et al. [45], also fabricated flexible and multifunctional silk textiles with biomimetic leaf-like MXene/silver nanowire nanostructures for EMI shielding applications. The EMI shielding efficiency of the flexible and multifunctional textile, with a low sheet resistance of 0.8 Ω/sq, exhibited excellent EMI shielding efficiency of 54 dB at a small thickness of 120 μm.

The creation of NW textiles-based materials for EMI shielding depends critically on our understanding of how they interact with the magnetic as well as electric fields within the radiation. Due to the interaction between the magnetic dipoles in the material and the magnetic field in the radiation, the magnetic property enhances radiation absorption. The magnetic dipole friction, magnetic susceptibility, dipole–dipole interaction, as well as magnetic continuity are important features of the magnetic character. These factors depend on the size and mobility of the magnetic domain boundaries: they increase with frequency. Due to the interaction between the electric dipoles in the material and the electric field in the radiation, the NW shielding material's electric polarizability also facilitates its absorption property. Electric dipole friction (which rises with frequency), dielectric connectivity, dipole–dipole interaction, as well as electric susceptibility are all important aspects of the dielectric character.

The Kramers–Kronig relationship connects the conduction behavior to the dielectric behavior: for instance, the conductivity but also the real as well as imaginary components of the permittivity all rise with increasing heat-treatment temperature (that is, with increasing levels of crystallographic structure) among carbon materials generated by heat treatment at different temperatures [47]. The imaginary part of the complex permittivity, which represents the conduction behavior, indicates that conduction behavior also contributes to the dielectric loss. It describes the energy lost during heating a dielectric substance in a fluctuating electric field. The frequency, as well as the dielectric material, are often the key determinants. The Loss of Tangent, often known as tan delta ($tan\delta$), is used to calculate the dielectric loss ($tan\delta$).

The phenomenon of dielectric polarization is thought to provide dielectric materials with their capacity to hold electrical charge despite their poor electrical conductivity. Dielectric loss is the amount of energy lost during heating an electrically conductive substance in various electric domains. In an alternating-current circuit, for instance, a capacitor is barely charged and discharged once every half cycle. Most crucially, dielectric losses are typically determined by the dielectric material and frequency. The Loss of Tangent, or tan delta, is used to measure dielectric loss (tan delta). Tan delta is the angle formed by the alternating field vector and the material's loss component or put another way; it is the tangent of that angle. Therefore, the value of Dielectric Loss should be significantly higher than that of tan delta. The drying of timber and other fibrous materials, the heating of thermosetting glues, the quick jelling and drying of foam rubber, and the preheating of polymers before molding are all common industrial applications for heating by dielectric losses. Numbers that help describe the permittivity of a dielectric substance include the dielectric constant and the loss tangent.

The Greek letter "ε" denotes the permittivity of dielectric substance. The electric field in a vacuum divided by the electric field in the dielectric material, or $E = {}^{E_0}/_{E}$, is the formula for the dielectric constant, which strongly relates to the material's polarizability. Dielectric Loss is the energy lost during the heating of a dielectric substance in a fluctuating electric field. It typically depends mainly on the frequency and the dielectric material. Dielectric loss is calculated using the Loss of Tangent, also known as tan δ. The probability of having a large dielectric loss increases with the value of tan delta. Describe a loss tangent. Loss Tangent is a dimensionless quantity, often known as tan δ. Due to the fundamental EM energy dissipation in electronic equipment like the printed circuit board, it frequently calculates the predicted Loss of signal.

$$LossTangent = tan\delta = cot\theta = {}^{1}/_{(2\pi R_P C_P)} \tag{12}$$

The symbol δ, θ, f, R_P, and C_P denote the Loss angle, phase angle, frequency, equivalent parallel resistance, and equivalent parallel capacitance. Loss Tangent plays a crucial role in determining the signal attenuation for analog transmissions at extremely high frequencies exceeding 1 GHz.

In extremely high frequencies, or frequencies above 1 GHz, the Loss Tangent plays a crucial role and frequently matched signals to determine their transmission loss.

It is also crucial to consider the elements that lead to dielectric loss in dielectric materials like EMI shields and energy storage systems. With the least amount of energy lost as heat, a coherent dielectric can accommodate a range of charges. In a dielectric, energy can be lost by one of two main types of loss. A charge passage through a material causes energy dissipation during conduction loss. The dielectric loss tangent is the energy lost by the displacement of charges in a replacement EM field as polarization changes directions. In addition, dielectric losses are particularly large near polarization processes' resonance or relaxation frequencies. The polarization delays the applied field, which causes an interaction between the field and the polarization of the dielectric that heats the material. A dielectric loss is more likely to occur in materials with higher dielectric constants. Employing these materials in practical applications has this significant disadvantage. For instance, dielectric loss is used in microwave ovens to heat meals. Nearly the same frequency as the relaxation frequency of the orientational polarization mechanism in water is used in the microwave. This implies that any water present absorbs a significant amount of energy, which is then released as heat. To prevent the microwave from becoming completely engulfed by the first layer of water they encounter and prevent improper heating of the food, the specific frequency used is slightly off from the frequency at which maximum Dielectric Loss occurs in water. An effective dielectric often supports a range of charges while minimizing energy loss in the form of heat. Two main forms of losses can cause energy to be lost within a dielectric. One is conduction loss, which happens when a charge passes through a substance and energy is lost. The other type of energy loss is called dielectric loss, and it happens when polarization changes the direction of a magnetic field, causing charges to flow in that field and dissipate energy. Around the resonance or relaxation frequencies of the polarization mechanisms, the second type of loss is particularly prone to be high. This is mostly due to the fact that the applied field interacts with the polarization of the dielectric, which in turn causes heating as a result of the dielectric's polarization trailing behind it. The one disadvantage of using dielectric materials in real-world applications is that materials with higher dielectric constants suffer from more dielectric loss.

Dielectric additional factors that affect the loss of dielectric materials are thus: After being added to the test cell, insulating oils' D.C conductivity and dielectric losses decrease over time, except for electric stress and room temperature. The Loss of tangent and D.C conductivity increase to their maximum when the cell is heated immediately after filling. However, they decrease over time as the temperature remains constant to a considerably lower value. Basic characteristics of the thermal capacity and form of the cell include the maximum value, the rate of increase to that value, and the subsequent reduction over time. It is used to clean the oil's cell, temperature, and oxygen content. Despite the possibility that ions may be confined at this surface, the following drop-in Dielectric Loss is taken into account due to the catalytic oxidation of most elements in the oil at the metal-electrode surface. A low-viscosity cable infusion, transformer oil, and a synthetic hydrocarbon are employed to detect the effects. These materials are both widely contaminated and underused. The effect's imputations are further studied in relation to routine oil testing, an analysis of the impacts of contamination on oils, and work on oil-infused paper. The use of plastic-coated electrodes could eliminate the impact completely or partially.

Insulating oils' D.C conductivity and dielectric loss tend to decrease over time after being applied to the test cell. However, the ambient temperature and the electric stress are absent in this scenario. As soon as the cell is heated after filling, the tan delta and D.C conductivity tend to increase to their maximum levels. But they fall to a much lower value over time and at a constant temperature. The maximum value, the rate of increase to that value, and the subsequent reduction over time are some of the fundamental properties of the cell's shape in addition to its thermal capacity. This procedure cleans the cell, the temperature, and the oil's oxygen component. Even though ions may merely limit the metal-electrode surface, the following drop-in Dielectric Loss is taken into account because most of the elements are catalytically oxidized at the metal-electrode surface in the oil. In addition, in relation to the standard testing of oils, the imputations of the aforementioned effect are carefully evaluated for an analysis of the impacts of contamination in oils, as well as to work on paper that has been infused with the oil itself. Using electrodes with a plastic coating could partially or completely eliminate the effect, depending on the situation. Dielectric refers to a material with low electrical conductivity that can store an electrical charge due to dielectric polarization. Therefore, it only exhibits displacement current, which makes it ideal for building a capacitor, which can store and release electrical energy. You need to grasp what dielectric loss is and other related ideas in order to comprehend the subject matter better.

High conductivity among non-magnetic materials is frequently regarded in the industry as the primary factor in achieving high shielding. This focus on conductivity is partly due to how simple it is to measure conductivity. However, high conductivity is not always the main requirement for shielding among non-magnetic materials.

A contributing component has to do with the shielding material's surface area or interface area. Due to the Skin Effect, a high specific surface/interface area (i.e., area per unit volume) encourages the volume of the specimen's radiation-interacting portion, increasing the shielding efficiency. The term "interface" refers to the boundary between a material's shielding (such as a filler) and non-shielding (such as the matrix/binder) components. Due to the low level of interaction with the radiation, the non-shielding component is essentially transparent to it. A smaller feature size of the porous microstructure results in a higher specific surface area for a given porosity in a porous material, which increases shielding efficiency. A smaller unit size of the filler produces a higher specific interface area for a given filler volume fraction in a composite, which encourages shielding. This contributes to the appeal of nanofillers for composite shielding materials.

Another component is the electrical connection, which enhances shielding since the material's electric field lines are continuous. Additionally, this continuity permits the flow of eddy current generated by the magnetic field, which encourages magnetic power loss. Electrical percolation (electrical connection) in a composite with a conductive filler and a nonconductive matrix is, therefore, advantageous for shielding. When the filler's aspect ratio is larger, the percolation threshold is lower: The aspect ratio of a nanofiber is often greater than that of a microfiber, which is another factor that makes nanofillers appealing.

Again, the magnetic continuity of the magnetic component is required for a magnetic shielding material because continuous magnetic field lines are a must. As a result, magnetic percolation in a composite made of a non-magnetic matrix and a magnetic filler is crucial for shielding.

The efficiency of the shielding is influenced by the magnetic, dielectric, conduction characteristics, and the particular surface and interface region. Additionally, the frequency and temperature affect each behavior. In addition to being useful to applications, the effects of frequency and temperature also provide insight into the shielding's workings. The primary shielding mechanism may depend on the interaction of temperature and frequency for a particular material.

It is important for researchers working on textile materials such as NW-based EMI shields to have proper knowledge of the dielectric and electrical properties of commonly used textile fibers: in this regard, we have presented these property parameters in Table 1. Cotton and viscose fiber's ability to regain high moisture within their structure gives them high dielectric constant. Since water has a relative dielectric constant that is several tens of times greater than that of dry textile material, the dielectric constant of the fiber changes depending on how much moisture is present in the textile material. The materials' dielectric constant is additionally affected by frequency, temperature, and contaminants. Also, it is vital to note that the electrical conductivity of textile materials is expressed as specific resistance. There are usually three representations: volume-specific resistance, mass-specific resistance and surface-specific resistance, as presented in Table 1 [48].

Table 1 Dielectric and electrical properties of commonly used textile fibers at a relative humidity of 65% and frequency of 1 kHz

Textile fiber(s)	Dielectric constant	Electrical properties			Ref
	-	lg ρm	n	lg K	
Cotton	18	6.8	11.4	16.6	[49]
Ramie	-	7.5	12.3	18.6	[49]
Silk	5.5	9.8	17.6	26.6	[49]
Wool	-	8.4	15.8	26.2	[49]
Washed wool	-	9.9	14.7	26.6	[49]
Viscose fiber (Viscose wire)	8.4 (15)	7.0	11.6	19.6	[49]
Acetate fiber (Acetate staple fiber)	4.0 (3.5)	11.7	10.6	20.1	[49]
Acrylic	-	8.7	-	-	[49]
Acrylic (degreasing) (Acrylic staple fiber (de-oiled))	(2.8)	14	-	-	[49]
Polyester	-	8.0	-	-	[49]
Polyester (degreasing)	-	14	-	-	[49]
Nylon yarn	4.0	-	-		[49]
Nylon staple fiber	3.7	-	-	-	[49]
Polyester staple fiber (de-oiled)	4.2 (2.3)	-	-	-	[49]

Assessment of EMI shielding materials

Increased electrical conductivity is a tried-and-true strategy to be utilized by researchers to increase the functionality of most NW textile materials/composites used as EMI shields, but significant EM wave reflection has been reported to be typically produced during the shielding process as a result of secondary EM pollution [21]. Textile-based NW environmentally friendly EMI shielding materials must be created with an actual shielding performance of $SE_T > 20$ dB and a low reflectance of R 0.5. (Or SE_R 3 dB).

Assessment methods

SER assessment method

To establish whether a circuit is capable of shielding, an EMI shielding appraisal is always required, and it consists of SE_R and SE_A values written as follows:

$$SE_R = 10\log\left(\frac{1}{1-R}\right) = 10\log\left(\frac{P_i}{(P_i - P_r)}\right) \quad (13)$$

$$SE_A = 10\log\left(\frac{1-R}{T}\right) = 10\log\left(\frac{P_i - P_r}{P_0}\right) \quad (14)$$

where the SER value is unaffected by the corresponding R coefficient, The critical SER value is shown to be 3 dB when R is 0.5 (the critical value for evaluating the primary shielding system for effective shielding). For EMI shields with effective shielding (SET > 20 dB), the related R-value is lower than 0.5 when SER 3 dB, suggesting low reflection and high absorption. In general, low reflectivity environmentally friendly EMI-shielding materials imply that the shields have a low EM reflection of R 0.5 (or SER 3 dB) under effective EMI shielding of SET > 20 dB.

The R-value methodology is simpler to understand, but both methods can be used to evaluate environmentally acceptable EMI shields with low reflectivity. Because the R-A measurements unambiguously show the power ratio of reflected and absorbed EM waves for the shields, comparing A and R readings supports the predominant shielding mechanism. However, the method of SE_R-value assessment has limitations because it cannot identify the R-A coefficients that are utilized to calculate the SE_R-SE_A values and the dominant shielding system by comparing the SE_R and SE_A values.

R-A assessment methods

The ratio of incident EM power to that which is absorbed and reflected can be calculated intuitively using EMI shields. According to the previously mentioned shielding method, incident transmitted signals that penetrate the EMI shields could be reduced through EM absorption and reflection (caused by a difference in electrical resistance between the material surface and the air) (produced from the dielectric loss, magnetic loss, and multiple reflections). According to Eqs. (2) and (3), it is straightforward to evaluate the subjugated shielding mechanism by evaluating the A and R coefficients of the EMI shields. This is because these coefficients may be utilized to determine the ratio of incident EM power to absorbed and reflected EM power. If A > R, the majority of incident EM waves were absorbed by the material. On the other hand, an increased R coefficient shows that most incident EM waves were reflected, leading to fewer penetrating waves being absorbed. Consider the phrase that follows as well:

$$A = 1 - R - T \quad (15)$$

$$\text{If}\, T \ll A\&R \approx 1 - R \quad (16)$$

If the T value is sufficiently low, which is always true under effective shielding when the SE value is greater than 20 dB (T < 0.01), the reference of A or R coefficients with the crucial threshold of 0.5 could be used in the assessment approach of conducting polymer nanocellulose fibers nanocomposite EMI shields with low reflectivity.

