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Review

Conducting Polymer Nanocomposites for Electromagnetic Interference Shielding—Radical Developments

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Abstract: Electromagnetic interference disturbs the working of electronic devices and affects the surroundings and human health. Consequently, research has led to the development of radiation-protection materials. Inherently conducting polymers have been found to be suitable for electromagnetic interference (EMI) shielding owing to their fine electrical conductivity properties. Moreover, nanoparticle-reinforced conjugated polymers have been used to form efficient nanocomposites for EMI shielding. Nanoparticle addition has further enhanced the radiation protection capability of conducting polymers. This state-of-the-art comprehensive review describes the potential of conducting polymer nanocomposites for EMI shielding. Conducting polymers, such as polyaniline, polypyrrole, and polythiophene, have been widely used to form nanocomposites with carbon, metal, and inorganic nanoparticles. The EMI shielding effectiveness of conducting polymers and nanocomposites has been the focus of researchers. Moreover, the microscopic, mechanical, thermal, magnetic, electrical, dielectric, and permittivity properties of nanocomposites have been explored. Electrically conducting materials achieve high EMI shielding by absorbing and/or dissipating the electromagnetic field. The future of these nanomaterials relies on nanomaterial design, facile processing, and overcoming dispersion and processing challenges in this field.

Keywords: EMI; shielding; conducting polymer; mechanism; nanocomposite; nanocarbon

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1. Introduction

There are several sources of electromagnetic radiation, such as solar radiation, lightning, and human-made devices [1]. The resulting electromagnetic interference (EMI) affects the surroundings, including human beings, the environment, and the working of electronic devices [2]. Consequently, research efforts have focused on the fabrication of shielding materials to prevent the harmful effects of EMI radiation on humans and devices [3,4]. Primarily, metal-based materials are used for EMI shielding [5]. Other traditional materials, such as ceramics-, carbon-, and polymer-based shields, are also utilized [6]. However, metal shields have the disadvantages of high density, high cost, corrosion susceptibility, and formability. Subsequently, EMI shielding materials featuring light weight, mechanical strength, thermal stability, corrosion resistance, and high electron transport, have been developed [7]. In addition to polymers, various nanostructures, such as carbon nanoparticles and inorganic nanoparticles, have been investigated in combination with polymers [8–10]. Nanofiller addition has been found to enhance the electrical, anticorrosion, thermal, and mechanical properties of polymer materials [11]. Moreover, polymer nanocomposites are characterized by a low cost, fine processability, high electromagnetic absorption, permittivity, and dielectric properties. Generally, high electron conductivity enhances the EMI shielding properties of nanocomposites [12]. Therefore, among the polymers, conducting polymer matrices are preferred for EMI shielding. Conducting polymers have been used to form highly conducting and electromagnetic absorption materials [13,14].

This state-of-the-art review describes the fundamentals, design, and properties of EMI shielding materials based on conducting polymer-derived nanocomposites. Here, understanding the EMI shielding mechanism was found to be important for the overall radiation protection performance of nanomaterials. Numerous conducting polymers have been employed to form EMI shielding materials. Correspondingly, carbon nanofillers (graphene, graphene oxide, and carbon nanotubes), and inorganic and metal nanoparticles have been found to be suitable for enhancing the EMI shielding of conducting polymers. Accordingly, this overview presents the current state of the field, encouraging the pursuit of future research on innovative conducting materials for EMI shielding.

2. EMI Shielding

Electronic devices continuously generate an electromagnetic field [15]. The created field not only interacts and interferes with other devices' functioning but also affects the surrounding environment and human health [16]. To overcome electromagnetic field interference, shielding materials with fine electron transportation and magnetic permeability properties have been researched [9]. Conventional electromagnetic shields have a low capability to shield these radiations. Consequently, metal- and polymer-based shielding materials have been utilized for electromagnetic defense [17]. Among the polymers, conducting polymers are successful in radiation protection applications. Relative to conventional metallic or polymeric shields, conducting polymers and the derived nanocomposites have advantageous radiation-shielding performance [18]. Moreover, these nanomaterials feature a light weight, low cost, mechanical robustness, and thermal stability [19]. Electromagnetic shielding features rely on the inherent electron transference of materials [20]. It was observed that the material utilized for EMI shielding needs to be electron-conducting in nature, i.e., it needs to have mobile charge carriers [21]. When incident electromagnetic radiations interact with the mobile charge carriers of the conducting material, charges start flowing. As a result, the charges are redistributed along the conducting material, generating an opposite electromagnetic field [22]. In this way, the material can shield the incoming electromagnetic radiations.

In conducting polymer nanocomposites, electrical conductivity usually depends on nanofiller type, contents, and dispersion in the polymer matrix. For instance, including carbon nanotubes or nanofibers in conducting polymers enhanced the electromagnetic interference shielding interference (EMI SE) effects [23]. The mechanism of the electromagnetic shielding of conducting polymers and their derived nanocomposites has been explored in the literature [24]. The electromagnetic shielding mechanism has been found to be complicated by several reflections and multiple reflections (Figure 1) [25]. Multiple reflections happen when the incoming light falls on a surface, and the reflected radiation is reflected again on another surface. The reflected radiation again strikes back and forth between the reflecting surfaces. Conversely, several reflections may occur when numerous incident radiations fall on the surface and cause several reflecting rays. Conducting materials with finely dispersed nanoparticles offer efficient radiation absorption properties. Additionally, nanocomposites with randomly scattered nanoparticles provide low radiation protection and cause a complex shielding phenomenon due to internal reflections [26–28]. The electromagnetic shielding mechanism generally comprises the absorption or reflection of incident radiations. Thus, appropriately designed polymers or nanomaterials display high EMI shielding performance. To improve the radiation defense of polymers or conducting polymers, various nanoparticles have been reinforced, including carbon nanoparticles [29].

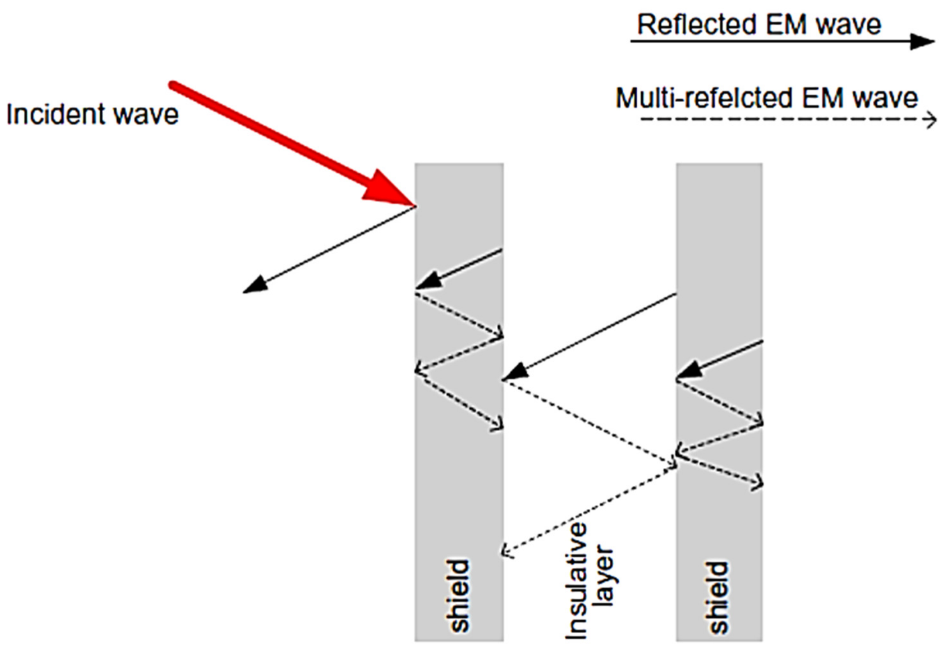

Figure 1. EMI shielding mechanism showing reflections and multiple-reflection phenomenon [30]. Reproduced with permission from Wiley.

Among the carbon nanofillers, graphene, carbon nanotube, carbon black, etc., have frequently been used for EMI shielding [31]. Electromagnetic interference can also be blocked using magnetic nanoparticles [32]. For radiation defense, inorganic- and metal-nanoparticles-based nanofillers provide high electrical conductivity and efficiency [33]. Here, high-performance nanomaterials need to be designed, i.e., fine nanoparticle dispersal and minimal nanofiller aggregation for effective radiation absorption [34]. The shielding mechanism is usually supported by the interconnected network formation of nanoparticles leading to high electrical conduction [35]. Furthermore, shielding materials must possess high thermal, mechanical, and anticorrosion stability for technical purposes [36]. EMI shielding nanomaterials have been effectively applied in industries such as engineering, energy devices, electronics, sensors, biomedical devices, and aerospace and defense [37,38].

3. Conducting Polymers in EMI Shielding

Due to their high electrical conductivity, metal-based shields were initially used for EMI shielding [39]. However, using metal-based materials in industries causes major corrosion problems due to their heavy weight [40]. Therefore, research has shifted toward the development of durable and efficient materials [41–43]. Here, polymers have been applied due to their light-weight, anticorrosion, and radiation-protection properties. A number of thermoplastics and thermosets have been explored for EMI shielding, including polyethylene, polypropylene, polystyrene, phenolics, epoxies, and others [44–47]. Hence, polymers and their derived blends or composites have been utilized for EMI shielding applications.