Mechanisms to mitigate EM reflection of non-woven fabrics

The design and fabrication of EMI shields having excellent characteristics is of paramount importance to research and the industrial sector: this has led to a massive search for approaches and mechanisms aimed at mitigating EM reflection, which is not desirable, especially in military applications. Researchers have reported some approaches of techniques for mitigating EM waves reflection, such as coating [19, 21], electrospinning [50], electroless coating, sandwiching, etc., as depicted in Fig. 7 below: with reference to Table 2, which is obtained as per literature, we found out that the approaches adopted for the processing and/or enhancement of non-woven-based EMI shields performance are thus: needle punching: 27 to 112 dB > coating: 14 to 110 dB > ES: 22 to 100.9 dB > others: 10 to 81 dB > vacuum-assisted filtration: 14 to 75 dB > in situ polymerization: 20 to 67 dB > sandwiching: 20.42 to 63.1 dB. Surprisingly, sandwiching which for other materials have been shown to give extremely high EMI SE, is at the bottom here with respect to non-woven EMI shields. This may be largely due to the high permeableness of the NW shield to EM waves, leading to extremely high multiple internal reflection, which results in reflection loss. Also, where the non-woven is impacted with excellent magnetic and conductive properties, their shielding effect is expected

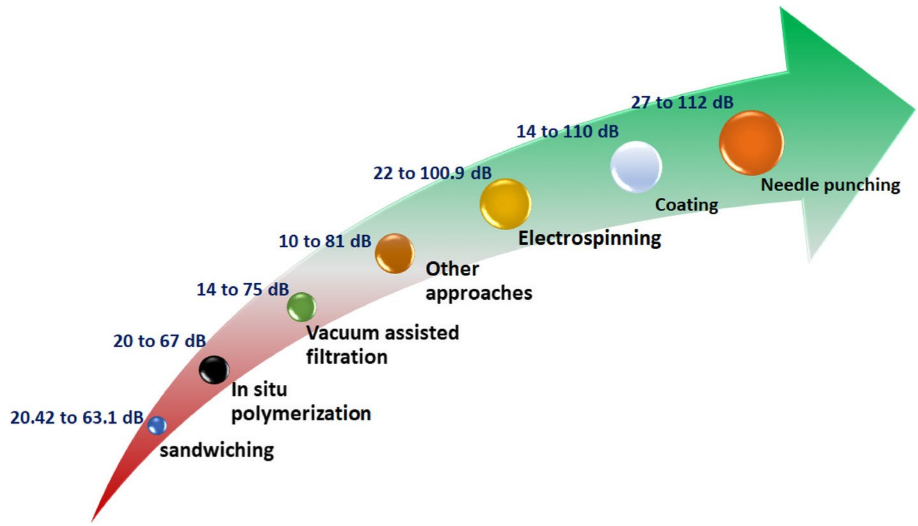

Fig. 7 Novel process adopted for mitigating EM reflection to obtain high SE in non-woven EMI shields

to be even higher. Our findings as per literature are not exhaustive but inclusive with regard to currently available literature. We must remember that researchers must look out for advances in this niche as per their period of work/investigation(s).

With regards to non-woven textile fabric-based EMI shields, researchers have presented interesting findings as presented in Table 2 above. These systems fall within one, or two classes of EMI shielding data for textiles as can be confirmed with the aid of Table 3 [72].

The electrical conductivity and permeability have the biggest impact on the SE_R and SE_A values, according to Eqs. (1) and (2), for a material with constant thickness, and the associated correlations are presented as follows:

$$SE_R \cong \frac{\sigma}{\mu} \tag{17}$$

$$SE_A \cong \sigma \mu \tag{18}$$

wherein contextual SE_R and SE_A improve with increasing electrical conductivity, indicating that electrical conductivity positively impacts both EM reflection and EM absorption. However, increasing permeability would result in a lower SE_R score and a higher SE_A, suggesting that greater magnetism may help to reduce EM reflection while enhancing EM absorption.

In essence, Γ value intuitively reveals the shield's capability to reflect EM waves, and the commensurate equations are as follows:

$$\Gamma = {}^{(Z-Z_0)}/_{(Z+Z_0)} \tag{19}$$

$$\text{For}\Gamma = 0; Z = Z_0 \tag{20}$$

where Z and Z_0 stand for the sample and air impedances, respectively. The electrical resistance related to the sample and the air is identical when $\Gamma = 0$, attaining electrical resistance matching, which is controlled by the associated permeability as well as permittivity. Incident EM waves entirely flow through the material without being reflected [99]:

$$Z = \sqrt{{}^{\mu}/_{\varepsilon}} \tag{21}$$

Equation (21), when combined, yields the following expression:

$$\frac{\mu}{\mu_0} = \frac{\varepsilon}{\varepsilon_0} \tag{22}$$

Both the relative permeability and permittivity of a material must be equal in order for the incident EM waves to penetrate the material for absorption rather than being reflected on the outside. In contrast, a smaller difference between a material's relative permeability and permittivity may lead to a significant improvement in the electrical resistance match between the material surface and the air, resulting in less reflection and more absorptivity.

Coating/electroless deposition

In materials science and surface engineering, coating, more especially electroless deposition, is a flexible and frequently employed technology. Without using an external electrical current, a chemical reaction is used to deposit a thin coating of a metal or other material

Table 2 Techniques utilized by researchers as per literature in mitigating EM wave reflection of NW fabric-based EMI shields

Formulation	Technique adopted to mitigate EM waves	EMI SE (dB)		Reasons for enhanced EMI shielding	Ref
		Before technique adoption	After technique adoption		
Coating					
TPU-CNTs/$Ti_3C_2T_x$	Dip-coating	-	~43	The in-situ coating of the non-woven fabric with CNTs and MXene resulted in enhanced EM wave absorption due to enhanced conductivity, interaction of the EM waves with the high-density free electrons of the fabric, and permeableness	[51]
Cotton@Cu@PDMS	Electroless plating + dip coating	-	110	The introduction of absorption loss (by Cu), interfacial polarization by Cu/CuO heterojunctions as well as fabric permeableness by the porous architecture of the non-woven enhanced EM waves absorption	[52]
Waterborne polyurethane (WPU)@Ag/NWF/FeCo@rGO	Wet electroless deposition	-	77.1	The introduction of magnetic loss (by FeCo), dielectric loss (by FeCo & rGO) as well as enhanced permeableness by the porous architecture of the non-woven enhanced EM waves absorption	[53]
WPU@Ag/NWF	Solution casting-based coating	-	72.5	Enhanced conductivity and multiple internal reflections followed by absorption	[53]
Cotton fibers @Ag	Wet electroless deposition	~0	17 (Ag@CFs-10) & 111 (Ag@CFs-180)	Interfaces abound as well as the structure was permeable: The numerous reflections plus subsequent absorptions in the materials weakened EM waves	[19, 21]
PET@Cu@Ag	Coating + plating	-	61	Due to the coated materials' excellent electrical conductivities, this behavior was linked to a higher reflection of EM waves	[54]
PE@ polydopamine (PDA) (PP/PDA/AgNPs-50/PFDT-50)	In situ polymerization-coating + Ag coating	-	49	Enhanced conductivity and multiple internal reflections followed by absorption	[55]

Table 2 (continued)

Formulation	Technique adopted to mitigate EM waves	EMI SE (dB)		Reasons for enhanced EMI shielding	Ref
		Before technique adoption	After technique adoption		
Cu/Ni@PET (MEFTEX 20)	'Roll on roll' coating	-	70	Increase in the number of layers as well metal coating resulting in reduced aperture area and enhanced EM wave absorption	[56]
PP@Ni/Cu (SNW)	Metallic ion sputtered NW	< 5	> 40	Coating with Ni/Cu	[57]
PET@Cu/Zn/Sn (CNW)	Metallic ion sputtered Nonwoven	< 5	> 50	Coating with Cu/Zn/Sn	[57]
PP/rGO	Dip coating or impregnation	< 2	-15	The coating of the non-woven fabric with rGO resulted in enhanced EM wave absorption due to enhanced permeableness	[58]
Poly(m-phenylene isophthalamide) (PMIA)/Ag@PEDOT:PSS	Dip coating	~ 0	56.6	The coating of the non-woven fabric with Ag@PEDOT resulted in enhanced EM wave absorption due to enhanced permeableness	[59]
PET/PPy (CNT + Ppy NW)	Knife over roller coating	-	14.1	The coating of the non-woven fabric with PPy resulted in enhanced EM wave absorption due to enhanced permeableness	[17]
PAN-based CFs@Cu	Electroplating	-	70–90	The coating of the non-woven fabric with Cu resulted in enhanced EM wave absorption due to enhanced reflection loss within the fabric due to conduction	[60]
PET/ Ni-based alloy(Ni–Fe)	Electroless plating	5%	99.98%	The coating of the non-woven fabric with Ni-based alloy resulted in enhanced EM wave absorption due to enhanced reflection loss within the fabric	[61]
Viscose@Ag	Electroplating	~ 0	91	The coating of the non-woven fabric with Ag resulted in enhanced EM wave absorption due to enhanced internal multiple scattering absorption	[62]
In situ polymerization					
PET@Fe_3O_4/rGO@PANI/Ni–P (1-layer)	In situ polymerization and Ni–P electroless plating	< 3	27	Enhanced dielectric and magnetic loss via Fe_3O_4/rGO@PANI/Ni–P in situ polymerization and plating leading to enhanced EM waves absorption	[63]

Table 2 (continued)

Formulation	Technique adopted to mitigate EM waves	EMI SE (dB)		Reasons for enhanced EMI shielding	Ref
		Before technique adoption	After technique adoption		
PET@Fe_3O_4/rGO@PANI/Ni–P (2-layers)	In situ polymerization and Ni–P electroless plating	< 3	42	Enhanced dielectric and magnetic loss via Fe_3O_4/rGO@PANI/Ni–P in situ polymerization and plating leading to enhanced EM waves absorption	[63]
PET@Fe_3O_4/rGO@PANI/Ni–P (3-layers)	In situ polymerization and Ni–P electroless plating	< 3	81	Enhanced dielectric and magnetic loss via Fe_3O_4/rGO@PANI/Ni–P in situ polymerization and plating leading to enhanced EM waves absorption	[63]
PET (WO-ME150)@PPy	Dip coating-co-in situ polymerization	< -7	-20	Enhanced R_L resulting in increase in absorption of EM waves	[64]
PET/PANI	In situ polymerization com-dip coating	< 3	37	The in situ covering of the PET non-woven fabric surface with PANI lead to absorption of the EM wave within and on the surface of the covered fabric	[65]
PET/PPy	In situ polymerization com-dip coating	< 1	67.08	The in situ covering of the PET non-woven fabric surface with PPy leads to absorption of the EM wave within and on the surface of the covered fabric	[66]
PET@PPy/Ag	In situ polymerization	0	15.5	The in situ covering of the PET non-woven fabric surface with PPy and Ag leads to absorption of the EM wave within and on the surface of the covered fabric due to enhanced dielectric loss and conductivity	[67]
Vacuum assisted filtration					
Non-woven MXene fabric	Vacuum assisted filtration	-	75	The vacuum-assisted coating of the non-woven fabric with MXene resulted in enhanced EM wave absorption due to enhanced permeableness	[68]
MXene/CNFs/silver (MCS)	Vacuum assisted filtration	0	50.7	The vacuum-assisted preparation of the non-woven fabric with surface-covered Ag@MXene resulted in enhanced EM wave absorption due to enhanced permeableness	[69]

Table 2 (continued)

Formulation	Technique adopted to mitigate EM waves	EMI SE (dB)		Reasons for enhanced EMI shielding	Ref
		Before technique adoption	After technique adoption		
MXene/CNF (MC)	Vacuum assisted filtration	0	14.98	The vacuum-assisted preparation of the non-woven fabric with surface-covered MXene resulted in enhanced EM wave absorption due to enhanced permeableness	[69]
$Ti_3C_2T_x$ @GO@SiO_2 NW PP	Vacuum assisted filtration	-	52.8	Increased interlayer spacing of Ti_3C_2Tx and increased porosity of M/DLCNSs HF-10% successfully enabled numerous EM wave reflection losses to boost EMI SE. This outcome demonstrates once more that electrical conductivity alone is unable to consistently improve the EMI SE for 2D materials	[70]
Sandwiching (layer by layer assembly)					
CNF/Nylon@Ni-Cu	Sandwiching (In situ plating + solution casting + sandwiching)	~ 30	63.1	Sandwiching, coating high porosity, and high conductivity of the coatings resulted in absorption-dominated SE due to reflection and conduction loss	[71]
PET@ $Ti_3C_2T_X$	Needle-punched nonwoven fabric + spray drying + superimposition of layers	0.12	Specific shielding effectiveness (SSE) to thickness "SSE_t" (891.94 $dB/cm^2/g$)	Sandwiching, high porosity, soft character as well as high conductivity plus Mxenes' hydrophilicity resulted in absorption-dominated SE	[24]
Cotton@$Ti_3C_2T_X$	Needle punched NW fabric + spray drying + superimposition of layers	0.05	SSE_t (2301.95 $dB/cm^2/g$)	Sandwiching, high porosity, soft character as well as high conductivity plus Mxenes' hydrophilicity resulted in absorption dominated SE	[24]
Calcium alginate (CA)@ $Ti_3C_2T_X$	Needle punched nonwoven fabric + spray drying + superimposition of layers	0.09	SSE_t (1735.72 $dB/cm^2/g$)	Sandwiching, high porosity, soft character as well as high conductivity plus Mxenes' hydrophilicity resulted in absorption dominated SE	[24]
PET/Cu (MEFTEX 30)		< 1	58.92	The enhancement in the mass per unit area via a combination of several layers resulted in better SE due to better EM wave(s) absorption	[72]

Table 2 (continued)

Formulation	Technique adopted to mitigate EM waves	EMI SE (dB)		Reasons for enhanced EMI shielding	Ref
		Before technique adoption	After technique adoption		
CFs/PP/PE (core/sheath) (CEF-NF)	Sandwiching/ lamination	0.48	38.6	Sandwiching, high polarization loss, enhanced ohmic loss due to high conductivity of CFs resulting in absorption dominated SE	[73]
Poly (2-hydroxyethyl methacrylate) (PHEMA)-CNTs	Cross-stacking ES	-	20.42	In order to stop wave radiation from invading, layers of cloth are used more CNTs. Even at extremely low CNT loading amounts, the CNT-PHEMA has good EMI shielding properties thanks to its distinctive porous cross-stacking aligned structure (0.17 wt. percent)	[74]
Aramid@Ni/Cu-Fe_3O_4/WPU	Sandwiching (wet-laid protocol) + solution coating	-	34.3	Multiple internal reflections, good impedance matching, good conductivity enhances the shielding process of the aramid NW fabric's having a foam-like structure	[75]
AF@Cu/Fe_3O_4/WPU			35.4	Multiple internal reflections, good impedance matching, good conductivity enhances the shielding process of the aramid nonwoven fabric's having a foam-like structure	[75]
AF@Ni/Fe_3O_4/WPU			39.2	Multiple internal reflections, good impedance matching, good conductivity enhances the shielding process of the aramid NW fabric's having a foam-like structure	[75]
Electrospinning					
Poly(L-lactic acid) (PLLA)/Cu	Electrospinning-in situ reductive metal coating	-	32.85	Through the combination of electrospinning and coating, the material was provided with enhanced permeability and conductivity which lead to enhanced EM wave absorption	[76]
TiO_2/SiO_2@PPy (TSPG-10)	ES + in situ polymerization	< 2	30	Through the combination of electrospinning and in situ polymerization, the material was provided with enhanced permeability and conductivity which lead to enhanced EM wave absorption	[77]

Table 2 (continued)