Conducting polymers have a strong ability to shield incoming electromagnetic waves [48]. Likewise, conducting polymers and their derived materials have been used for EMI shielding [49]. Important conducting polymers have been applied such as polyaniline, polypyrrole, polythiophene, and polythiophene derivatives. Doping process was also found to be essential to improve the electrical conductivity and EMI shielding of conjugated polymers [50]. Bhadra et al. [51] fabricated polyaniline using the oxidative emulsion polymerization method. Polyaniline was blended with a copolymer of ethylene 1-octene. Adding 40% of polyaniline enhanced the EMI SE of the materials. Mäkelä et al. [52] developed camphor sulfonic acid doped polyaniline. The thick 30 μm material sheet had a high electrical conductivity of ~100 Scm^{-1}. Consequently, the shielding effectiveness was >40 dB. The electrical conductivity and EMI SE increased with material thickness. For the improved

EMI shielding of frequencies ranging from low to high values, thicker shields were be more effective. An increased material thickness enhanced both the magnetic conductivity as well as the electric conductivity to provide better radiation protection [53]. Moreover, electrical conductivity was significantly enhanced with increasing thickness. Thick radiation shields basically avoid unwanted effects at lower frequencies (<40 MHz). However, a thin layer of conducting material was found to be enough to shield high frequencies > 40 MHz [54].

He et al. [55] prepared phosphoric-acid-doped polyaniline-based material. The nanocomposite offered a high EMI SE of ~45–60 dB. Kim et al. [56] coated polyethylene terephthalate film using a polyaniline layer. The nanomaterial was efficiently applied as an EMI shield [57,58]. In addition to using neat polyaniline or blends, nanofillers have been filled in a polyaniline matrix to improve the electrical conductivity and EMI shielding characteristics [59,60]. Nanofiller addition was found to produce interfacial interactions and develop a strong interface to create dielectric and polarization effects in EMI shielding materials [61]. In this regard, both carbon and metal/inorganic nanoparticles have been researched [62,63]. For example, graphene was used as effective nanocarbon nanofiller in a polyaniline matrix to increase the electrical conductivity up to 1 Scm^{-1} [64]. It was observed that nanoparticles formed an interconnecting network in a polymer matrix, facilitating electron hopping [65]. Ferrite nanoparticles were effectively used to attain an EMI SE of 42 dB [66]. Here, the high shielding was attributed to the π-electron delocalization effect. Polyaniline was reinforced with silver nanoparticles in combination with carbon black and graphite [67]. A high EMI SE was found, in the range of 20 to 50 dB.

In addition to polyaniline, polypyrrole has been studied as an important conjugated polymer with superior electron conductivity [68]. Gahlout et al. [69] synthesized polypyrrole via in situ polymerization using pyrrole as the monomer and $FeCl_3$ as the oxidant. Figure 2 portrays the EMI shielding mechanism comprising absorption, reflection, and multiple internal reflection losses. Consequently, properties such as shielding effectiveness absorption (S_{EA}), shielding effectiveness reflection (S_{ER}), and shielding effectiveness multiple reflections (S_{EM}) have been studied [70]. The reflection phenomenon usually occurs when light bounces back from a surface. Absorption occurs when light disappears by passing across a surface and converting to another form of energy. S_{ER} is also defined as reflection loss, whereas S_{EA} can be considered absorption loss. The overall shielding of electromagnetic radiation comprises shielding from both reflection loss S_{ER} and absorption loss S_{EA}. Reflection loss S_{EA} occurs due to the impedance disparity between free space and the shield surface and mobile charge interactions with incident electromagnetic radiation. Absorption loss S_{EA} can be defined as the electromagnetic wave attenuation inside the shield due to interactions with the electric or magnetic dipoles. Multiple reflection losses can be observed in nonhomogeneous multilayer shields due to multiple wave scatterings. Total wave shielding S_{ET} is the total of reflection loss S_{ER}, absorption loss S_{EA}, and multiple reflections loss S_{EM}.

Including nanoparticles was found to enhance the shielding effectiveness of polythiophene materials via dispersion and interconnecting network formation [71]. Polythiophene-derived nanomaterials feature a high electrical conductivity of 42 Scm^{-1} and an EMI SE of 126 dB [72]. Polythiophene has also been applied to form EMI shielding materials due to its high electrical conductivity [73,74]. However, it has been relatively less explored compared with polyaniline and polypyrrole matrices. Polythiophene-based nanocomposites have an EMI shielding efficiency of up to ~44 dB and 99% absorption [75]. The EMI shielding efficiency of materials usually increases with increasing content of conducting components for resisting undesired radiation [76]. Moreover, the thickness, permittivity, and permeability of the materials are important factors to enhance EMI shielding defense [77]. Generally, the shielding mechanism depends upon the absorption of incident radiations via electric/magnetic dipole formation [78,79].

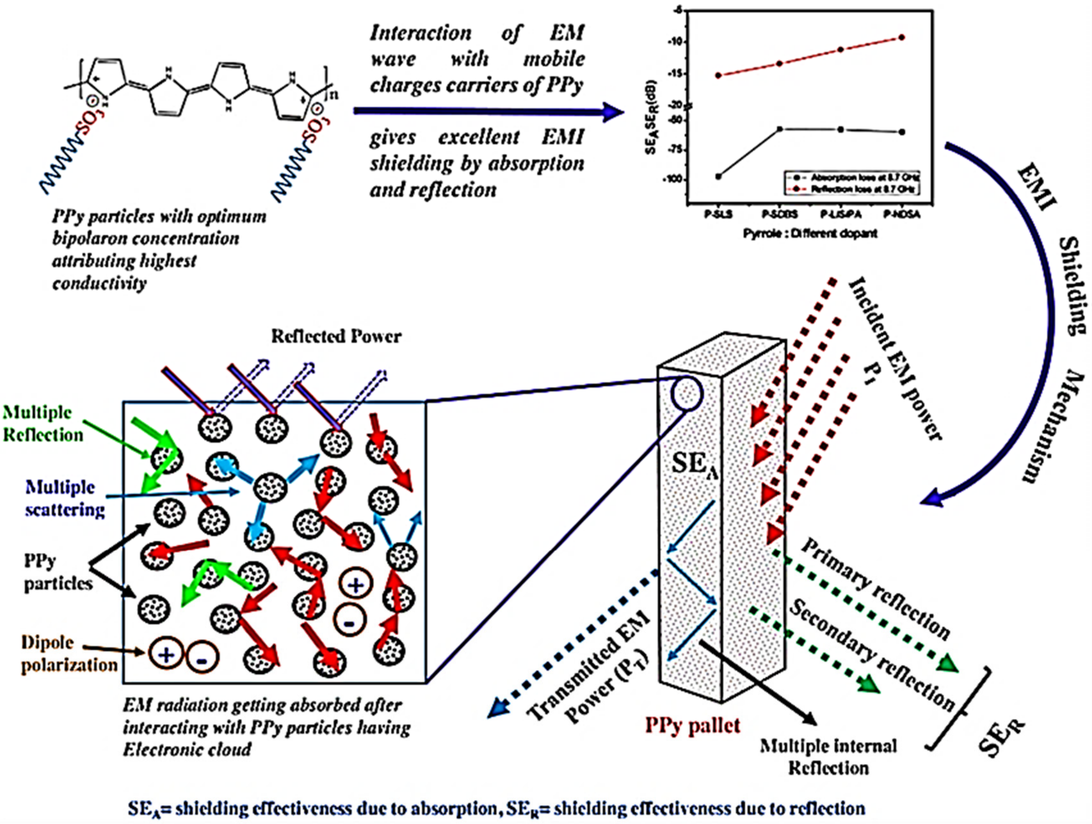

Figure 2. Schematic of mechanism of the electromagnetic interference (EMI) shielding by conducting polymers [69]. PPy = polypyrrole. S_{EA} = shielding effectiveness absorption; S_{ER} = shielding effectiveness reflection. Reproduced with permission from Elsevier.

4. Conducting Polymer Nanocomposites in EMI Shielding

In the literature, researchers have focused on the enhancement in the electrical conductivity of conducting polymers via the inclusion of nanofillers [80]. Consequently, the type of nanofiller, aspect ratio, amount, and dispersion were found influence electron conductivity, dielectric, and EMI shielding features [81]. Carbon nanofillers are important polymer reinforcements [82]. Efficient carbon nanofillers, including graphene, carbon nanotube, nanodiamond, carbon black, and others, have been identified [83–85]. The combination of nanocarbons with conjugated polymers has been studied to enhance the EMI shielding performance and physical properties of nanocomposites [86]. Moreover, inorganic and metal nanoparticles can effectively enhance EMI SE performance [87,88].

Conducting materials are considered wave-reflection materials for EMI shielding due to the presence of conducting electrons. The mobile charge carriers better interact with the incoming electromagnetic radiation in terms of either absorption or reflection. According to research efforts on nanocomposite systems, the nanofiller dispersion in polymers affects electromagnetic shielding [89]. Usually, better-dispersed nanoparticles show increased interaction with incident electromagnetic radiation and develop a connecting network in the matrix to improve electron conduction. However, researchers also found that the formation of a moderate nanoparticle aggregation in the matrix leads to enhanced electrical conductivity and related shielding effectiveness [90]. Nevertheless, bigger nanoparticle aggregates hinder conductive network formation and electron mobility, which decrease the EMI shielding ability.

Among the conducting polymers, polyaniline has been widely applied for EMI shielding [91,92]. The formation of polyaniline nanocomposites further improved radiation defense [93]. Nanocarbon nanofillers show essentially enhanced conductivity and shielding properties in polyaniline-based materials [94]. Consequently, polyaniline was used as a matrix for graphene nanofiller [95]. The resulting nanocomposites presented an EMI SE of 40 dB and superior mechanical properties. Adding up to 3 wt.% graphene was found to be effective for EMI shielding [96]. Yu et al. [97] prepared polyaniline- and graphene-based nanocomposites. High electrical conductivity, corrosion resistance, and EMI shielding were observed with the resulting material [98]. Here, nanofiller aggregation was found to hinder the physical as well as EMI shielding characteristics [99]. Pal et al. [100] also developed polyaniline/graphene nanocomposites. Nanomaterials were prepared by adding 2–8 wt.% nanofiller. Aniline monomer was in situ polymerized in presence of aniline as the monomer, cetyl trimethyl ammonium bromide (CTAB) as the surfactant, and ammonium persulfate (APS) as the oxidant. Figure 3 shows a scheme of the formation of nanocomposites. Figure 4 presents the mechanism of EMI shielding. The mechanism depends on electromagnetic wave attenuation as well as dielectric loss properties. Highly conducting materials achieve enhanced shielding effectiveness via absorption. At the polymer/graphene interface, mobile electrons interact with incident radiation via absorption or reflection. Figure 5a–c show the absorption, reflection, and total shielding effectiveness of nanocomposite materials. The EMI SE of a nanomaterial depends on the nanofiller content and application frequency. Nanofiller addition usually enhances the charge mobility of the system, which enhances the electrical conductivity properties. Neat polyaniline shows a lower absorption shielding effectiveness of ~16 dB. Including 2–8 wt.% nanofiller enhances EMI SE values from ~29 to 49 dB (8.2 GHz). The total shielding effectiveness (combination of absorption and reflection) of neat polyaniline is 15 dB, which can be enhanced to 64 dB with nanofiller loading; however, it decreases to 49 dB with a reduction in thickness from 1 to 2 mm (Figure 5d). A thinner shield provides low EMI shielding due to its lower conductivity and radiation protection efficiency. Figure 5e shows the effect of graphene loading on total shielding effectiveness. Increasing the nanofiller content up to an optimum value is usually important to attain a high EMI SE. At the percolation threshold, high electrical conductivity and EMI shielding can be observed. However, further increasing the nanofiller loading may cause aggregation, which decreases the shielding effectiveness of the nanocomposite. Consequently, shielding effectiveness can be enhanced with nanofiller loading. Polyaniline/graphene nanocomposites have a high electrical conductivity in the range of 11–102 Sm^{-1} and high dielectric losses of $\varepsilon'' \approx 35$–175. A well-dispersed conducting nanofiller is capable of forming an interconnected network that supports the electrical conductivity properties. Moreover, a strong polarization effect can be achieved via the nanofiller dispersion and dielectric constant of the materials. The interaction between polyaniline and graphene leads to strong polarization via the development of localized polaronic and bipolaronic states. Accordingly, the electrical conductivity of the material is enhanced; i.e., it needs to have a long-range hopping mechanism to improve dielectric loss. The dielectric loss is actually the energy loss of radiation upon the interaction with a dielectric material in a varying electric field. The greater dielectric loss of the material, the higher the EMI shielding effectiveness. Consequently, these high shielding materials have been recommended for aerospace and defense applications.

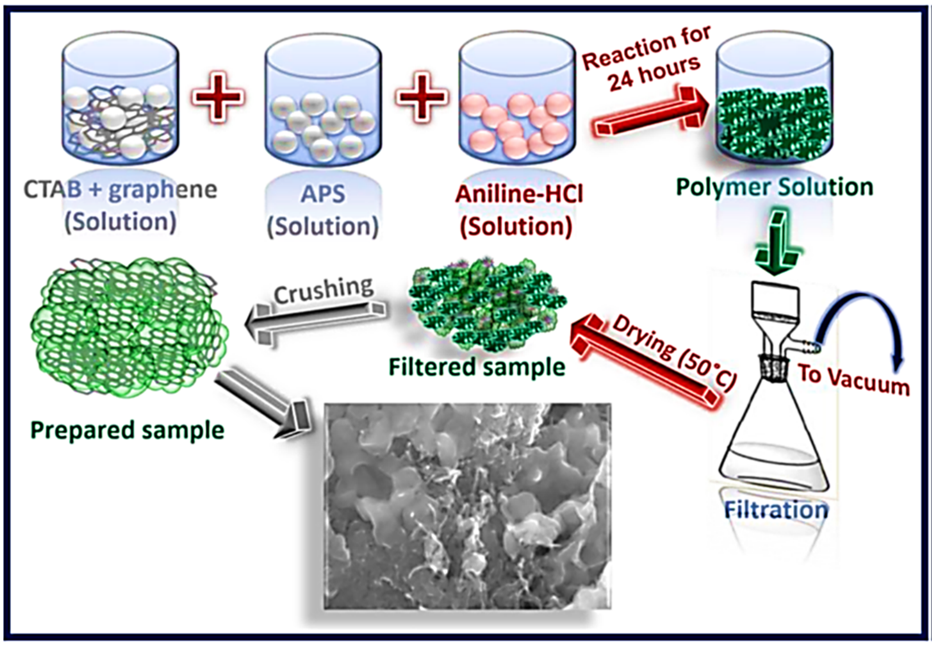

Figure 3. Scheme of facile growth of polyaniline and graphene-based nanocomposites [100]. Reproduced with permission from Elsevier.

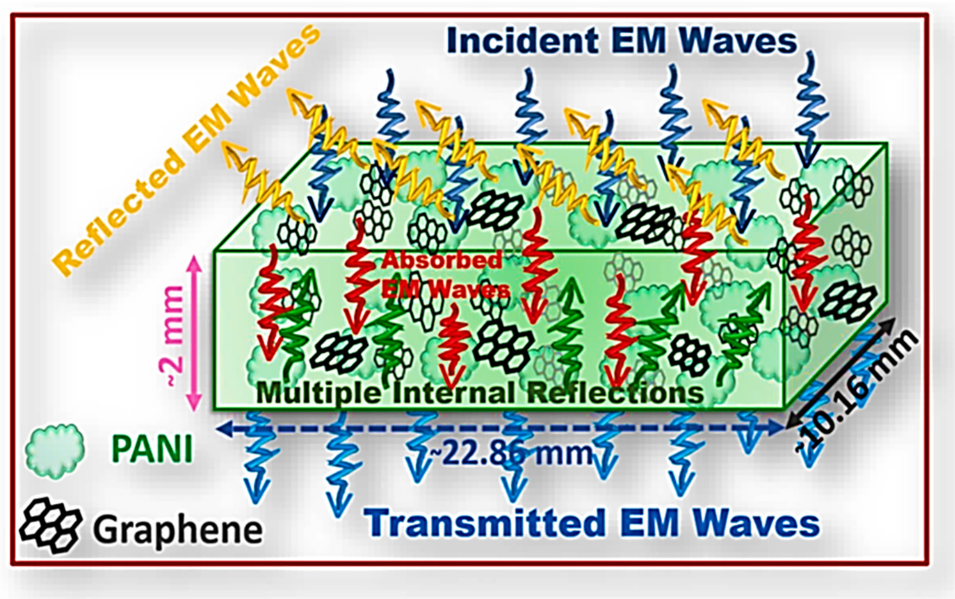

Figure 4. The attenuation mechanism of electromagnetic radiation through reflection, absorption, and multiple internal reflections in polyaniline (PANI)/graphene nanocomposite samples [100]. Reproduced with permission from Elsevier.