Formulation	Technique adopted to mitigate EM waves	EMI SE (dB)		Reasons for enhanced EMI shielding	Ref
		Before technique adoption	After technique adoption		
PVA@PANI-AuNPs	ES	-	22.99	Enhanced EM waves absorption was achieved via the incorporation of PANI/AuNP which imparted the system with enhanced conductivity as well as dielectric permittivity	[78]
Nylon@PANI	ES + in situ polymerization	< 2	40	Through the combination of electrospinning and in situ polymerization, the material was provided with enhanced permeability and conductivity which lead to enhanced EM wave absorption	[79]
TaC/Fe_3C/C	ES + pyrolysis	32.5	46.4	Through the combination of electrospinning, carbonization, and inclusion of magnetic NPs, provided the material with enhanced permeability and conductivity which lead to enhanced EM wave absorption	[80]
PAN/$W_{18}O_{49}$@Ag	ES with or without heat treatment	< 20	~ 100.9	Through the combination of electrospinning, heat treatment, and inclusion of conductive/magnetic NPs, was provided the material with enhanced permeability and conductivity which lead to enhanced EM wave absorption	[81]
ZrO_2/CF/epoxy (8 layers stacked, 0.72 mm)	ES + carbonization	-7.7	-94	Through the combination of electrospinning, carbonization, and inclusion of magnetic NPs, provided the material with enhanced permeability and conductivity which lead to enhanced EM wave absorption	[82]
PDMS/MWCNTs/Fe_3O_4@TPU	ES + coating	-	85.4	Through the combination of electrospinning, carbonization, and inclusion of magnetic NPs, provided the material with enhanced permeability and conductivity which lead to enhanced EM wave absorption	[83]

Table 2 (continued)

Formulation	Technique adopted to mitigate EM waves	EMI SE (dB)		Reasons for enhanced EMI shielding	Ref
		Before technique adoption	After technique adoption		
r-PET/magnetite@SiO_2	ES + dip-coating	0	22	Through the combination of electrospinning, carbonization, and inclusion of magnetic NPs, provided the material with enhanced permeability and conductivity which lead to enhanced EM wave absorption	[84]
EVA@PDA@Ag	ES + in situ polymerization + electroless coating	0	87	Through the combination of electrospinning, in situ polymerization, and electroless coating of conductive Ag, the material was provided with enhanced permeability and conductivity which lead to enhanced EM wave absorption	[85]
PAN@SiO_2-4 wt.% Ag-12 h	ES + coating	0	80–82	Through the combination of electrospinning and electroless coating of conductive Ag, the material was provided with enhanced permeability and conductivity which lead to enhanced EM wave absorption	[86]
TaC/C	ES + carbonization	24.2	37.7	Through the combination of electrospinning, carbonization, and inclusion of magnetic NPs, provided the material with enhanced permeability and conductivity which lead to enhanced EM wave absorption	[50]
Needle punching					
PP/CFs	Fiber blending and needing punching approach	< 5	42.1	The incorporation of conductive CFs which enhanced the EM wave(s) absorption via its electrical percolation threshold within the shield	[87]
Polyacrylonitrile PAN-based CFs/sheath/core (PET/stainless steel) (80/20, stainless steel/carbon) fabric	Fiber blending and needing punching approach	-	44.7	The smart amalgamation of PAN based CFs with sheath/core (PET/stainless steel) resulted in enhanced EM wave(s) absorption	[88]
PP/Zn-Bi	Magnetron sputtering	-	45	Zn-Bi metallization of PP resulted in enhanced EM waves absorption	[89]

Table 2 (continued)

Formulation	Technique adopted to mitigate EM waves	EMI SE (dB)		Reasons for enhanced EMI shielding	Ref
		Before technique adoption	After technique adoption		
SWNTs/GA-chitosan@PET NW	Spray deposition/coating	7	29	SWCNTs covering of the nonwoven PET resulted in enhanced EM waves absorption via conduction loss	[90]
Cotton@PDA@Ag	In situ polymerization + electroless deposition + polymer coating	-	112	The coating of the non-woven fabric with Ag resulted in enhanced EM wave absorption due to enhanced multiple internal reflection leading to reflection loss and interfacial polarization within the fabric due to conduction	[91]
Stainless steel/PET (core/sheath) bicomponent fibers mat (thrice-needle-punched)	Needle punching	22	27	Needle punching impacted the NW fabric with more porous architecture and therefore enhanced permeableness to EM waves leading to more absorption	[92]
Polysulfonamide (PSA)	Needle punching + coating	-	45.5	Needle punching along with Fe_3O_4 and Ag coating impacted the nonwoven fabric with more porous architecture, magnetic, as well as conductive character and therefore enhanced shielding layer to air impedance matching, and permeableness to EM waves leading to high absorption	[93]
Carbonized acrylic fibers web	Needle punching + carbonization	0	28.29	Needle punching and carbonization impacted the NW fabric with more porous architecture as conductive character leading to enhanced absorption and permeableness to EM waves	[94]
Carbonized acrylic mat	Needle punching + carbonization	27.64 for carbonized system at 800 °C	33.7 for carbonized system at 1000 °C	Needle punching and enhanced carbonization impacted the non-woven fabric with more porous architecture as conductive character leading to enhanced absorption and permeableness to EM waves	[95]

Table 2 (continued)

Formulation	Technique adopted to mitigate EM waves	EMI SE (dB)		Reasons for enhanced EMI shielding	Ref
		Before technique adoption	After technique adoption		
Carbonized Kevlar mat	Needle punching + carbonization	28.85 for carbonized system at 800 °C	39.73 for carbonized system at 1000 °C	Needle punching and enhanced carbonization impacted the NW fabric with more porous architecture as conductive character leading to enhanced absorption and permeableness to EM waves	[95]
Others					
PP/PE (core/sheet) bicomponent fibers / carbon fibers (CFs) (CEF-NF)	Wet papermaking-thermal-bonding with CFs	~ 0	30.29	The incorporation of conductive CFs which enhanced the EM wave(s) absorption via its electrical percolation threshold within the shield	[22]
CFs mat	Catalytically grown non-woven CFs mat	-	52–81	Conductive nature of the CFs as well as its intrinsic ability to absorb EM waves resulted in enhanced absorption of the waves by the fabric	[96]
PVDF/VG (Vapor grown)-CNFs	Melt spinning	-	10		[97]

Table 3 EM SE value classification for fabrics intended for general use as EMI shields

Category/item or EMI shielding parameter	Class I (Professional use) [98]					Class II (General use) [98]
SE (dB)	SE > 60	60 ≥ SE > 50	50 ≥ SE > 40	40 ≥ SE > 30	30 ≥ SE > 20	SE > 30
Categorization	Excellent	Very good	Good	Moderate	Fair	Excellent
EM wave shielding % (%)	ES > 99.9999%	99.9999% ≥ ES > 99.999%	9.999% ≥ ES > 99.99%	99.99% ≥ ES > 99.9%	99.9% ≥ ES > 99.0%	ES > 99.9%
Grade	AAAAA	AAAA	AAA	AA	A	AAAAA

onto the surface of a substrate. Chemical deposition or autocatalytic deposition are other names for electroless deposition.

In autocatalytic processes, a substrate's surface catalyzes a chemical reaction that causes the deposition of a desired substance. This is how electroless deposition works. Unlike electroplating, which requires an electrical current, this reaction can happen without the use of an outside power source. The electroless deposition procedure typically entails the following crucial steps:

Surface preparation: The substrate's surface is cleaned and prepared to ensure good adhesion of the deposited material.
Activation: A catalytic layer is often applied to the substrate's surface. Common activation methods include sensitization and activation baths.
Deposition bath: The substrate is immersed in a deposition bath containing a solution with the desired metal ions or other materials to be deposited.
Chemical reaction: Chemical reactions between the substrate's surface and the deposition solution reduce the metal ions, resulting in the formation of a uniform and adherent coating on the substrate.

The electroless deposition has a wide range of applications across various industries, including corrosion protection (coatings can be applied to prevent corrosion of metal substrates), electrical conductivity (it's used to deposit conductive materials onto non-conductive substrates, such as plastics, to create electronic components), wear and abrasion resistance (coatings can enhance the wear resistance of components, extending their lifespan), decorative finishes (in industries like automotive and jewelry, electroless deposition is used for decorative purposes, creating a shiny and durable finish), printed circuit boards (PCBS) (electroless copper deposition is a critical step in PCB manufacturing),

Electroless deposition offers several advantages, including uniform coating thickness, the ability to coat complex and irregularly shaped objects, excellent adhesion, and the ability to deposit a wide range of materials, including metals, alloys, and ceramics.

While electroless deposition is a valuable technique, it also presents challenges, such as controlling the deposition rate, maintaining bath chemistry, and addressing waste disposal concerns.

Electroless deposition is a flexible and frequently used method for depositing thin coatings on various surfaces for various applications, from corrosion prevention to electronics fabrication. It is an important tool in surface engineering and materials research because of its exceptional capacity to deposit materials without external electrical currents.

A facile wet electroless coating/deposition approach has been reported by Tan et al. [21], as depicted in Fig. 8. Their process was thus: The NW cotton fibers (CFs) were washed using water and ethanol with the aid of ultrasonication prior to electroless deposition. To create the nuclei ($Sn.^{2+}$) on the surface of the cleaned CFs, they were submerged in a solution of 0.1 M tin(II) chloride ($SnCl_2$) and 0.1 M hydrochloric acid (HCl) for 10 min. Then, as shown in Fig. 8, the sensitized CFs were immersed in the Tollen's reagent and reducing solution with stirring to produce Ag deposition after being washed with distilled water. The extra NH_3-H_2O was added to a 2.0 wt.% $AgNO_3$ solution while stirring to make the Tollen's reagent. The reducing solution contained 50 mL of deionized water, 0.5 g of sodium hydroxide, 0.7 g of glucose, and 5.0 g of potassium sodium tartrate ($NaKC_4H_4O_{64}H_2O$). Ag particle deposition amount and timing were both regulated. Here, the influence of Ag quantity on the EMI shielding was investigated using depositing times of 10, 20, 30, 40, 60, 120, and 180 s, which were named Ag@CFs-10, Ag@CFs-20, Ag@CFs-30, Ag@CFs-40, Ag@CFs-60, Ag@CFs-120, and Ag@CFs-180 for convenience, respectively [21]. The extra NH_3-H_2O was added to a 2.0 wt.% $AgNO_3$ solution while stirring to make the Tollen's reagent. The reducing solution contained 50 mL of deionized water, 0.5 g of sodium hydroxide, 0.7 g of glucose, and 5.0 g of potassium sodium tartrate ($NaKC_4H_4O_6$ $4H_2O$). Ag particle deposition amount and timing were both regulated. Here, the influence of Ag quantity on the EMI shielding

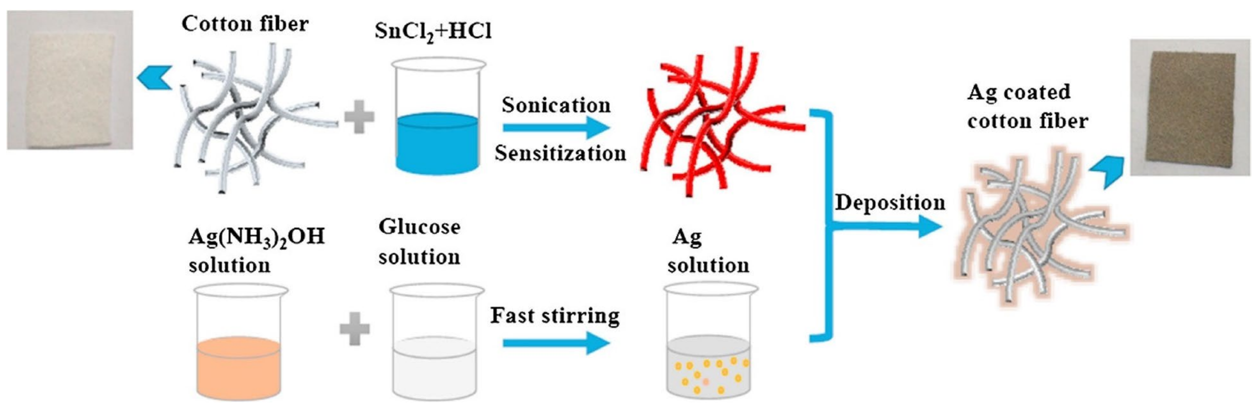

Fig. 8 The schematic diagram of the processing procedures of Ag@CFs non-woven fabrics.

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was investigated using depositing times of 10, 20, 30, 40, 60, 120, and 180 s, which were named Ag@CFs-10, Ag@CFs-20, Ag@CFs-30, Ag@CFs-40, Ag@CFs-60, Ag@CFs-120, and Ag@CFs-180 for convenience, respectively [21]

Figure 9 shows the morphology of pure non-woven CFs and Ag@CFs with various coating times. The individual CFs were discovered to be randomly compacted to create non-woven textiles with porous structures, which is a suitable structure for high-performance EMI shielding via multiple reflections and then absorption attenuation. The surface of CFs was particularly smooth for the pure NW materials (Fig. 9a). The Ag did, however, cause the CFs to become rough. Ag particles were firmly adhered to the CF surface, showing that there was a positive interfacial interaction between the Ag particles and cotton fibers. To learn more about how well the Ag clad layer adheres to the CF substrate, a peel test using tape was performed. After the tape was taken off the surface, it was discovered to have little Ag particles and fiber failure, showing good interfacial interaction between the Ag particles and CFs. The catalyzer (Sn2+), which exhibits a high level of contact with fiber hydroxyls, was likely responsible for the favorable interfacial interaction [21].

Additionally, when the coating period rose, the amount of Ag particles also increased. The Ag particles for the Ag@CFs-10 NW textiles were sparsely adherent to the

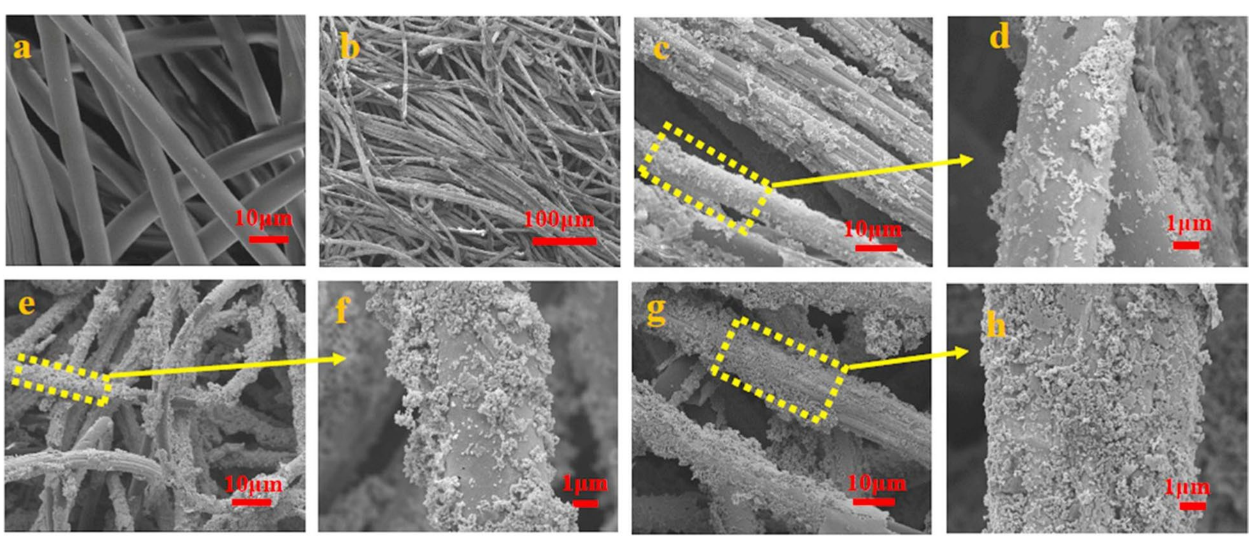

Fig. 9 SEM images for the neat CFs (**a**), Ag@CFs-10 (**b**, **c**, and **d**), Ag@CFs-20 (**e** and **f**), and Ag@CFs-180 (g and h) non-woven fabrics.

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CFs (Fig. 9d), but the Ag@CFs-20 non-woven fabrics had densely adhered Ag particles that came into contact with one another to form conductive channels (Fig. 9f). The surface of cotton fibers in the Ag@CFs-180 non-woven fabrics was entirely covered with Ag particles (Fig. 9h), indicating excellent conductive routes. Furthermore, even for samples with 180 s of deposition time, the porous Ag layer structure that would provide numerous surfaces to reflect microwaves was well produced throughout the Ag deposition technique. These authors revealed in their report, as shown in Fig. 10 that the EMI SE of the pristine NW fabric was found to be approximately zero while the EMI SE of the Ag-coated fabric "Ag@ACFs-10 (thickness of 0.5 mm)" was 99.999993% within the 8.2–12.4 GHz band. This implies that only 0.000007% of the incident EM wave(s) passed through the shield/filter, [21] report signifying the enhancement of EMI SE of non-woven fabric system is the use of ultrafine PET coated with PPy via in situ polymerization [64]. The authors reportedly prepared the shield(s) by immersing the PET fabric(s) into diverse concentrations of ASP solution containing the dopant, followed by immediate exposure of the immersed fabric to pyrrole vapor and finally drying. The prepared shield(s) having 10 layers of the PET@PPy (0.5 mm thick) could successfully absorb 99% of incident EM waves [64]. The approach reported by these researchers, if augmented, can be adopted for the fabrication of high-performance EMI shields with the inclusion of functional conductive and magnetic nanoparticles.

Roll-on-roll coating techniques have also been used to coat Cu/Ni onto ultrathin non-woven PET fabric "MEFTEX 20" leading to an increase in the fabric(s) conductivity and, ultimately, the EMI SE of the shields [56]. The report showed that the coated non-woven fabric sample with single and double layers exhibited an EMI SE of 53 and 73 dB at a frequency of 1.5 GHz. A vital observation was made by these researchers: they found that the area per aperture showed a direct relationship to the EMI SE of the fabricated shields [56].

The adoption of low production cost dip coating or impregnation of rGO onto the surface of PP NW fabric by firstly coating the fabric with GO followed by curing/reduction of GO to rGO at a temperature of 100 °C for 10 h as depicted schematically in Fig. 11 has been reported [58].

The double dip coating approach of PMIA NW fabric(s) has been reportedly reported by Lele et al., as depicted in Fig. 12 [59]. The authors first coated the virgin NW fabric with Ag nanoparticles using dip coating and subsequently dried the coated material. Afterwards, they again coated the Ag-coated fabric with PEDOT: poly(styrenesulfonate) by dipping the fabric into PEDOT:PSS solution, where the blended polymers were dissolved in a binary solvent made of water and DMSO. The coated fabric(s) was then dried and ready for characterization with the inclusion of EMI SE [59]. They fabricated highly flexible hybrid EMI shield having a low electrical conductivity of $0.92 \pm 0.06\ \Omega\ sq^{-1}$,

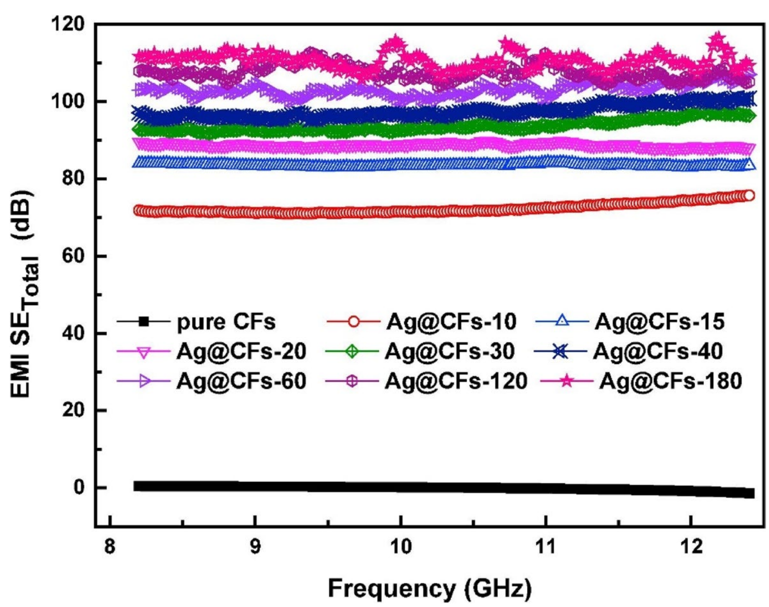

Fig. 10 EMI SE of the Ag@CFs non-woven fabrics with various Ag depositing times as a function of frequency in the range of 8.2–12.4 GHz (X band).

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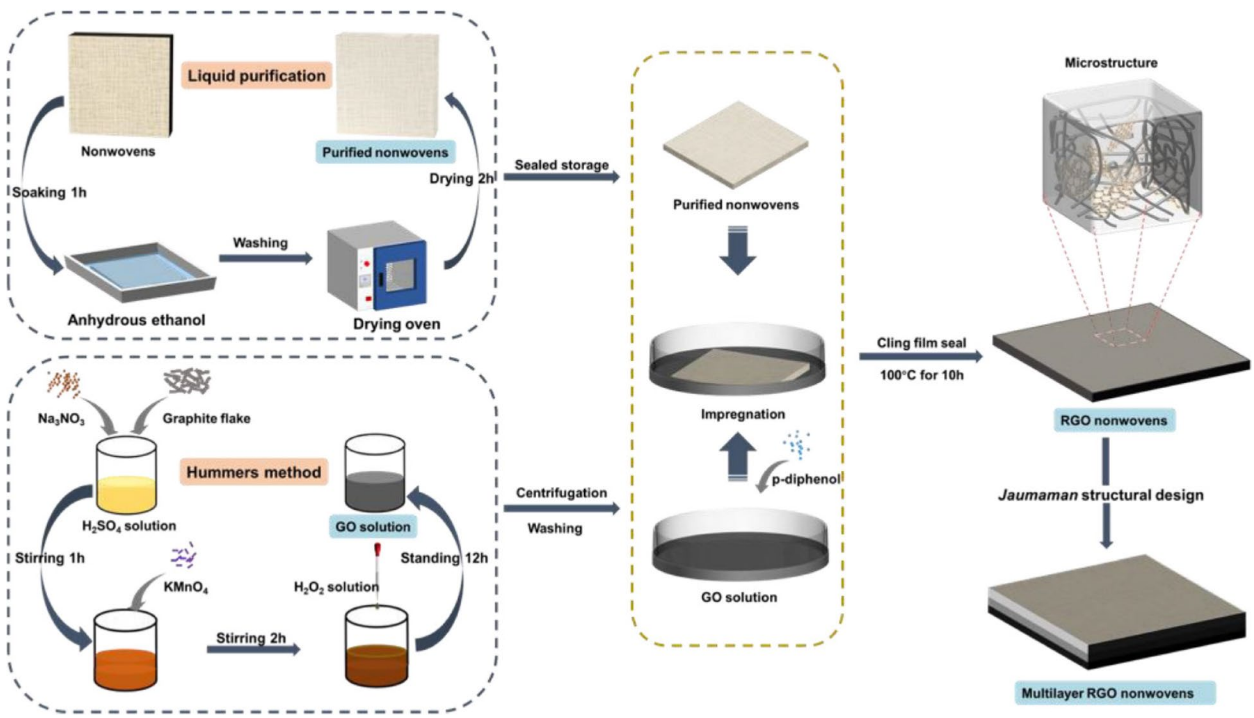

Fig. 11 Preparation process of RGO/NW composite. Reproduced with copyright permission from Song et al. [58], Copyright 2023, MDPI

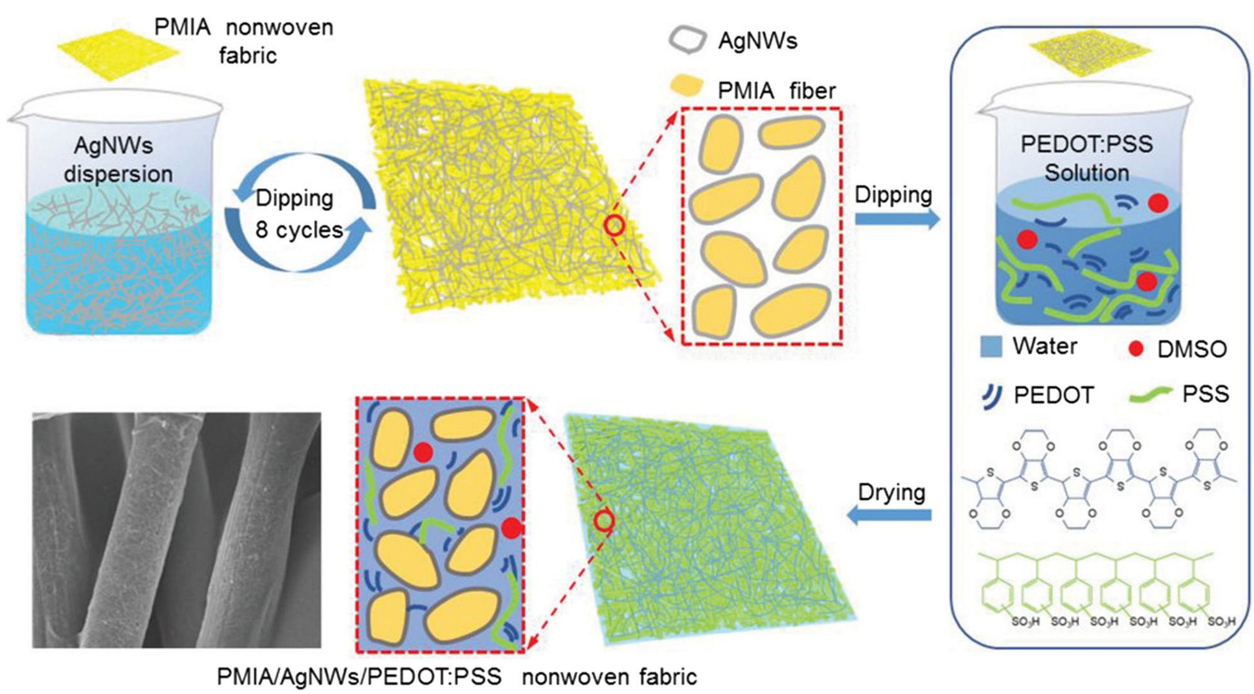

Fig. 12 Schematic illustration of the procedure for preparing PMIA/AgNWs/PEDOT:PSS nonwoven fabric.

Reproduced with permission from Li et al. [59], Copyright 2021, Wiley and presented an EMI SE of 56.6 dB within the X-band with [59].

Electrospinning

Electrospinning is an innovative approach adopted for preparing polymeric NW fabric systems composed of fibers with diameters within μm to nm length scale. The NW fibrous materials prepared by this system possess very high porosity at nm to μm length scale, which is vital to the permeability of shields fabricated from them to EM waves. Upon imparting the polymeric nanofibers produced via these systems with magnetic and conductive properties, their EMI SE is enhanced to a very great extent [9, 76]. In this vein, Chang et al. [76] reportedly prepared a Cu-coated acetone heat-treated PLLA as well as the non-treated NW electrospun nanofibrous membrane. They reported that owing to the ability of the fabric to efficiently absorb EM wave(s) with the presentation of EMI SE of 33.65 dB at a reaction time of 8 h for their sample, named Cu/PLLA-8 h.

The adoption of the electrospinning process for the preparation of highly flexible and efficient EMI shields has been demonstrated by Wei et al. [85], where the researchers first of all prepared EVA electrospun mat followed by dip-coating and finally, electroless coating of Ag as shown in Fig. 13.

The results reveal that EVA has no shielding against EM waves while its hybrid system "EVA@PDA@Ag" presented SE_T value of 86.75 dB (SE_M is ignored; SE_A is 65.74 dB; and SE_R is 21.01 dB) as depicted in Fig. 14a. They also compared their findings with previously reported literature and found that, their electrospun hybrid shield performed better (Fig. 14b): the shielding mechanism of the hybrid shield was said to be dominated by absorption (Fig. 14c) due to the excellent permeableness as well as conductivity of the fabric.

Another instance where ES has been utilized for the preparation of a high-performance EMI shield is in work reported by Li et al. [86]: the authors firstly prepared, and electrospun PAN@SiO_2 mat trailed by in situ electroless Ag coating and finally perfluorodecanethiol (PFDT) to provide the system with hydrophobic properties as depicted in Fig. 15. The fabricated hybrid/nanocomposite reported by these researchers presented an outstanding

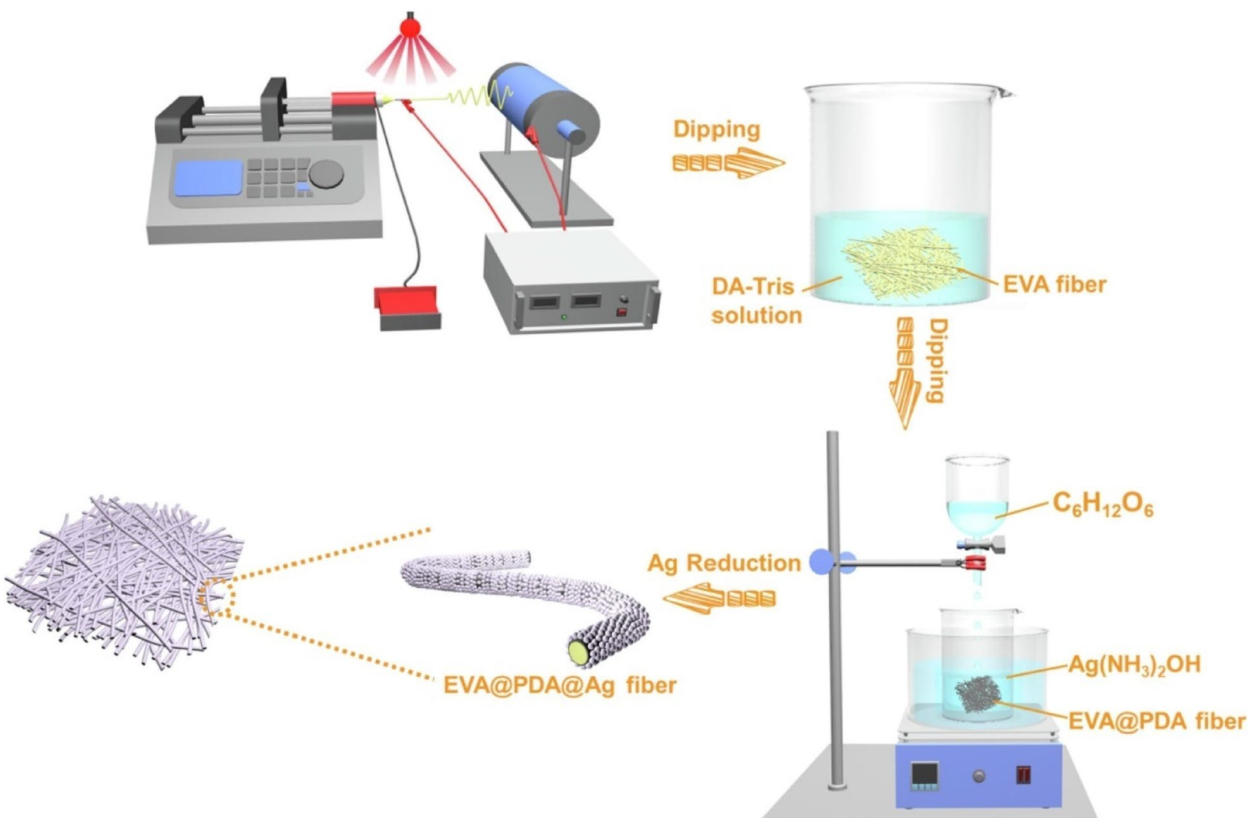

Fig. 13 Schematic demonstration for the preparation of EVA@PDA@Ag fibrous composite.