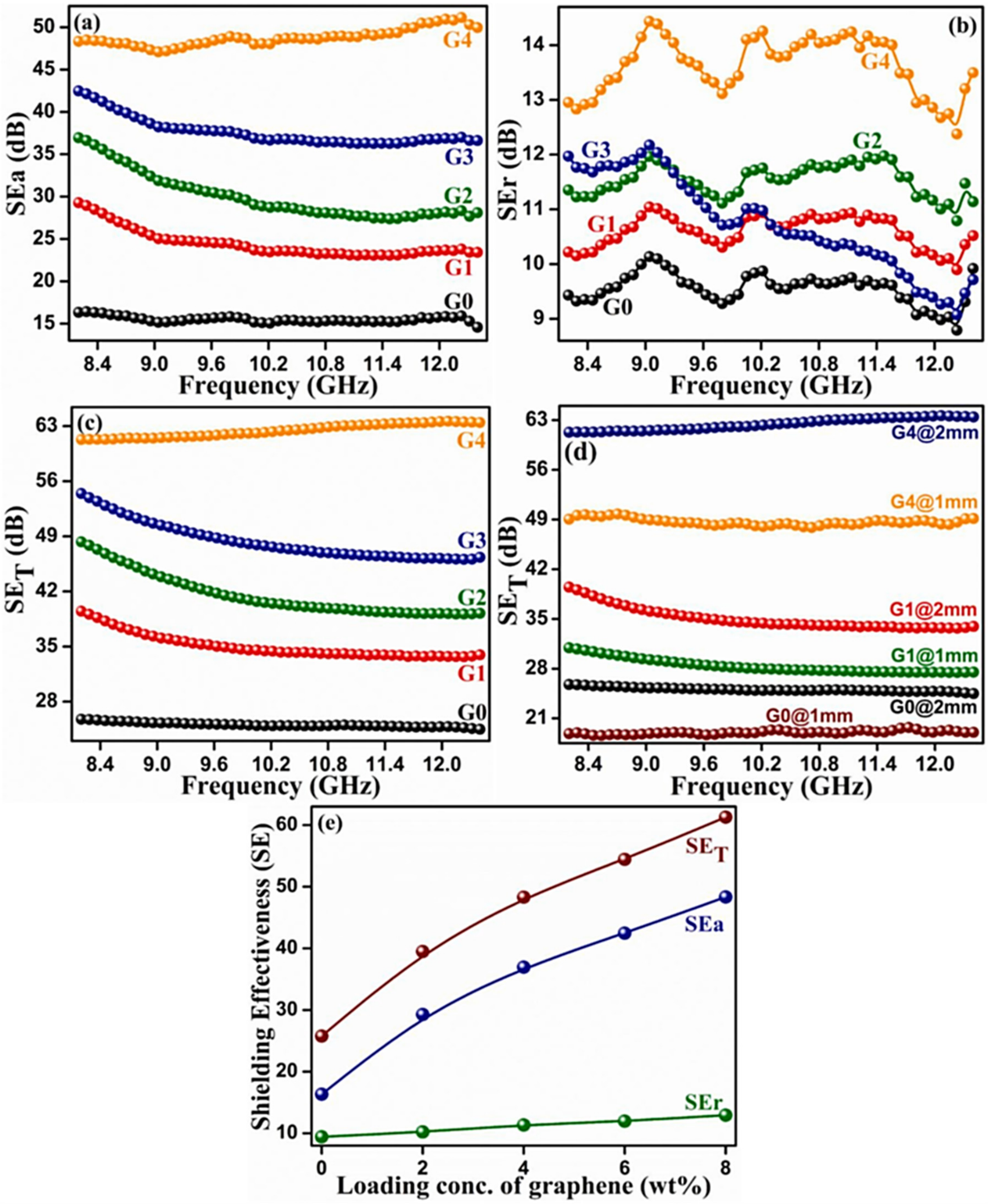

Figure 5. Variation in shielding effectiveness via (**a**) absorption, (**b**) reflection, and (**c**) total shielding effectiveness as a function of frequency; (**d**) total shielding effectiveness at barrier thicknesses of 2 mm and 1 mm as a function of frequency; (**e**) variation in shielding effectiveness as a function of graphene loading concentration in polyaniline [100]. G0 = pristine polyaniline; G1 = polyaniline with 2 wt.% graphene; G2 = polyaniline with 4 wt.% graphene; G3 = polyaniline with 6 wt.% graphene; G4 = polyaniline with 8 wt.% graphene. Reproduced with permission from Elsevier.

Khasim et al. [101] prepared para-toluene sulfonic acid doped polyaniline and graphene-nanoplatelet-derived nanomaterials via in situ polymerization. The polyaniline/graphene nanoplatelet nanocomposite loaded with 10 wt.% nanofiller had a shielding efficiency of >95%. A nanocomposite was prepared with a thickness of ∼1.5 mm. In addition to its strong electrical conductivity properties, the nanocomposite demonstrated fine EMI shielding in the X band. Owing to the π–π stacking interactions of the polyaniline and graphene nanoplatelets, an interconnecting network was developed that supported charge carrier density. The doping of polyaniline with para-toluene sulfonic acid further enhanced electron conduction by many folds. Figure 6 shows the change in electrical conductivity with the variation in frequency. At a high nanofiller content, more graphene galleries are available for compensating for the aniline monomer for in situ polymerization. Therefore, the electrical conductivity of the nanocomposites enhanced with increasing nanofiller loading. Figure 7 shows the effect of the nanofiller on the real and imaginary parts of the dielectric constant of a shielding material. The real part of the complex permittivity increased from 18.4 to 23.2. The imaginary part of the complex permittivity was increased in the range of 14 to 21.8. Figure 8 displays the mechanism behind EMI shielding for the interactions of incident radiation with polyaniline/electromagnetic wave shields. Incident electromagnetic waves in the frequency range of 8–12 GHz fell on a rectangular sample. The reflected, absorbed, transmitted, and internal reflections are presented. All these phenomena contributed to the overall EMI shielding efficiency of the material. The influence of the scattering parameters of electromagnetic reflection and transmission on electromagnetic properties were analyzed.

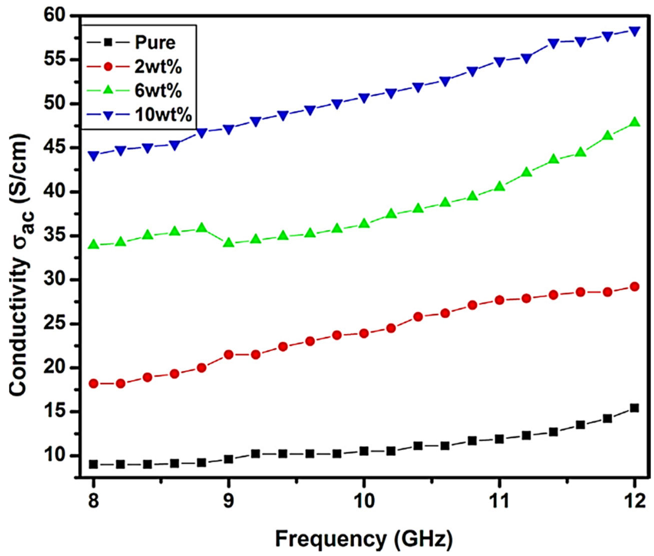

Figure 6. AC conductivity as a function of frequency for pure polyaniline (PANI) and polyaniline/graphene nanoplatelets (PANI-GRNPs) nanocomposites in X band [101]. Reproduced with permission from Elsevier.

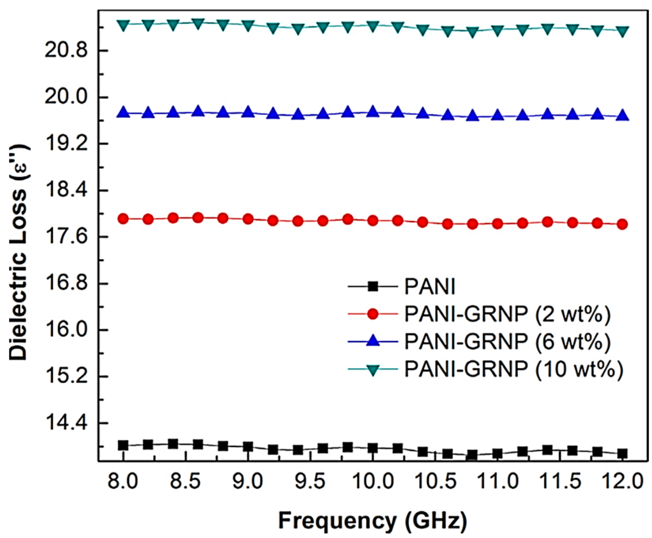

Figure 7. Variation in dielectric loss as a function of frequency for polyaniline (PANI) and polyaniline/graphene nanoplatelets (PANI-GRNPs) nanocomposites in X band [101]. Reproduced with permission from Elsevier.

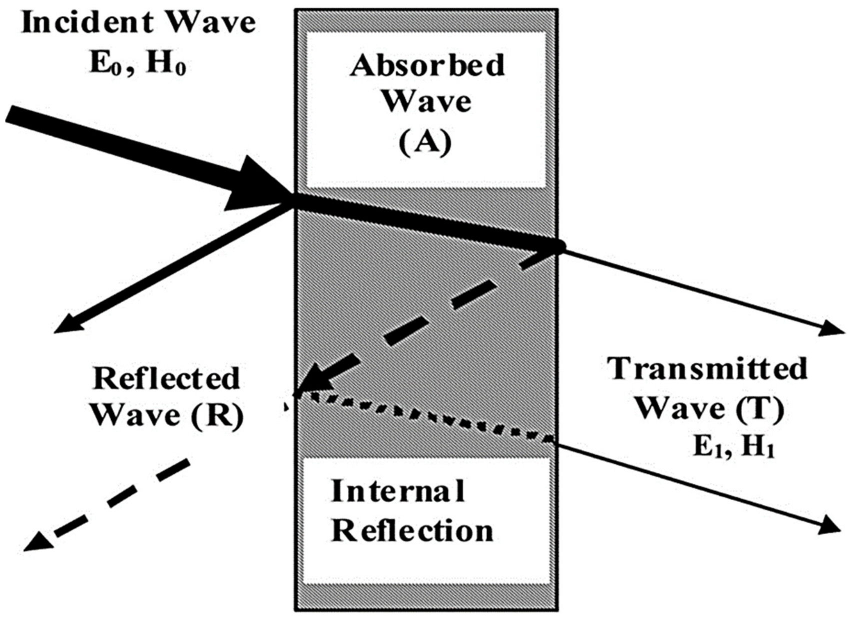

Figure 8. Schematic representation of interaction of electromagnetic wave shield [101]. Reproduced with permission from Elsevier.

In this regard, polyaniline- and carbon nanotube-based nanocomposites have been designed and explored [102]. Saini et al. [103] used in situ polymerization to develop polyaniline and multiwalled carbon nanotube derived nanomaterials. The addition of carbon nanotubes enabled the development of an interlinked network in a polyaniline matrix [104]. Polyaniline/multiwalled carbon nanotube nanocomposites feature superior electrical conductivity due to the formation of electron conducting paths and π–π interactions between conducting polymer chains and the conducting nanofiller structure [105]. As a result, a charge transfer complex forms between polyaniline (an electron donor) and carbon nanotube (an electron acceptor) [106]. Figure 9 displays the mechanism of the formation of polyaniline and multiwalled carbon nanotube-based nanocomposites. Initially, the aniline monomer is dispersed in water.

Afterward, HCl is added drop-wise for the adsorption of the aniline monomer on the carbon nanotube surface. This results in the in situ polymerization of the adsorbed aniline monomer on the carbon nanotube surface [107]. Optimum nanofiller contents and aniline monomer concentrations are required for the formation of polyaniline/multiwalled carbon nanotube nanocomposites. However, increasing the multiwalled carbon nanotube concentration causes nanofiller aggregation. In the same way, enhancing the aniline monomer concentration leads to the formation of polymer agglomerates. Therefore, optimization of polymerization conditions is essential. Yun et al. [108] also fabricated polyaniline/multiwalled carbon nanotube nanocomposites via in situ polymerization. To attain a better shielding effect for the polyaniline and multi-walled carbon nanotube nanocomposites, γ-Fe_2O_3 nanoparticles were included [109]. Consequently, the synergistic effect of carbon nanotubes and γ-Fe_2O_3 nanoparticles resulted in enhanced ferromagnetic, electrical, and dielectric properties. As a result, high EMI shielding effectiveness was observed in the range of 28.2–34.1 dB. Likewise, the dielectric permittivities of polyaniline/multi-walled carbon nanotube nanocomposites were improved with nanofiller addition.

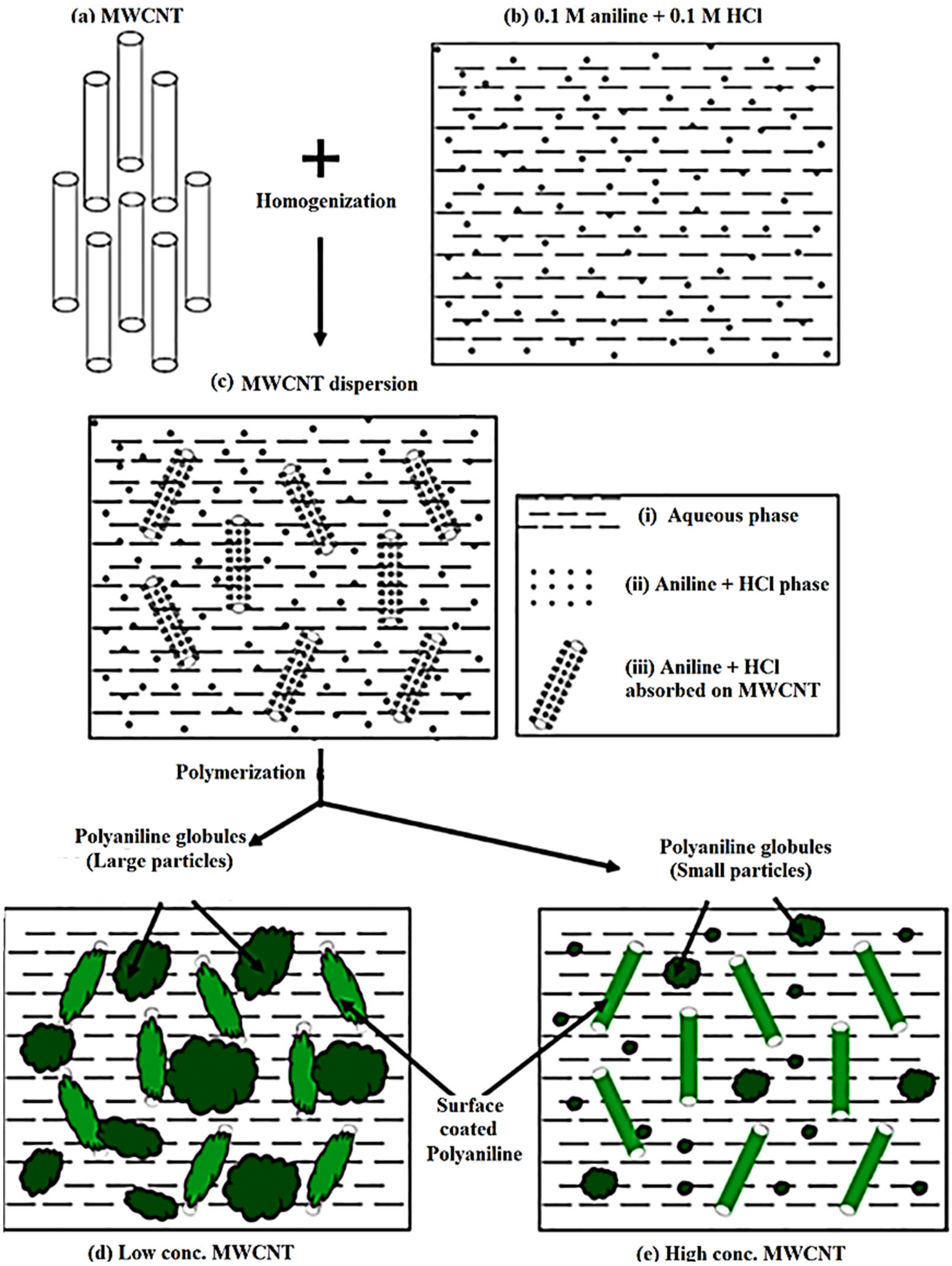

Figure 9. Proposed mechanism for the formation of polyaniline/multiwalled carbon nanotube (PANI/MWCNT) nanocomposites: (**a**–**c**) in situ polymerization and nanocomposite formation; and (**d**,**e**) dispersion states at low and high concentrations [103]. Reproduced with permission from Elsevier.

Nanofiller loading not only enhances conductivity and shielding properties but also improves the overall physical property profile (heat stability, strength, etc.) of nanomaterials. Saini et al. [110] reported polyaniline and multiwalled carbon nanotube nanocomposites for electromagnetic radiation shielding. In addition, a polyaniline matrix was used in combination with a polystyrene matrix to form a nanocomposite. Moreover, to enhance the EMI shielding effect, an iron catalyst was applied. Perfectly designed polystyrene/polyaniline/multiwalled carbon nanotube nanocomposites were reported for improving EMI shielding properties including superior dielectric, electrical conductivity, and magnetic properties [111]. The morphology of polyaniline/multiwalled carbon nanotube nanocomposites and polystyrene/polyaniline/multiwalled carbon nanotube nanocomposites was studied. Both nanocomposites have Fe catalyst in their matrix. According to the high resolution transmission electron microscopy images of polyaniline/multiwalled carbon nanotube nanocomposites, the conducting polymer was found to be layered on the nanofiller surface (Figure 10). Moreover, fine carbon nanotube dispersion was observed in the polyaniline matrix. Fe catalyst nanoparticles were dispersed at the interface between the polyaniline and multiwalled carbon nanotube components [112]. In the case of polystyrene/polyaniline/multiwalled carbon nanotube nanocomposites with iron nanoparticles, a unique type of interpenetrating network morphology was observed. In the high resolution transmission electron microscopy micrographs, the nanoparticles appeared to be decorated on the network nanostructure. Hence, interpenetrating network formation was considered to be responsible for the strong electron conductivity properties. The Fe nanoparticles generated a magnetic nanophase, which produced high electromagnetic attenuation properties. Figure 11 depicts the total shielding effectiveness (SE_T) of polyaniline/multiwalled carbon nanotube nanocomposite and polystyrene/polyaniline/multi walled carbon nanotube nanocomposite. Increasing the multiwalled carbon nanotube loading improved properties such as electron conduction, magnetic permeability, and dielectric losses [113]. Consequently, a polystyrene/polyaniline/multiwalled carbon nanotube/iron nanoparticle nanocomposite exhibited an RL_{min} of -45.7 dB. The enhanced shielding effectiveness was attributed to the interconnecting network morphology and the synergistic effects of nanofillers, which improved the radiation absorption ability and EMI defense mechanism [114]. Kaur et al. [115] developed polypyrrole and multiwalled carbon nanotube nanocomposites. Adding nanotube nanofiller improved the electrical conductivity up to 22 Scm^{-1}. Consequently, radiation protection effectiveness was enhanced up to 49 dB. Ebrahimi et al. [116] prepared a polypyrrole nanocomposite with multiwalled carbon nanotubes. The nanotubes were modified and decorated with silver nanoparticles to increase electrical conductivity and shielding effectiveness. The nanocomposite exhibited fine dispersion and homogeneous morphology [117]. This carefully designed nanocomposite provided a high electrical conductivity of 5.12 Scm^{-1} and a high EMI SE value of 30 dB. Better nanofiller dispersion, morphology, and interconnected network formation was thought to be responsible for enhancing the conductivity and EMI-shielding features.