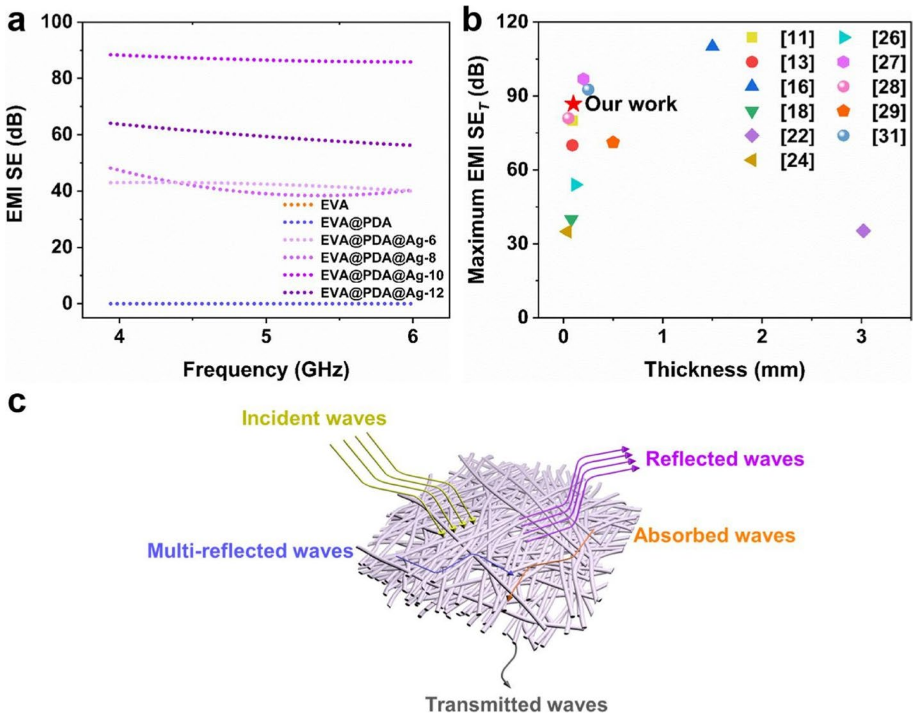

Fig. 14 (**a**) Total EMI SE of EVA fiber membrane and its composites in C band. **b** Comparison of EMI SE$_T$ for our work with polymer fiber-based composites having different thickness. **c** EMI shielding mechanism of EVA@PDA@Ag-10–40 °C fibrous composite.

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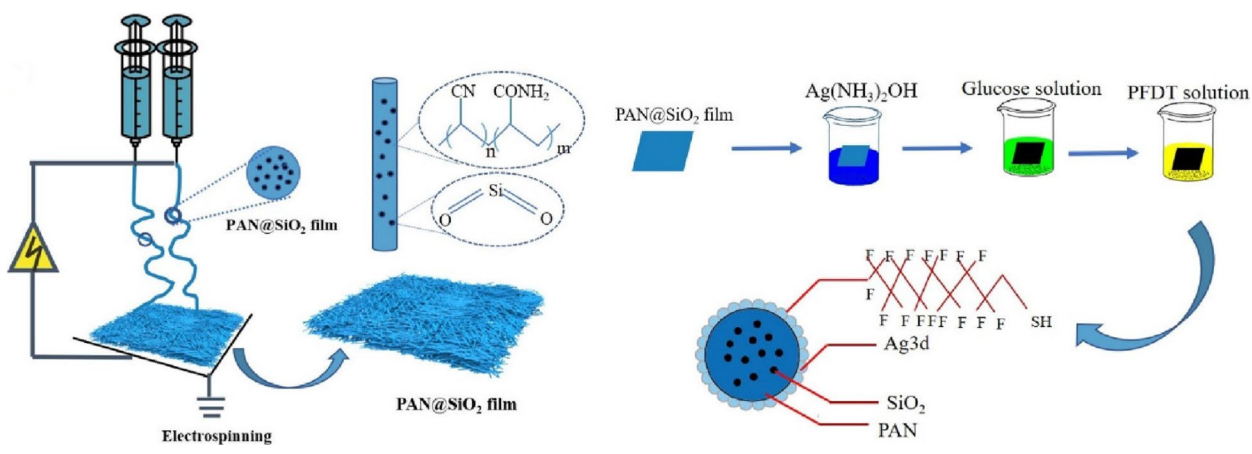

Fig. 15 Schematic illustration for preparation of the PAN@SiO2-4 wt%Ag–X-PFDT composite film.

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EMI SE of 80–82 dB due to multiple internal reflections, reflection loss, and absorption of the EM waves by the highly conductive fabric [86].

According to a report by Guo et al. [50], the electrospinning process was adopted as a preparation to fabricate TaC/C NW fabrics as depicted in Fig. 16. The electrospinning solution was made as follows: A specific amount of PAN powder was mixed with DMF, followed by the addition of $TaCl_5$ powder with varying contents (the mass fraction of $TaCl_5$ and PAN was 0.1, 0.2, 0.4, and 0.6), to a solution of PAN that was 12 weight percent, and magnetic stirring was performed for 12 h at room

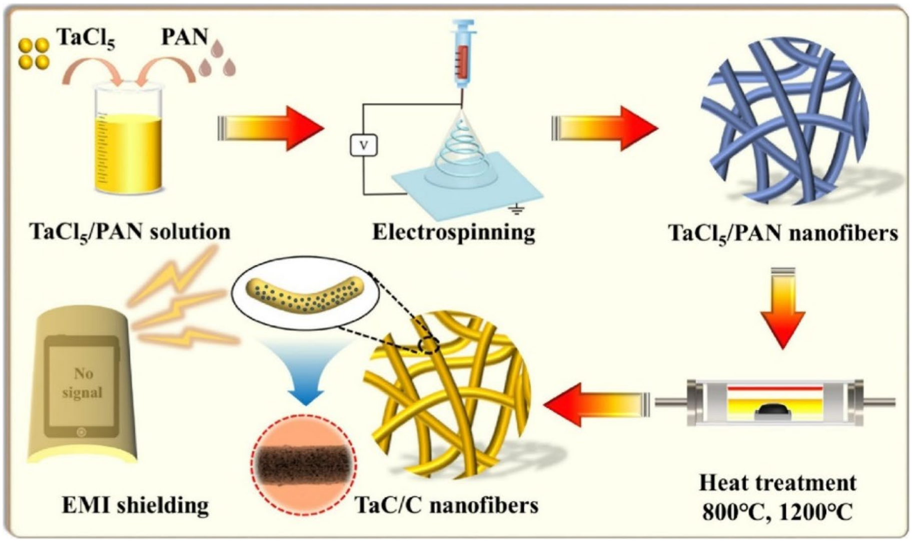

Fig. 16 Schematic illustration of the fabrication process of TaC/C electrospun non-woven fabrics.

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temperature. The PAN used in this work as raw material for electrospinning has an average M_w of 150,000 g/mol. In our pre-electrospinning experiments, we discovered that a PAN concentration of 12 wt.% might achieve a continuous electrospinning process, and the resulting fibers have good quality, uniform shape, and beads-free structure. In their typical ES approach, a stainless-steel needle was used to transfer the combined solution into the syringe (10 ml, inner diameter: 14.48 mm). The voltage source for electrospinning (DW-N303-1ACDFO, Dong Wen High Voltage Co., Ltd., China) was set to 24–25 kV, and the syringe thrust speed was set to 1.5 ml/h. $TaCl_5$/PAN nanofibers were extracted from aluminum foil that had been wrapped around the roller (JDS02, Changsha Nanoapparatus Co., Limited, China; rotational speed: 1500 rpm); the distance between the needle and the collector was 15 cm. It was 25 °C outside, and there was 50% relative humidity plus 5%. The obtained NW materials were put in a vacuum oven at 80 °C for four hours to remove extra solvent. Dry $TaCl_5$/PAN NW fabrics were treated to cure nanofibers at 220 °C in the air with a heating rate of 2 °C min^{-1} for 2 h. The NW fabrics were subsequently carbonized at 800 °C for 1 h and heated to 1200 °C for 1 h. The carbothermal reduction reaction caused the Ta_2O_5 crystal to develop at pyrolysis temperatures of 800 °C and change into crystalline TaC at 1200 °C. These electrospun NW fabrics are created by combining 0 wt.%, 10 wt.%, 20 wt.%, 40 wt.%, and 60 wt.% of the materials. $TaCl_5$ was given the designations of CNF, TCNF-1, TCNF-2, TCNF-3, and TCNF-4, accordingly [50].

The utilization of the ES technique has been proven over and over again as an effective way to fabricate advanced high-performance EMI shields: the exciting thing about this approach is that it is scalable for commercial application.

Sandwiching/lamination

Sandwiching is an excellent technique that has reportedly been proven to enhance the EMI shielding performance of fabricated EMI filters [24].

In the report by Zhang et al. [24], the authors presented a novel approach where NW fabrics made of cotton, polyester, and sodium alginate were first coated with MXene ($Ti_3C_2T_X$) on both sides via a spray drying technique followed by superimposition of the sprayed fabrics. As per their approach, the needle-punched NW fabrics were coated with 2 mg/ml Mxene solution on either face of the fabrics until a 20% increment in the sprayed fabric weight was obtained. The Fabrics were then superimposed via a layer-by-layer assembly approach to get multilayered EMI filer fabrics made of cotton/Mxene, polyester/Mxene, as well as CA/Mxene having 2, 3, and 4 layers, respectively [24]. These authors reported that the SE of the pristine fabrics having no coating was found to be 0.05, 0.12, but also 0.09 dB for cotton, PET, and CA, respectively; though upon coating plus sandwiching, the electrical conductivities of cotton-coated Mxene PET coated Mxene, and CA coated Mxene rose from 5.04 S/m, 1.41 S/m and 9.32 S/m to 13.24 S/m, 1.66 S/m and 13.44 S/M correspondingly [24]. With the enhancement in the EC of the systems, the $SE_{T,}$ which is closely correlated to it, was enhanced, though also followed by the absorption of the EM waves, seeing their obtained EC values were not high enough. The SE of the spray-coated systems were reportedly enhanced with increasing layers (from 2 to 4) [24]. In their report, cotton-coated Mxene showed the highest SSE_t ($SSE_t = 2301.95$ dB/cm/g) owing to its small cross-section, lightweight, as well as medium SE, which was seconded by CA-coated Mxene ($SSE_t = 1735.72$ dB/cm/g) and lastly PET coated Mxene filters ($SSE_t = 891.94$ dB/cm/g).

In another study, a group of researchers have established that a practical textile-based NW EMI shield composed of cotton fibers coated with graphene stabilized chitosan could be fabricated via self-assembly using a layer-by-layer approach [6]. Their fabricated system, having ten layers, presented an outstanding EC of 1.67×10^3 S m^{-1} and showed an EMI SE of 30.04 dB along with outstanding heating character even upon the subjection of the fabric system to several cycles of washing.

An increase in the number of layers in non-woven-based textile EMI shield have been proven to result in a concurrent improvement in the EM wave(s) absorption capacity. This concept has been validated by several studies [24, 72]. However, an interesting report in this regard is the study carried out by Hu et al. [72], where the authors reportedly found out that the EMI SE of Cu-coated PET non-woven fabric shields could be enhanced by increasing the number of layers even up to 4-layer but with the addition of the fifth layer, no significant improvement was observed when compared to the sample having 4-layers as presented in Fig. 17 below.

Thus, by increasing the number of layers of NW -based textile EMI shield, researchers have proven that a concurrent improvement in the EM wave(s) absorption capacity

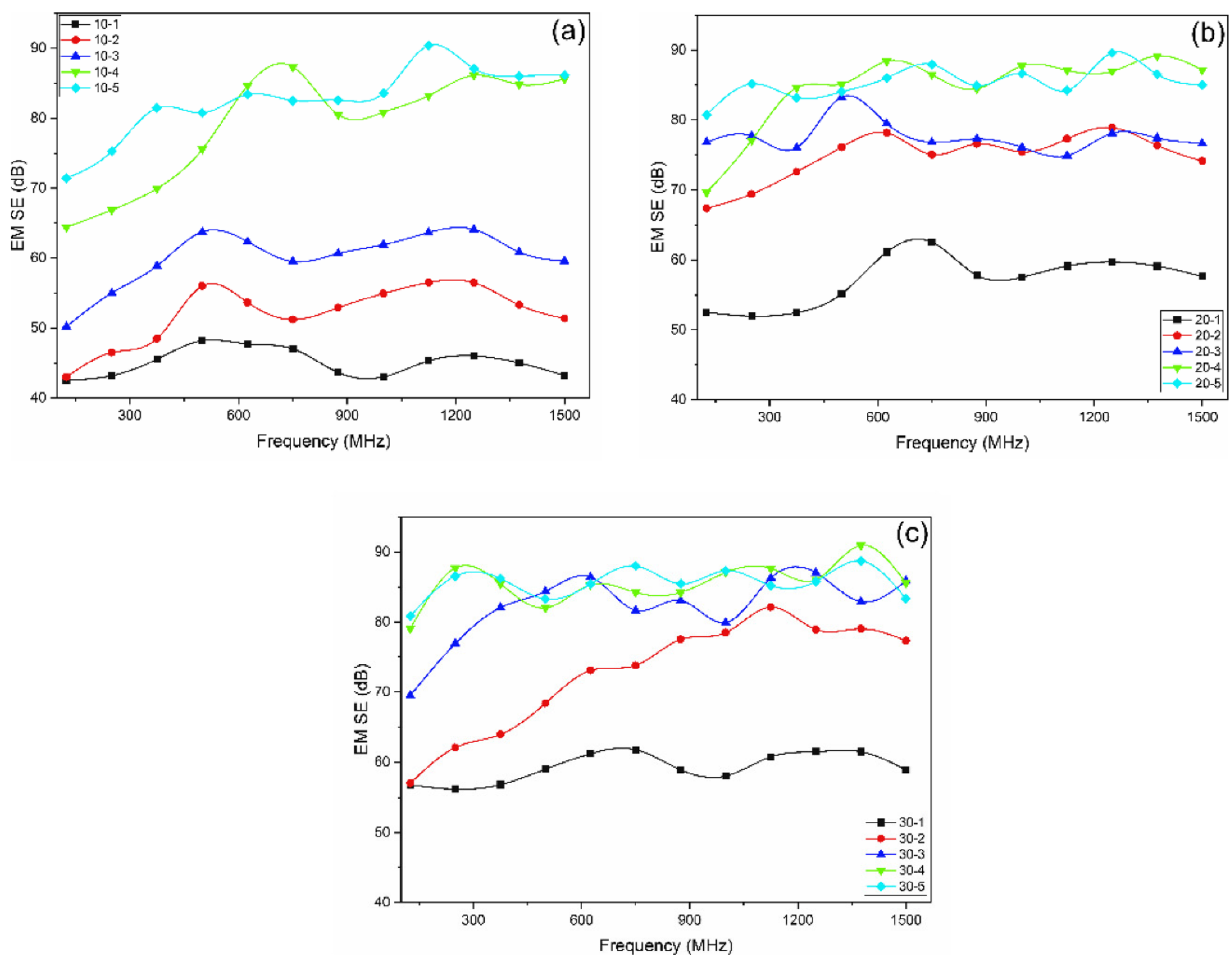

Fig. 17 EMI shielding effectiveness (EMSE) of increasing layers for MEFTEX. **a** MEFTEX 10 (**b**) MEFTEX 20 (**c**) MEFTEX 30.