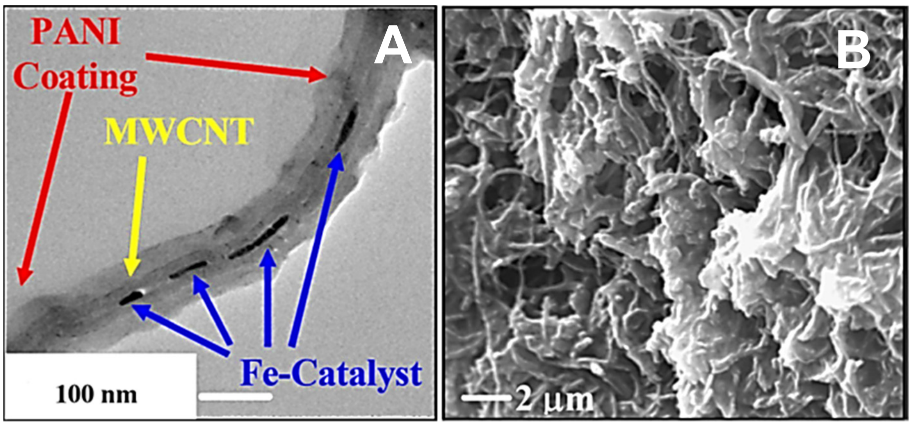

Figure 10. (**A**) High-resolution transmission electron microscopy (HRTEM) image of polyaniline/multiwalled carbon nanotube/iron (PANI/MWCNT/Fe) catalyst nanofiller and (**B**) scanning electron microscopy (SEM) image of the fracture surface of polystyrene/polyaniline/multiwalled carbon nanotube (PS/PANI/MWCNT) nanocomposite [110]. Reproduced with permission from Elsevier.

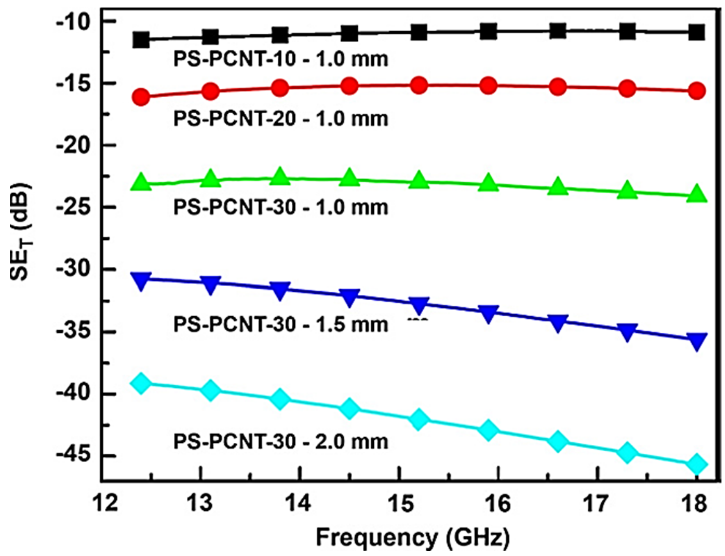

Figure 11. Dependence of total shielding effectiveness (SE_T) of polyaniline blends on frequency and shield thickness [110]. Reproduced with permission from Elsevier.

Aghvami-Panah et al. [118] compared the EMI shielding features of polystyrene nanocomposite foams with carbon nanotube, graphene, and carbon black. The foams were formed via the supercritical carbon dioxide method. A 1 wt.% nanofiller content was used, which caused 90% porosity in the foams. Table 1 provides the electrical conductivity and EMI-shielding related properties of nanocomposite foams for different radiation durations. EMI shielding was found to be dependent on factors such as the nanofiller type, morphology, and electrical conductivity of the materials. The effect of carbon nanotube addition seemed to be stronger than that of other carbonaceous nanofillers for enhancing electrical conductivity, dielectric properties, and the EMI SE. The carbon nanotubes produced better network and dispersion, which supported the material's conductivity, dielectric, and shielding properties than graphene and carbon nanotubes.

Table 1. The electrical conductivity, dielectric, and EMI shielding related properties of nanocomposite foams [118]. Reproduced with permission from Taylor and Francis.

Sample	Radiation Duration (s)	Filler Content (wt. %)	Electrical Conductivity (S/cm)	EMI SE (dB)	Dielectric Constant at Frequency of 100 Hz
Polystyrene/ carbon nanotube	45	1	3.29×10^{-6}	4.4	11.1
	60	1	3.05×10^{-7}	2.9	19.2
	90	1	8.31×10^{-7}	3.3	14.5
Polystyrene/graphene	120	1	9.23×10^{-8}	2.2	14.1
	150	1	5.31×10^{-8}	2.0	12.3
	180	1	4.31×10^{-8}	1.9	10.8
Polystyrene/ carbon black	120	1	4.42×10^{-9}	0.9	10.3
	150	1	6.34×10^{-9}	1.0	8.7
	180	1	8.13×10^{-9}	1.0	8.5

Metal and inorganic nanoparticles have also been filled in conducting polymers to improve the EMI SE. Nanocomposites have been developed using copper, nickel, silver, and other metal and inorganic nanoparticles [119]. For instance, Fang et al. [120] reinforced a polyaniline matrix with 14 vol.% of silver nanowires. The metal nanowires considerably improved the electrical conductivity and EMI SE up to 5300 Scm^{-1} and 50 dB, respectively. Moreover, polypyrrole- and silver-nanowire-derived nanocomposites were developed [121]. Nanomaterials can provide a high electrical conductivity and EMI SE of 62.73 Scm^{-1} and 22.38 dB, respectively [122]. Additionally, inorganic metal oxides have been added to conducting polymers to achieve high dielectric and shielding properties in the resulting nanocomposites [123,124]. Bora et al. [125] formed polyaniline and nickel oxide nanoparticles-based nanocomposites. The nanomaterials offered a shielding of ~27–24 dB, which were thus suggested for EMI shielding applications in robotics and vehicles [126,127]. Phang et al. [128] filled a polyaniline matrix with titania nanoparticles. The nanomaterials exhibited a high electrical conductivity of 1.27 Scm^{-1}. The nanocomposite had a radiation absorption of $\sim$92% and an EMI SE of 21.7 dB. Thus, metal and inorganic nanostructures effectively enhance the EMI SE effect of the conducting polymers.

5. Future Forecasts

Electromagnetic interference creates electronics pollution, which is harmful for human health and the surrounding devices [129]. Owing to their weight, cost, and corrosion issues, metallic shields are no longer used in industry. Therefore, research has shifted toward the development of advanced materials [130]. Conducting polymers and their derived nanocomposites offer an efficient alternative to metal shields, having a high EMI SE. These materials feature superior electrical conductivity, dielectric/magnetic, mechanical robustness, thermal stability, and corrosion-resistance properties. Conducting polymers have been effectively filled with carbon nanofillers, such as graphene and its derivatives and carbon nanotubes, to achieve high EMI shielding efficiency [131]. Conducting polymers have been filled with metal-based and inorganic nanoparticles to achieve a high EMI SE [132]. The mechanisms of EMI shielding must be understood to design of high performance materials [133]. The future of these materials depends on further understanding various factors such as the choice of nanoparticles, matrix modification, processing method, nanofiller dispersion, and mechanisms of action [134]. Controlling all parameters may result in superior electromagnetic absorption properties of advanced conducting-polymer-derived materials. Optimizing the nanofiller type, content, and dispersion is critical for developing homogeneous nanocomposites facilitating EMI shielding and conductivity. However, adjusting the nanofiller dispersion and processing parameters is challenging when producing high-tech nanomaterials. Using modified conducting polymers or blending two or more conducting polymers can provide improved EMI SE performance. Moreover, adjusting the shield thickness is indispensable for achieving superior electromagnetic features [135]. The development of three-dimensional architectures using conducting polymers and nanostructures may also enhance electron transport and the physical aspects of nanostructures [136]. In this way, highly efficient conducting nanocomposites can be designed to produce high electromagnetic shielding effects in the future [137].

6. Conclusions

In this comprehensive review, conducting-polymer-derived nanocomposite nanostructures were discussed, explaining the EMI shielding phenomenon and the fundamentals of EMI shielding effectiveness. Conducting nanomaterials provide an excellent alternative to metal-based radiation shields due to their low density, durability, electrical conductivity, and high radiation protection. Polyaniline, polypyrrole, and polythiophene matrices with nanocarbons and metal/inorganic nanofillers have mostly been used. Furthermore, the features of conducting-polymer-derived nanocomposites include facile processing, controllable thickness, and high radiation absorption properties for EMI shielding applications. The important factors controlling the electric, magnetic, and shielding properties include the nanofiller type, concentration, and dispersion; nanomaterial morphology; and physical characteristics (electrical, thermal, and mechanical). Efficient conducting nanocomposites must also feature a balance between the conductivity and permittivity of the materials. Hence, this review highpoints the research and development on conjugated polymer-based nanocomposites for high-tech EMI shielding materials.