Reproduced with permission from Hu et al. [72], Copyright 2021, MDPI is obtainable: this concept can be adopted even in other material systems to improve their SE.

Vacuum-assisted filtration/deposition (VAF/D)

Techniques like vacuum deposition use a vacuum filtration method to target the deposition onto the substrate, where the force exerted by the focus material sediment on the support material is used to produce the deposition. A conductive layer is repeatedly deposited on the NW fabric surface using vacuum deposition to provide an effective shielding cover that can block extraneous EM waves inside the shield. By adjusting the vacuum pressure or operation time in this method, it is feasible to control both the quantity and further propagation of the working media into microporous material. Of course, in practice, the concentration of the mixture and the material's permeability are the only drawbacks. NW materials offer an advantage over solid systems in that the working medium is more closely linked with the material when it is filtered into the pores instead of accumulating on the surface. In the end, improving the vacuum deposition procedure is not difficult.

A good instance where VAF/D has been used is in the report by Xin et al. [69], where the authors synthesized an ecofriendly MXene/Ag (nanosilver)@CNFs (cellulose nanofibers) and MXene/CNFs using VAD/F. The VAF/D preparation of the NW fabric with the surface covered with Ag@MXene resulted in enhanced EM wave absorption (with a SE of 50.7 dB from 0 dB) due to enhanced permeableness and conductivity of the final fabric. On the other hand, the VAF/D preparation of the NW fabric with the surface covered with MXene alone resulted in enhanced EM wave absorption (with a SE of 14.98 dB from 0 dB) due to enhanced permeableness and conductivity [69].

Another report by Li and his colleagues [70] on $Ti_3C_2T_x$@GO@SiO_2/PP where the novel preparation approach resulted in increased interlayer spacing of $Ti_3C_2T_x$ and increased porosity of M/DLCNSs HF-10% successfully enabled numerous EM wave reflection losses to boost EMI SE. Their outcome demonstrated once more that electrical conductivity alone is unable to consistently improve the EMI SE for 2D materials [70]: an astonishing EMI SE of 52.8 dB was obtained even via a facile VAF/D.

In a particular instance, NW MXene fabric prepared via the VAF/D resulting in an MXene fabric EMI shield displayed enhanced EM wave absorption due to enhanced permeableness of the fabric and excellent conductivity of MXene [68].

The VAF/D is a very facile approach that can be adopted for diverse NW materials; though used by researchers for the preparation of high-performance NW EMI shields; this process requires too much time, can be only used to fabricate films of limited thickness and area, its scalability is limited, the mechanical properties of the deposit and their influence by control parameters on residual stress molded thin films as well as highly porous membranes are also little understood, it is unclear how the applied pressure of the depositing species affects interfacial contact, nucleation, and deposit formation. More work is therefore required from researchers in this area.

Spray deposition

The spray deposition method is widely used for the deposition of thin-layer metallic layer(s) of functional nanoparticles onto the surface of substrates like traditionally produced NWs and/or electrospun NFs-based NWs, where metal (nano)particles are evenly attached to the exterior portion of the electrospun NFs/substrate. By employing this technique with a change in their EMI SE, a limitless impact on the EM wave shielding performance of NWs sprayed with various NPs has been studied. This research is limited at the time, but curiosity is expanding [24, 90]. A typical illustration of the spray deposition technique, which is adaptable for NW EMI shields preparation, is illustrated in Fig. 18.

The spraying of $Ti_3C_2T_X$ onto the surface of PET NW fabric/laminates with the aim of mitigating EM wave reflection and enhancing its absorption has been shown to yield a system "PET@$Ti_3C_2T_X$" having a specific shielding effectiveness (SSE) to thickness "SSEt" of 891.94 dB/cm^2/g. In contrast, the virgin PET NW materials showed an EMI SE of only 0.12 dB [24]. In the same study, the authors demonstrated that the EMI SE of non-woven cotton fabric as well as CA with $Ti_3C_2T_X$ using the spray deposition approach where they interestingly obtained SSE_t of 2301.95 dB/cm^2/g from SE of 0.05 dB for the cotton coated $Ti_3C_2T_X$ sample (Cotton@$Ti_3C_2T_X$) and SSE_t of 1735.72 dB/cm^2/g (from SE of 0.09 dB for virgin CA) for the CA coated $Ti_3C_2T_X$ samples respectively [24].

In another instance, Zhu et al. [90] Spray deposited SWNTs/GA-chitosan onto the surface of PET NWs (as per Fig. 19), leading to enhanced EM waves absorption in SWNTs/GA-chitosan@PET NW having SE of 29 dB (from 7 dB for the virgin fabric). The high SE obtained for the reported shield was due to the fabric's high conductivity and permeableness to incident EM waves.

NWs EMI shields modified/prepared vis spray deposition technique (which is merged with other coating approaches undercoating technique at broader overview) have reportedly displayed outstanding EMI shielding performance as discussed above. This approach is facile and scalable for commercial applications, making it attractive.

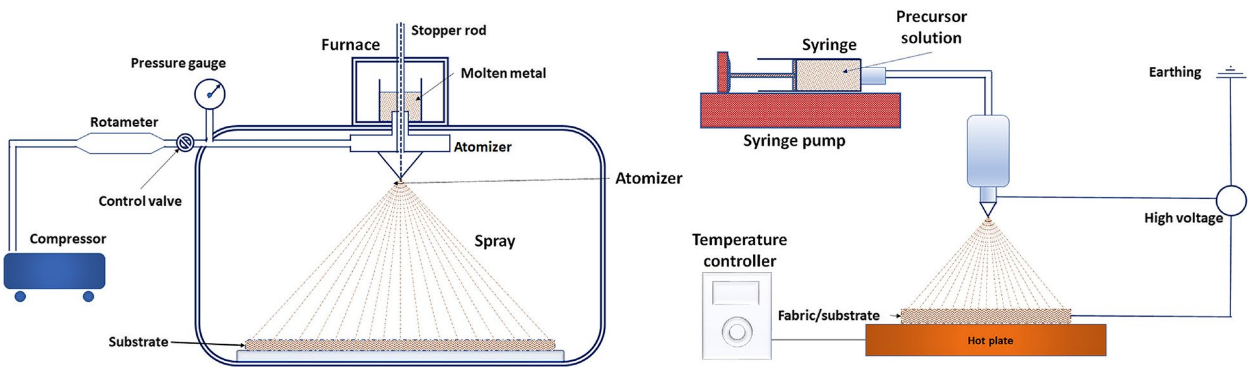

Fig. 18 (**a**) Schematic representation of basic spray deposition technique for the deposition of metallic particles upon a substrate and (**b**) experimental procedure for ESD illustrated schematically.

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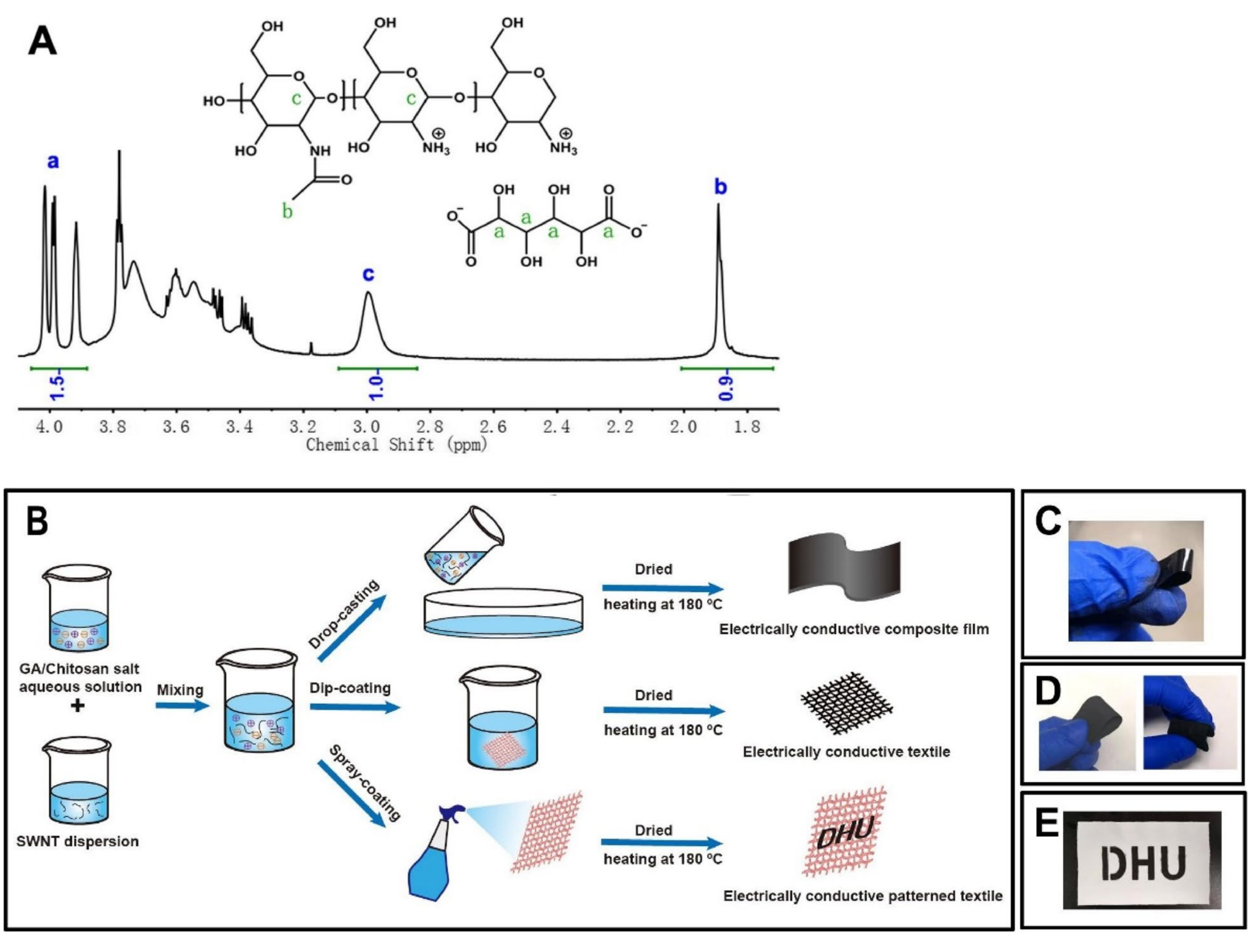

Fig. 19 (**A**) Chemical structure and [1] H NMR spectrum of GA-Chitosan organic salt. **B** Schematic of the procedure for the fabrication of electrically conductive SWNTs/GA-chitosan polymer composite coatings and textiles; **C** electrically conductive polymer composite film fabricated by drop-casting; **D** electrically conductive weaving fabric and non-woven fabric fabricated by dip-coating; **E** weaving fabric with electrically conductive, patterned coating fabricated by spray-coating.

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In situ polymerization

This approach involves the fabrication of NW EMI shields via an in-situ polymerization reaction where the non-woven textile material is covered in situ with another polymerized active polymeric matric with the aim of enhancing its property performance towards EM wave sheltering. In situ polymerization as a way of preparing NW-based EMI fabric shields has been utilized effectively by a handful of researchers [8, 12, 63].

An interesting instance where in situ polymerization has been utilized for the preparation of EMI shields having excellent SE is in the report by Sedighi, Naderi, and Brycki [63], where the authors polymerized PANI onto the surface of NW PET fabric(s) as depicted in Fig. 19. They first deposited Fe_3O_4 on the surface of the non-woven fabric followed by spray deposition of GO which was later reduced to rGO. Again, PANI was then polymerized in situ on the surface of the Fe_3O_4@rGO coated fabric. Finally, Ni–B and NI–P were electroplated onto the Fe_3O_4@rGO@PANI coated fabric(s), clearly illustrated in Fig. 20 [63]. The fabricated PET/Fe_3O_4@rGO@PANI fabric shields the highest EMI SE of 81, 42, and 27 dB for the 3, 2, and 1 layered samples, respectively, which was largely due to the fabric being endowed with multi-interfaces and heterojunctions by the NI–P nanoparticles, magnetic and dielectric loss provided by the Fe_3O_4 nanoparticles as well as enhanced conductivity provided by PANI and rGO [63].

Another example of the use in-situ polymerization for the fabrication/enhanced reflection mitigation of a NW EMI shield is presented in the work by Avloni et al. [65]. The in-situ polymerization of PANI on the surface of PET NW impacted the PET fabric with enhanced conductivity, leading to a very low surface resistivity and enhanced SE of 37 dB. The authors postulated that the EMI shielding mechanism was mainly dominated by multiple internal reflections of the EM waves along with absorption and reflection [65].

Needing punching

Another instance of the fabrication of a NW EMI shield composed is using needle punching directly.

A group of authors have used the needle punching technique for the realization of non-woven EMI shield(s) made of PP/CFs directly via the process of blending the fibers by the adoption of punching technology, which is an industrially applicable approach for non-woven fabrics production [87]. These authors reportedly varied the wt.% of CFs in the PP non-woven mat using 30, 20, and 10 wt.%, respectively. Their report portrayed the EMI shielding mechanism of the mats to be majorly dominated by absorption and reflection, though the shield containing 30 wt.% CFs presented a better EMI SE of 42.1 dB, while the systems containing 20 and 10 wt.% presented SE of 32.2 and 15.6 dB respectively [87]. The approach reported herewith can be easily scaled up for commercial production of these novel systems for advanced EMI shields production for real-life applications.

NW technology is interesting in that it is an industrially proven scalable approach that, if adopted properly, can be utilized to prepare novel advanced EMI shields and/or other high-performance materials applicable to diverse niches.

Others

Some other approaches researchers use to design NW -based EMI shields with high reflection mitigation are limited or rare. One of these approaches is wet papermaking-thermal-bonding, where the authors utilized a NW textile made of PP/PE (core/sheath) bicomponent fibers reinforced with 40 wt.% CFs [22].