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References

1. Chandra, R.J.; Shivamurthy, B.; Kumar, M.S.; Prabhu, N.N.; Sharma, D. Mechanical and Electrical Properties and Electromagnetic-Wave-Shielding Effectiveness of Graphene-Nanoplatelet-Reinforced Acrylonitrile Butadiene Styrene Nanocomposites. *J. Compos. Sci.* **2023**, *7*, 117. [CrossRef]
2. Akram, S.; Ashraf, M.; Javid, A.; Abid, H.A.; Ahmad, S.; Nawab, Y.; Rasheed, A.; Xue, Z.; Nosheen, A. Recent advances in electromagnetic interference (EMI) shielding textiles: A comprehensive review. *Synth. Met.* **2023**, *294*, 117305. [CrossRef]
3. Kallambadi Sadashivappa, P.; Venkatachalam, R.; Pothu, R.; Boddula, R.; Banerjee, P.; Naik, R.; Radwan, A.B.; Al-Qahtani, N. Progressive Review of Functional Nanomaterials-Based Polymer Nanocomposites for Efficient EMI Shielding. *J. Compos. Sci.* **2023**, *7*, 77. [CrossRef]
4. Mudhar, R.; Mucolli, A.; Ford, J.; Lira, C.; Yazdani Nezhad, H. Electrical and Magnetic Properties of 3D Printed Integrated Conductive Biodegradable Polymer Nanocomposites for Sustainable Electronics Development. *J. Compos. Sci.* **2022**, *6*, 345. [CrossRef]
5. Wanasinghe, D.; Aslani, F. A review on recent advancement of electromagnetic interference shielding novel metallic materials and processes. *Compos. Part B Eng.* **2019**, *176*, 107207. [CrossRef]
6. Zhang, Y.; Wang, X.; Cao, M. Confinedly implanted $NiFe_2O_4$-rGO: Cluster tailoring and highly tunable electromagnetic properties for selective-frequency microwave absorption. *Nano Res.* **2018**, *11*, 1426–1436. [CrossRef]
7. Zhou, S.; Wang, J.; Wang, S.; Ma, X.; Huang, J.; Zhao, G.; Liu, Y. Facile preparation of multiscale graphene-basalt fiber reinforcements and their enhanced mechanical and tribological properties for polyamide 6 composites. *Mater. Chem. Phys.* **2018**, *217*, 315–322. [CrossRef]
8. Yang, Z.; Hao, X.; Chen, S.; Ma, Z.; Wang, W.; Wang, C.; Yue, L.; Sun, H.; Shao, Q.; Murugadoss, V. Long-term antibacterial stable reduced graphene oxide nanocomposites loaded with cuprous oxide nanoparticles. *J. Colloid Interface Sci.* **2019**, *533*, 13–23. [CrossRef]
9. Wang, C.; Murugadoss, V.; Kong, J.; He, Z.; Mai, X.; Shao, Q.; Chen, Y.; Guo, L.; Liu, C.; Angaiah, S. Overview of carbon nanostructures and nanocomposites for electromagnetic wave shielding. *Carbon* **2018**, *140*, 696–733. [CrossRef]
10. Jiang, D.; Murugadoss, V.; Wang, Y.; Lin, J.; Ding, T.; Wang, Z.; Shao, Q.; Wang, C.; Liu, H.; Lu, N. Electromagnetic interference shielding polymers and nanocomposites—A review. *Polym. Rev.* **2019**, *59*, 280–337. [CrossRef]
11. Kargar, F.; Barani, Z.; Balinskiy, M.; Magana, A.S.; Lewis, J.S.; Balandin, A.A. Dual-functional graphene composites for electromagnetic shielding and thermal management. *Adv. Electron. Mater.* **2019**, *5*, 1800558. [CrossRef]
12. Shen, Q.; Li, H.; Lin, H.; Li, L.; Li, W.; Song, Q. Simultaneously improving the mechanical strength and electromagnetic interference shielding of carbon/carbon composites by electrophoretic deposition of SiC nanowires. *J. Mater. Chem. C* **2018**, *6*, 5888–5899. [CrossRef]
13. Wu, H.-Y.; Zhang, Y.-P.; Jia, L.-C.; Yan, D.-X.; Gao, J.-F.; Li, Z.-M. Injection molded segregated carbon nanotube/polypropylene composite for efficient electromagnetic interference shielding. *Ind. Eng. Chem. Res.* **2018**, *57*, 12378–12385. [CrossRef]
14. Jia, L.-C.; Yan, D.-X.; Jiang, X.; Pang, H.; Gao, J.-F.; Ren, P.-G.; Li, Z.-M. Synergistic effect of graphite and carbon nanotubes on improved electromagnetic interference shielding performance in segregated composites. *Ind. Eng. Chem. Res.* **2018**, *57*, 11929–11938. [CrossRef]
15. Kaczor-Urbanowicz, K.E.; Martín Carreras-Presas, C.; Kaczor, T.; Tu, M.; Wei, F.; Garcia-Godoy, F.; Wong, D.T. Emerging technologies for salivaomics in cancer detection. *J. Cell. Mol. Med.* **2017**, *21*, 640–647. [CrossRef]
16. Glyva, V.; Kovalenko, V.; Levchenko, L.; Tykhenko, O. Research into protective properties of electromagnetic screens based on the metal-containing nanostructures. *East.-Eur. J. Enterp. Technol.* **2017**, *3*, 50–56. [CrossRef]
17. González, M.; Pozuelo, J.; Baselga, J. Electromagnetic shielding materials in GHz range. *Chem. Rec.* **2018**, *18*, 1000–1009. [CrossRef]
18. Gupta, S.; Sharma, S.K.; Pradhan, D.; Tai, N.-H. Ultra-light 3D reduced graphene oxide aerogels decorated with cobalt ferrite and zinc oxide perform excellent electromagnetic interference shielding effectiveness. *Compos. Part A Appl. Sci. Manuf.* **2019**, *123*, 232–241. [CrossRef]
19. Jia, Y.; Li, K.; Xue, L.; Ren, J.; Zhang, S.; Li, H. Mechanical and electromagnetic shielding performance of carbon fiber reinforced multilayered (PyC-SiC) n matrix composites. *Carbon* **2017**, *111*, 299–308. [CrossRef]
20. Bheema, R.K.; Etika, K.C. The influence of hybrid decorated structures on the EMI shielding properties of epoxy composites over the X-Band. *Mater. Today Proc.* **2023**, *76*, 398–402. [CrossRef]
21. David, D.A.; Jabeen Fatima, M.; Khan, A.; Joy, R.; Thakur, V.K.; Ruiz-Rosas, R.R.; Ozden, S.; Raghavan, P. Porous Carbon Materials and Their Composites for Electromagnetic Interference (EMI) Shielding: The State-of-the-Art of Technologies. In *Handbook of Porous Carbon Materials*; Springer: Berlin/Heidelberg, Germany, 2023; pp. 669–702.