In an interesting instance, a group of researchers amalgamated several approaches (Fig. 21) at the fabricated of novel WPU@Ag/FeCo@rGO nanohybrid, resulting in a system with several characteristic advantages which are beneficial for EMI shielding application(s) [53]. In their work, the authors, first of all, plated the NWF with Ag via an electroless plating technique followed by solution casting of WPU onto the Ag-plated non-woven fabric and dried properly. Afterwards, a solution of FeCO@rGO was cast onto the NWF@Ag/WPU fabric to obtain the final composite, named Ag/NWF/FeCo@rGO/WPU [53].

Another instance in this regard is the adoption of a hybrid processing technique by Gao et al. [91], where the authors amalgamated in situ polymerization of DA solution (monomer) on the surface of cotton non-woven fabric to produce Cotton@PDA (PDA@NWCFs) followed by electroless deposition of Ag to realize Cotton@PDA@Ag (AgNPs/PDA@NWCFs) fabric and lastly accompanied by coating of the fabric(s) with PDMS and PI polymers as depicted in Fig. 22. Their fabricated systems, PI/AgNPs/PDA@NWCFs and PDMS/AgNPs/PDA@NWCFs hybrids presented an EMI SE of ~ 112 dB owing to the high conductivity and porous architecture of the shield(s). The authors also revealed that PI and/or PDMS coating on the composite fabric did not affect its EMI SE.

The adoption of other approaches for the fabrication of NW -based EMI shields has also been proven effective but also is an essential avenue towards impacting the designed shields with additional properties not just for NW -based shields but also other structurally designed systems.

Atomized layered deposition (ALD) is an innovative process that is adaptable for enhancing the property performance of NW shields is atomized layered

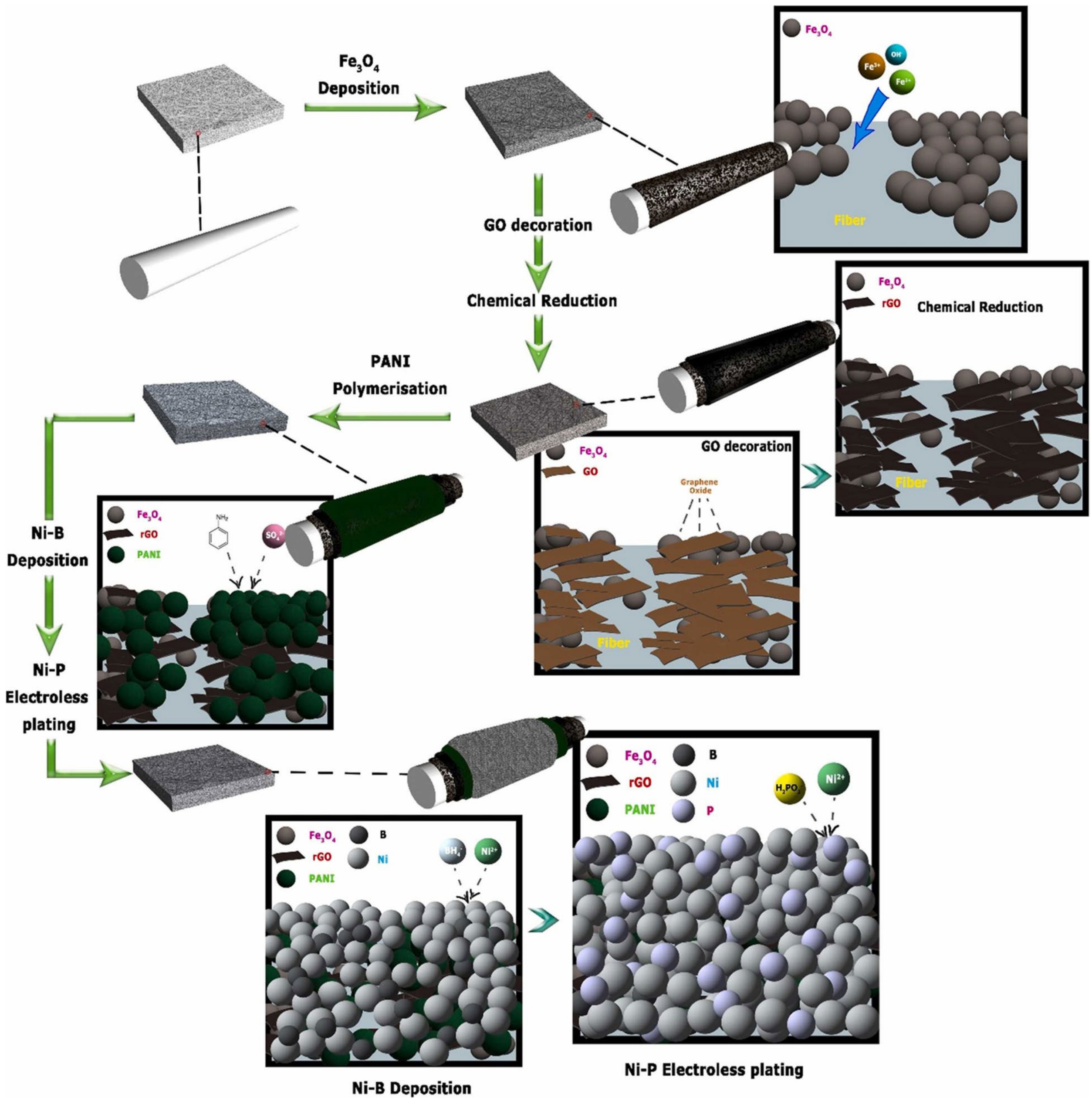

Fig. 20 Schematic illustration of the fabrication of the MrGPN-nonwoven fabric.

Reproduced with permission from Sedighi, Naderi, and Brycki [63], Copyright 2023, Elsevier Science Ltd

deposition. The deposition of functional particles (such as aluminum oxide (Al_2O_3)) upon the surface of virgin NW PET materials via plasma-enhanced atomic layer deposition has been shown to enhance the overall property performance of the NW shields [100].

Fabrication techniques for nonwoven and nonwoven EMI shields

Wetlaid, meltblown, airlaid, drylaid, spunlaid, and in a few rare cases, ES are the NW production techniques that have generally been successfully employed to create

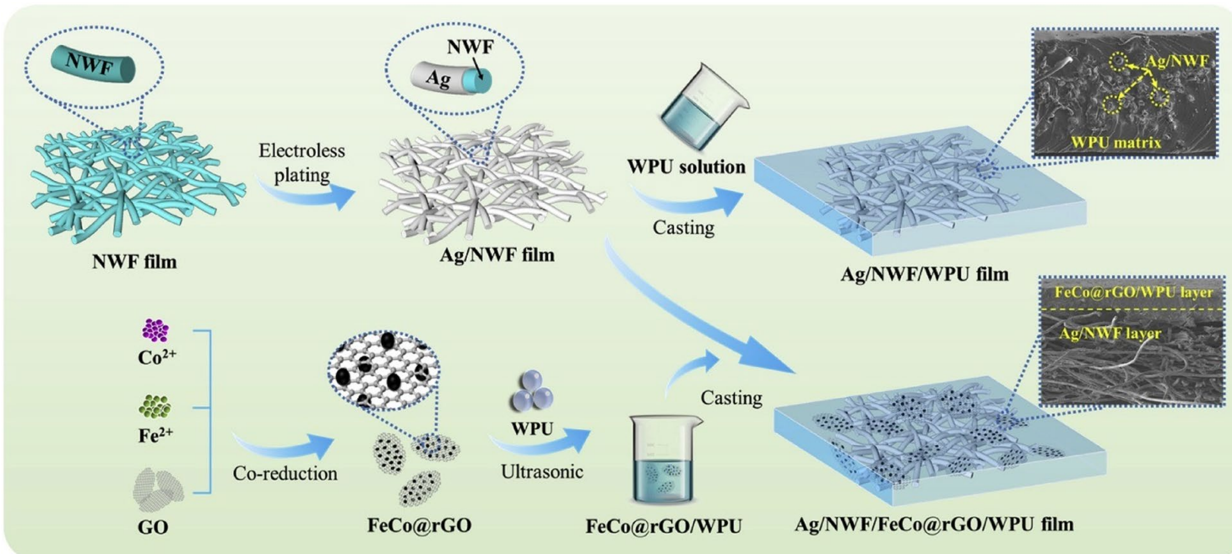

Fig. 21 Schematic illustration for the preparation of WPU composite films.

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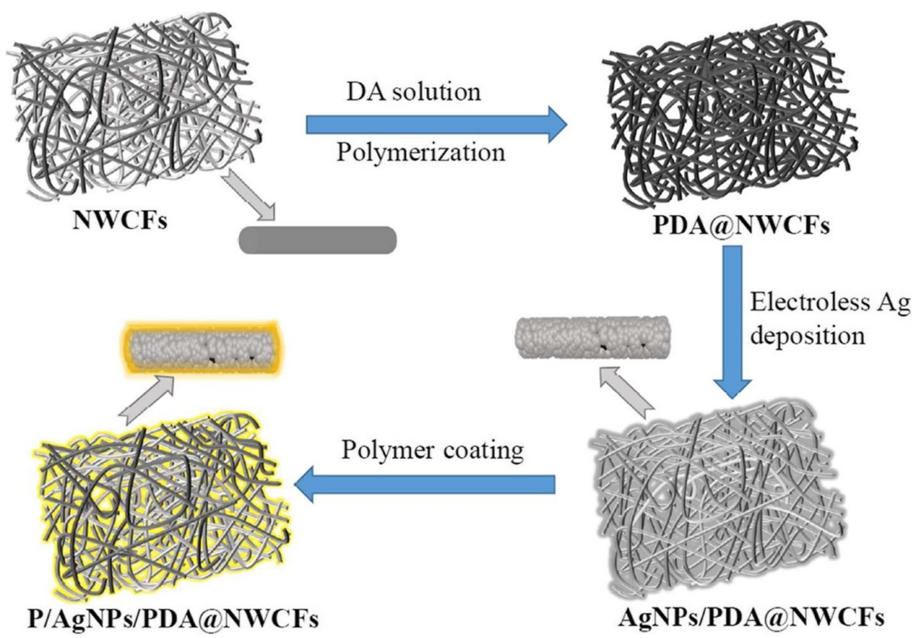

Fig. 22 Schematic of processing procedure for fabricating P/AgNPs/PDA@NWCF composite fabrics.

Reproduced with permission from Gao et al. [91], Copyright 2021, Elsevier Science Ltd

NW webs/fabrics. The fibers of webs are joined together using hydroentanglement, thermal bonding (using calendaring rollers and hot air ovens), needle punching, and stitch bonding. The bond formation and the technologies used for web making directly influence the functional characteristics and price of NW webs/fabrics. Conventionally, the approaches adopted for NWs aimed for EMI shield fabrication towards enhanced shielding performance are in situ polymerization [8, 12, 63], polymer intercalation/film casting [8], melt compounding/

extrusion [4, 12], Electrospinning [9] coating [9], and others, as earlier discussed.

Natural fibers like jute fibers, cellulose-based fibers like wood pulp and cotton, synthetic fibers like poly (ethylene terephthalate) (PET), polypropylene (PP), and rayon, and specialty materials like bi-component fibers and nanofibers are the main raw materials used to make NWs fabrics [101]. Due to the inclusion of wood pulp fibers, airlaid NWs are isotropic, lofty, high porosity (95–99%), suitable for ecofriendly EMI shield fabrication, and are more sustainable than their synthetic counterparts. They also have a softer handle, strong resilience, and appropriate tensile strength for wearable electronics materials fabrication. As a result, some makers of NW fabrics choose airlaid-thermal bonded materials over carded-spunlaced ones because they feel softer and have cheaper production costs. Contrarily, the web bonding method known as needle punching involves mechanically aligning and connecting the fibers of a spun-bonded or carded web. Hundreds to thousands of sharp felting needles, made of either natural or synthetic fibers, constantly pass into and out of the web to create mechanical interlocking [102].

Again, Wetlaid and CoForm are two other web-making techniques. Using wet formed NW systems, the wetlaid process is connected to creating the precursor web for entanglement. Then, fibers are deposited on a screen after being distributed in water with a very high dilution [103]. Because of this, wet-forming methods may create uniform, almost completely isotropic sheet structures for hydroentangling. Wetlaid NWs have a wide range of uses: they can be used for many different things, including preforms for composite manufacturing for diverse advanced materials, wet wipes for cleaning, wet wipes for toilets, dental wipes, disinfection wipes, perfumed wipes, and more [103, 104]. The use of fine denier polypropylene spunbond, which has a denier of 1.0 to 1.2, is still on the rise. Beautiful composites can be created with airlaid and spunlace. Bicomponent polypropylene/polyethylene materials are used to create meltblown webs, improving the NWs property performance [105]. For the cover stock of advanced NW materials, spunbond fabric is used alone or in combination with ultra-lightweight meltblown fabric. With a polypropylene core that offers high strength and mechanical stability and a polyethylene sheath that adds softness and makes thermal bonding easier, bicomponent meltblown NWs made of both polypropylene and polyethylene have been developed. Spunbond (SB)/meltblown (MB), also known as SM, and SB/MB/SB, also known as SMS composites, are examples of architectures that are frequently employed [106].

With Kimberly-CoForm Clark's technology, fluffed wood pulp is added to a meltblown stream of polypropylene fibers, resulting in a soft, fairly strong entanglement of the two fibers [105]. Medical supplies and feminine hygiene products both employ these kinds of items.

Thus, we believe that researchers should focus on adopting conventionally industrially acceptable approaches or their modified forms for the fabrication of high-performance NW shields for diverse advanced applications. Most of the approaches that researchers or industrialists have adopted for the fabrication of high-performance NW EMEI shields have been discussed earlier. However, we have discussed the merits and demerits of these approaches for emerging researchers to channel their energy towards the most effective approaches(s), as presented in Table 4 below.

Nonwoven-based EMI shields application

The application of NW EMI shields spans from aerospace, automobile, electrical/electronics, personnel wearable devices [58], EMI shielding gaskets, containers, shielded enclosures, as well as shielding bags; architectural shielding materials, anti-static shields and grounding materials [107]. An industry called "Swift Textile Metalizing LLC" have shown that breathable NW EMI shield produced from NW nylon fabrics coated with Ni-Ag (heavy coat), Ni-Ag (light coat), and Ag alone can be practically applied in real-life situations. The STM NW line's nylon NW fabric coated with Ni-Ag (heavy coat) is reportedly strong and permeable, providing the best shielding. An exceptionally good conductivity and shielding are produced by a heavy-duty, point-bonded nylon foundation with Silver and Nickel coatings [107]. This functional NW fabric is applicable as an EMI shield, thus: EMI/radiofrequency interference (RFI) shielding gaskets; shielded enclosures, containers, and bags; architectural shield; anti-static and grounding materials. Once more, their Ni-Ag (light coat) product is marketed as a lighter-weight substitute for bulky NW fabric that maintains durability, conductivity, and shielding. Silver and Nickel coatings are applied to the point-bonded nylon foundation: this fabric shield is applicable as EMI/RFI shielding gaskets; shielded enclosures, containers, and bags; architectural shield; anti-static and grounding materials. Their point-bonded, lightweight, and robust non-woven nylon fabric is utilized as the foundation. It is coated with Ag. The fabric's better biocompatibility is a result of the absence of nickel. In order to optimize the advantages of silver's special qualities, it also enables the silver coating to be exposed. This shield is applicable mainly in the medical field [107]. The EMI SE of the aforementioned fabrics falls within 75 dB at a frequency of 1 GHz, along with a maximum resistance of 0.1 Ohms/sq.

Looking at the literature, we can deduce that NWs designed and fabricated for EMI shielding are more

Table 4 Merits and demerits of diverse approaches used to fabricate functional NW -based EMI shields

Approach	Merit(s)	Demerit(s)	Ref
Dip-coating	Approach is cheap Several coating layers can be administered It is feasible to prepare many layers of various materials simultaneously	Film surface quality is directly influenced by the annealing temperature, precursor content, as well as any additives or solvents utilized Control of coating thickness is challenging	[9]
Melt extrusion/compounding	Suitable for processing polymeric composite materials Solvent free Scalable No need for processing downstream High outlook Broad application in advanced materials Limited exposure to oxygen within the extrusion channel It is a continuous process	Not suitable for metal–metal composite systems Degradation of some functional reinforcing fillers may occur during processing Raw materials with high flow characteristics are needed Energy consuming	[9]
Electroless deposition	There are no issues with the current network Insulators like glass, ceramics, and polymers could be covered with nanosheets of metals, alloys, as well as compounds It is just a basic deposition tool Compared to other vacuum deposition techniques, this method has a low temperature It is not necessary to create a vacuum environment produces homogeneous, high-quality films cheaper than the standard vacuum deposition, spray pyrolysis technique The least amount of energy is required to produce one unit area of chemically deposited materials, such as CdS film deposition	Byproducts may react as the solution ages, altering the fabrication Owing to contamination or other issues, nontargeted nucleation and failure to nucleate or develop films on specific regions solely with the catalyst surface The process is time-consuming The rate of deposition is not very high obtaining a film thickness greater than 1 m in a single-dip deposition is difficult	[9]
Electrospinning	Works well with polymeric composite systems Excellent approach to fabricate nanofibrous non-woven mats Scalable approach Inexpensive process Bicomponent fibers can be produced using this approach	Not very suitable for metal–metal composites It is expensive for scaled production Needle clogging is a great challenge Low feed rate and production rate Control of fiber size and morphology can be challenging Challenging to process immiscible polymer blends	
3D printing	Works well with polymeric composite systems Excellent approach to fabricate microfibrous non-woven mats Scalable	Not very suitable for metal–metal composites It is expensive for scaled production Not suitable for NF production	
Spray coating/deposition	It is simple to obtain a film that covers a sizable area It can be easily scaled Spray pyrolysis is a less costly alternative to the conventional vacuum deposition technique	Solvent recovery is a challenge Often made to include fibers and whiskers; therefore, the alternatives for matrix alloys are restricted	[9]
Vacuum-assisted filtration-based deposition	Simple to use	Require too much time It can be only used to fabricate films of limited thickness and area Its scalability is limited The mechanical properties of the deposit and their influence by control parameters on residual stress molded thin films as well as highly porous membranes are also little understood It is unclear how the energy of the depositing species affects interfacial contact, nucleation, and deposit formation	[9, 68]

of a hybrid material, potentially advanced materials for other technical applications such as sensors, heating devices, energy storage systems, piezoelectric generators, and so on. Therefore, researchers working on/with NWs engineered as EMI shields should consider the possibility of expanding the scope of application(s) possible for their materials.

Approaches towards enhanced nonwoven EMI shields performance

The enhancement of the EMI shielding performance of EMI filters is the drive of active researchers globally [4, 9, 12, 21]. The approaches reportedly utilized as per literature are the use of active fillers [4, 9], design/fabrication of finer NW materials having high porosity [9], enhancement of skin effect [4, 9], amalgamation of processing approaches [9, 21], structural control of the concerned filters [4], etc.

Present obstacles

Though researchers have made great strides in the niches of polymer-based NW EMI filters, there still exist some challenges. Conventionally, EM waves absorption, reflection, and multiple internal reflections occur within the EMI shield to attenuate the EM radiation. The overall EMI SE, referred to as $SE_{T,}$ is normally considered the summation of the three attenuations [4, 21]. We know that the SE_T value of 30 dB, which signifies attenuation of incident EM wave by 99.9%, is known to be the current commercially acceptable value. The development of highly effective/efficient flexible NW EMI filters via facile and commercially acceptable techniques remains a great challenge, though with the emergence of a novel state-of-the-art NW fabric processing systems; this challenge can be overcome through process amalgamation as we have herewith presented.

Another obstacle in this regard is the development of a transparent high-performance, NW EMI shield that meets the market standard. Additionally, it is challenging to produce durable electronic materials with high-performance EMI shielding and reliable use in all weather conditions. Though careful design and fabrication of high-performance NW EMI shields can overcome this challenge, researchers must look into this.

Also, the control of the structural parameters of NW fabric materials intended for EMI filters is still not or rarely considered by researchers because of available literature: we believe researchers should consider the structural parameters of NW materials as the main point of study towards enhancing their EMI SE property performance.

There still exists the challenge of optimization of the active filler material distribution within the NW individual structure(s), which is of paramount importance, seeing its optimization directly results in the preparation of EMI filters having high EM wave attenuation even with the inclusion of low filler content like in double percolation structures [26], segregated structures [108], as well as sandwiched structures.

The development of NW textile materials for EM wave shielding is hampered by the fact that it combines the fields of textile engineering and EM wave propagation. The main difficulties are listed below:

Effective shielding performance: Achieving high shielding effectiveness across various EM frequencies (from radiofrequency to microwave and beyond) is a significant challenge. Materials must effectively block or absorb EM waves to protect against various radiation sources, such as Wi-Fi, cellular signals, and even potentially harmful radiation like X-rays. Research reports where the fabricated NW-based EMI shield perform effectively against the aforementioned frequencies is still rare or unavailable.

Frequency range: Different applications require shielding against different frequency ranges. Designing NW materials covering a broad spectrum of frequencies while maintaining efficiency at each point is challenging.

Material selection: Identifying and developing suitable materials is crucial. Materials need to be lightweight, flexible, and comfortable to wear or use, which can be a challenge when optimizing their EM shielding properties while retaining their lightweight, flexibility, and comfort to wear or use.

Durability and washability: NW textiles for shielding purposes should be durable enough to withstand wear and tear over time and maintain their shielding properties even after multiple wash cycles. Ensuring that the shielding performance doesn't degrade with time is vital.

Thickness and comfort: Balancing thickness (which often correlates with shielding effectiveness) with user comfort and flexibility is essential. Thicker materials might offer better shielding, but they can be less comfortable and limit the range of applications.

Cost-effectiveness: Developing cost-effective manufacturing processes for these specialized materials can be challenging. For widespread adoption, these materials must be affordable to produce at scale.

Environmental impact: Considering the environmental impact of manufacturing, using, and disposing of these materials is increasingly important. Finding sustainable and eco-friendly solutions is a challenge.

Standards and testing: Establishing standardized testing procedures and metrics for evaluating the shielding performance of NW textiles is crucial for both manufacturers and consumers. This helps ensure that claims about shielding effectiveness are accurate and reliable.

Integration with other textile properties: Often, NW textiles need to combine EM shielding properties with other textile properties such as breathability, moisture-wicking, or flame resistance. Integrating these properties without compromising shielding effectiveness can be challenging.
Customization: Different applications may require tailored solutions. For instance, shielding requirements for medical devices, military equipment, and consumer electronics may vary significantly. Developing customizable materials that can meet specific needs is a challenge.
Regulatory compliance: Meeting regulatory requirements and safety standards is essential, especially for products that come in close contact with the human body or sensitive electronic equipment.
Research and development: Maintaining advancements in EM wave technology and textile materials is an ongoing challenge. Staying at the cutting edge of research and development is necessary to create materials that meet evolving needs.
Consumer acceptance: Convincing consumers of the importance of EM wave shielding and its benefits can be challenging, especially when dealing with intangible threats like EM radiation.

A multidisciplinary strategy combining skills in materials science, textile engineering, EM wave physics, and regulatory compliance is necessary for advancement in NW textile materials for EM wave shielding. By overcoming these obstacles, new materials that provide better safety in a world that is becoming more linked can be created.

Challenges and safety considerations nonwoven textile system as efficient EMI shields

The application of polymer NW textile materials for effective EMI shielding presents both opportunities and challenges in various industries, ranging from aerospace to consumer electronics. While these materials offer promising solutions for mitigating EMI, several challenges and safety considerations must be addressed to ensure their efficacy and reliability.

One of the primary challenges associated with the use of polymer NW textile materials for EMI shielding is achieving optimal shielding effectiveness while maintaining mechanical integrity and flexibility at higher filler content [109]. Polymer NW textiles are typically lightweight and flexible, making them ideal for integration into various electronic devices and components, though optimizing their EMI shielding performance without compromising their mechanical properties can be complex [110]. Balancing factors such as material thickness, conductivity, and surface treatment is essential to achieve the desired level of shielding effectiveness while ensuring the material remains flexible and durable.

Furthermore, the effectiveness of polymer NW textile materials in EMI shielding can be influenced by various factors, including frequency range, material composition, and environmental conditions. Different types of EM radiation require specific shielding approaches, and the performance of NW textiles may vary across different frequency ranges. Additionally, environmental factors such as temperature, humidity, and exposure to chemicals can impact the long-term stability and effectiveness of the shielding material. However, they are lacking in most articles related to NW fabric-based EMI shields. Therefore, comprehensive testing and characterization under relevant operating conditions are crucial to assess the suitability and durability of polymer NW textiles for EMI shielding applications.

Another significant challenge in the application of polymer NW textile materials for EMI shielding is ensuring compatibility with existing manufacturing processes and integration techniques. Industries such as aerospace and automotive require materials that can be easily incorporated into existing production processes without significant modifications or disruptions. Therefore, the development of polymer NW textiles with properties tailored to specific manufacturing methods, such as lamination or molding, is essential for widespread adoption in these industries. Additionally, compatibility with standard joining techniques, such as welding or adhesive bonding, is critical for ensuring seamless integration into electronic devices and systems.

Safety considerations also play a vital role in the application of polymer NW textile materials for EMI shielding, particularly concerning human health and environmental impact [111]. Many traditional EMI shielding materials, such as metal foils and coatings, contain hazardous substances such as heavy metals or volatile organic compounds (VOCs), posing potential risks to workers and end-users. In contrast, polymer NW textiles offer a safer alternative due to their non-toxic nature and reduced environmental footprint. However, the production and disposal of polymer-based materials still require careful consideration to minimize environmental pollution and ensure worker safety. This calls for the adoption of biopolymers for the fabrication of these EMI shields.

Moreover, the thermal properties of polymer NW textiles can affect their suitability for EMI shielding applications, especially in high-temperature environments. Some polymers may exhibit limited heat resistance or thermal stability, which can compromise the integrity of the shielding material under elevated temperatures. Therefore, selecting polymers with appropriate thermal properties and conducting thorough thermal analysis is essential to ensure the reliability and safety of EMI shielding solutions in demanding operating conditions.

Thus, the application of polymer NW textile materials in effective EMI shielding offers numerous benefits, including lightweight, flexibility, and environmental safety. However, several challenges and safety considerations must be addressed to maximize their performance and reliability in real-world applications. By addressing these challenges through advanced material design, thorough testing, and adherence to safety regulations, polymer NW textiles have the potential to revolutionize EMI shielding across various industries, paving the way for enhanced electronic device performance and reliability.

Overall conclusions and future outlook

Conclusion

One area of research and development that shows promise is the advancement of NW textile materials for EMW shielding. NW fabrics are well suited for electromagnetic shielding because of their flexibility, lightweight, and simplicity of incorporation into numerous applications. The invention of novel materials and fabrication methods, such as metallized NWs, conductive coatings, and composite structures, which increase their shielding efficiency, are among the key discoveries in this sector. These developments have made it possible for NW fabrics to be essential in reducing RFI and electromagnetic interference (EMI) in electronic devices, communication networks, and even protective equipment. Overall, there is a lot of promise in the development of NW textiles for electromagnetic wave shielding to meet the rising demand for EMI/RFI protection in our more connected world. Even more effective and adaptable shielding technologies are anticipated to be produced through additional research and development in this field.

We have explicitly discussed the current research status with respect to polymeric non-woven EMI shielding systems as well as their applications. Process-induced approaches towards enhanced EM wave mitigation for advanced shielding NW materials preparation, as per literature, have also been critically discussed. The challenges and future prospects with regard to these materials have been discussed as well with reference to presently available literature. This piece is of vital importance to both industries and researchers working within the niche of EMI shields/filters, as we have discussed not only NW EMI shields and their application areas but also process-induced approaches towards enhanced EM wave mitigation.

Future outlook

NW textile materials in electromagnetic wave shielding. However, please note that developments in this field may have occurred since then, and we recommend checking more recent sources for the latest information. With that said, here are some possible future trends and considerations for this area:

Advanced materials: Researchers will likely continue developing and refining new materials with improved electromagnetic wave shielding properties. This could involve the use of novel nanomaterials, metamaterials, and composites to achieve better shielding effectiveness while maintaining lightweight and flexible characteristics.

Multi-functional fabrics: Future NW textiles for electromagnetic wave shielding may incorporate multiple functionalities. For example, they could combine EM wave shielding with other properties like thermal insulation, moisture-wicking, and antimicrobial capabilities to create versatile materials suitable for various applications.

Wearable technology: With the growing demand for wearable technology and the increasing integration of electronic devices into clothing, NW textiles with EM wave shielding properties will become crucial for protecting users and sensitive electronic components from electromagnetic interference.

5G and beyond: As the deployment of 5G and future generations of wireless communication networks continues, there will be a greater need for effective EM wave shielding materials to mitigate potential health concerns and protect sensitive equipment from interference.

Environmental concerns: Sustainability will likely play a more significant role in developing NW textiles for EM wave shielding. Researchers may focus on creating eco-friendly, recyclable, and energy-efficient materials in production processes.

Standardization: As the field progresses, there may be efforts to establish standardized testing methods and performance criteria for EM wave shielding textiles. This will help ensure that products meet certain quality and effectiveness standards.

Integration with IoT and smart fabrics: The integration of NW textiles with the Internet of Things (IoT) and smart fabric technologies could create new opportunities for EM wave shielding. These textiles may be designed to interact with devices, monitor EM radiation exposure, and provide real-time feedback to users.

Regulatory developments: Governments and regulatory bodies may become more involved in setting guidelines and safety standards for EM wave shielding textiles, particularly in industries like healthcare, aerospace, and telecommunications.

Market growth: The market for EM wave shielding materials is likely to continue growing, driven by increased awareness of the potential health effects of EM radiation and the expanding use of wireless technologies. This growth may attract more investments and innovation in the field.

In conclusion, NW textile materials for electromagnetic wave shielding are anticipated to experience material advances, expanded usefulness, and deeper integration with newer technologies. The demand for efficient EM wave shielding solutions will stay high as our reliance on wireless communication and electronic gadgets grows. This will fuel continued research and development in this area.

Authors' contributions

JO, OR and LTT wrote the draft based on the concept jointly formulated under the supervision of SSR. They also did data analysis. SSR revised, commented and supervised the whole project.

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Availability of data and materials

This is a review article. Therefore, no new data or materials have been developed in this work.

Declarations

Competing interests

The authors declare no competing interests.

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