22. Gebrekrstos, A.; Ray, S.S. Superior electrical conductivity and mechanical properties of phase-separated polymer blend composites by tuning the localization of nanoparticles for electromagnetic interference shielding applications. *J. Polym. Sci.* **2023**. [CrossRef]
23. Voicu, V.; Pătru, I.; Dina, L.-A.; Nicolae, P.-M.; Smărăndescu, I.D. Shielding effectiveness evaluation using a non-standardized method. In Proceedings of the 2017 International Conference on Electromechanical and Power Systems (SIELMEN), Iasi, Romania, 11–13 October 2017; pp. 208–211.
24. Kashi, S.; Gupta, R.K.; Baum, T.; Kao, N.; Bhattacharya, S.N. Morphology, electromagnetic properties and electromagnetic interference shielding performance of poly lactide/graphene nanoplatelet nanocomposites. *Mater. Des.* **2016**, *95*, 119–126. [CrossRef]
25. Mittal, G.; Dhand, V.; Rhee, K.Y.; Park, S.-J.; Lee, W.R. A review on carbon nanotubes and graphene as fillers in reinforced polymer nanocomposites. *J. Ind. Eng. Chem.* **2015**, *21*, 11–25. [CrossRef]
26. Munalli, D.; Dimitrakis, G.; Chronopoulos, D.; Greedy, S.; Long, A. Electromagnetic shielding effectiveness of carbon fibre reinforced composites. *Compos. Part B Eng.* **2019**, *173*, 106906. [CrossRef]
27. Khalid, T.; Albasha, L.; Qaddoumi, N.; Yehia, S. Feasibility study of using electrically conductive concrete for electromagnetic shielding applications as a substitute for carbon-laced polyurethane absorbers in anechoic chambers. *IEEE Trans. Antennas Propag.* **2017**, *65*, 2428–2435. [CrossRef]
28. Kausar, A. Thermally conducting polymer/nanocarbon and polymer/inorganic nanoparticle nanocomposite: A review. *Polym.-Plast. Technol. Mater.* **2020**, *59*, 895–909. [CrossRef]
29. Wiroonpochit, P.; Keawmaungkom, S.; Chisti, Y.; Hansupalak, N. A novel preparation of natural rubber films with a conducting nanocarbon network for antistatic applications. *Mater. Today Commun.* **2023**, *34*, 105349. [CrossRef]
30. Al-Saleh, M.H.; Sundararaj, U. Electromagnetic interference shielding mechanisms of CNT/polymer composites. *Carbon* **2009**, *47*, 1738–1746. [CrossRef]
31. Jalali, A.; Zhang, R.; Rahmati, R.; Nofar, M.; Sain, M.; Park, C.B. Recent progress and perspective in additive manufacturing of EMI shielding functional polymer nanocomposites. *Nano Res.* **2023**, *16*, 1–17. [CrossRef]
32. Rayar, A.; Naveen, C.; Onkarappa, H.; Betageri, V.S.; Prasanna, G. EMI shielding applications of PANI-Ferrite nanocomposite materials: A review. *Synth. Met.* **2023**, *295*, 117338. [CrossRef]
33. Idumah, C.I. Recent advancements in electromagnetic interference shielding of polymer and mxene nanocomposites. *Polym.-Plast. Technol. Mater.* **2023**, *62*, 19–53. [CrossRef]
34. Kausar, A. Epitome of Fullerene in Conducting Polymeric Nanocomposite—Fundamentals and Beyond. *Polym.-Plast. Technol. Mater.* **2023**, *62*, 618–631. [CrossRef]
35. Luo, J.; Wang, L.; Huang, X.; Li, B.; Guo, Z.; Song, X.; Lin, L.; Tang, L.-C.; Xue, H.; Gao, J. Mechanically durable, highly conductive, and anticorrosive composite fabrics with excellent self-cleaning performance for high-efficiency electromagnetic interference shielding. *ACS Appl. Mater. Interfaces* **2019**, *11*, 10883–10894. [CrossRef] [PubMed]
36. Zhou, X.; Jia, Z.; Feng, A.; Wang, X.; Liu, J.; Zhang, M.; Cao, H.; Wu, G. Synthesis of fish skin-derived 3D carbon foams with broadened bandwidth and excellent electromagnetic wave absorption performance. *Carbon* **2019**, *152*, 827–836. [CrossRef]
37. Zhang, N.; Wang, X.; Geng, L.; Liu, Z.; Zhang, X.; Li, C.; Zhang, D.; Wang, Z.; Zhao, G. Metallic Ni nanoparticles embedded in hierarchical mesoporous $Ni(OH)_2$: A robust and magnetic recyclable catalyst for hydrogenation of 4-nitrophenol under mild conditions. *Polyhedron* **2019**, *164*, 7–12. [CrossRef]
38. Banerjee, R.; Gebrekrstos, A.; Orasugh, J.T.; Ray, S.S. Nanocarbon-Containing Polymer Composite Foams: A Review of Systems for Applications in Electromagnetic Interference Shielding, Energy Storage, and Piezoresistive Sensors. *Ind. Eng. Chem. Res.* **2023**, *62*, 6807–6842. [CrossRef]
39. Stunder, D.; Seckler, T.; Joosten, S.; Zink, M.D.; Driessen, S.; Kraus, T.; Marx, N.; Napp, A. In vivo study of electromagnetic interference with pacemakers caused by everyday electric and magnetic fields. *Circulation* **2017**, *135*, 907–909. [CrossRef]
40. Lee, S.H.; Yu, S.; Shahzad, F.; Hong, J.; Noh, S.J.; Kim, W.N.; Hong, S.M.; Koo, C.M. Low percolation 3D Cu and Ag shell network composites for EMI shielding and thermal conduction. *Compos. Sci. Technol.* **2019**, *182*, 107778. [CrossRef]
41. Chen, J.; Liu, B.; Gao, X.; Xu, D. A review of the interfacial characteristics of polymer nanocomposites containing carbon nanotubes. *RSC Adv.* **2018**, *8*, 28048–28085. [CrossRef]
42. Li, J.; Peng, W.-J.; Fu, Z.-J.; Tang, X.-H.; Wu, H.; Guo, S.; Wang, M. Achieving high electrical conductivity and excellent electromagnetic interference shielding in poly (lactic acid)/silver nanocomposites by constructing large-area silver nanoplates in polymer matrix. *Compos. Part B Eng.* **2019**, *171*, 204–213. [CrossRef]
43. Saini, M.; Shukla, R. Silver nanoparticles-decorated $NiFe_2O_4$/polyaniline ternary nanocomposite for electromagnetic interference shielding. *J. Mater. Sci. Mater. Electron.* **2020**, *31*, 5152–5164. [CrossRef]
44. Singh, B.; Choudhary, V.; Saini, P.; Pande, S.; Singh, V.; Mathur, R. Enhanced microwave shielding and mechanical properties of high loading MWCNT–epoxy composites. *J. Nanoparticle Res.* **2013**, *15*, 1554. [CrossRef]
45. Yu, F.; Deng, H.; Zhang, Q.; Wang, K.; Zhang, C.; Chen, F.; Fu, Q. Anisotropic multilayer conductive networks in carbon nanotubes filled polyethylene/polypropylene blends obtained through high speed thin wall injection molding. *Polymer* **2013**, *54*, 6425–6436. [CrossRef]
46. He, Q.; Yuan, T.; Zhang, X.; Yan, X.; Guo, J.; Ding, D.; Khan, M.A.; Young, D.P.; Khasanov, A.; Luo, Z. Electromagnetic field absorbing polypropylene nanocomposites with tuned permittivity and permeability by nanoiron and carbon nanotubes. *J. Phys. Chem. C* **2014**, *118*, 24784–24796. [CrossRef]

47. Jan, R.; Khan, M.B.; Khan, Z.M. Synthesis and electrical characterization of "carbon particles reinforced epoxy-nanocomposite" in Ku-band. *Mater. Lett.* **2012**, *70*, 155–159. [CrossRef]
48. Wei, W.; Yue, X.; Zhou, Y.; Chen, Z.; Fang, J.; Gao, C.; Jiang, Z. New promising hybrid materials for electromagnetic interference shielding with improved stability and mechanical properties. *Phys. Chem. Chem. Phys.* **2013**, *15*, 21043–21050. [CrossRef]
49. Yazdi, M.K.; Noorbakhsh, B.; Nazari, B.; Ranjbar, Z. Preparation and EMI shielding performance of epoxy/non-metallic conductive fillers nano-composites. *Prog. Org. Coat.* **2020**, *145*, 105674. [CrossRef]
50. Tantawy, H.R.; Aston, D.E.; Smith, J.R.; Young, J.L. Comparison of electromagnetic shielding with polyaniline nanopowders produced in solvent-limited conditions. *ACS Appl. Mater. Interfaces* **2013**, *5*, 4648–4658. [CrossRef]
51. Bhadra, S.; Singha, N.K.; Khastgir, D. Dielectric properties and EMI shielding efficiency of polyaniline and ethylene 1-octene based semi-conducting composites. *Curr. Appl. Phys.* **2009**, *9*, 396–403. [CrossRef]
52. Mäkelä, T.; Pienimaa, S.; Taka, T.; Jussila, S.; Isotalo, H. Thin polyaniline films in EMI shielding. *Synth. Met.* **1997**, *85*, 1335–1336. [CrossRef]
53. Wang, X.-X.; Zheng, Q.; Zheng, Y.-J.; Cao, M.-S. Green EMI shielding: Dielectric/magnetic "genes" and design philosophy. *Carbon* **2023**, *206*, 124–141. [CrossRef]
54. Yao, L.; Wang, Y.; Zhao, J.; Zhu, Y.; Cao, M. Multifunctional Nanocrystalline-Assembled Porous Hierarchical Material and Device for Integrating Microwave Absorption, Electromagnetic Interference Shielding, and Energy Storage. *Small* **2023**, 2208101. [CrossRef]
55. He, W.; Li, J.; Tian, J.; Jing, H.; Li, Y. Characteristics and properties of wood/polyaniline electromagnetic shielding composites synthesized via in situ polymerization. *Polym. Compos.* **2018**, *39*, 537–543. [CrossRef]
56. Kim, B.R.; Lee, H.-K.; Park, S.; Kim, H.-K. Electromagnetic interference shielding characteristics and shielding effectiveness of polyaniline-coated films. *Thin Solid Film.* **2011**, *519*, 3492–3496. [CrossRef]
57. Zhang, Y.; Pan, T.; Yang, Z. Flexible polyethylene terephthalate/polyaniline composite paper with bending durability and effective electromagnetic shielding performance. *Chem. Eng. J.* **2020**, *389*, 124433. [CrossRef]
58. Oh, H.-J.; Dao, V.-D.; Choi, H.-S. Electromagnetic shielding effectiveness of a thin silver layer deposited onto PET film via atmospheric pressure plasma reduction. *Appl. Surf. Sci.* **2018**, *435*, 7–15. [CrossRef]
59. Bhardwaj, P.; Kaushik, S.; Gairola, P.; Gairola, S. Exceptional electromagnetic radiation shielding performance and dielectric properties of surfactant assisted polypyrrole-carbon allotropes composites. *Radiat. Phys. Chem.* **2018**, *151*, 156–163. [CrossRef]
60. Raina, N.; Sharma, P.; Slathia, P.S.; Bhagat, D.; Pathak, A.K. Efficiency Enhancement of Renewable Energy Systems Using Nanotechnology. In *Nanomaterials and Environmental Biotechnology*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 271–297.
61. Sastry, D.N.; Revanasiddappa, M.; Suresh, T.; Kiran, Y.R.; Raghavendra, S. Electromagnetic shielding effectiveness studies on polyaniline/CSA-WO_3 composites at KU band frequencies. *AIP Conf. Proc.* **2018**, *1953*, 090067.
62. Vargas-Bernal, R. Mechanisms of Electrical Conductivity in Carbon Nanotubes and Graphene. In *Encyclopedia of Information Science and Technology*, 4th ed.; IGI Global: Hershey, PA, USA, 2018; pp. 2673–2684.
63. Yao, Y.; Jin, S.; Zou, H.; Li, L.; Ma, X.; Lv, G.; Gao, F.; Lv, X.; Shu, Q. Polymer-based lightweight materials for electromagnetic interference shielding: A review. *J. Mater. Sci.* **2021**, *56*, 6549–6580. [CrossRef]
64. Wan, Y.; Li, J.; Yang, Z.; Ao, H.; Xiong, L.; Luo, H. Simultaneously depositing polyaniline onto bacterial cellulose nanofibers and graphene nanosheets toward electrically conductive nanocomposites. *Curr. Appl. Phys.* **2018**, *18*, 933–940. [CrossRef]
65. Wang, H.; Zhu, E.; Yang, J.; Zhou, P.; Sun, D.; Tang, W. Bacterial cellulose nanofiber-supported polyaniline nanocomposites with flake-shaped morphology as supercapacitor electrodes. *J. Phys. Chem. C* **2012**, *116*, 13013–13019. [CrossRef]
66. Kumar, S.; Kumar, P.; Gupta, R.; Verma, V. Electromagnetic interference shielding behaviors of in-situ polymerized ferrite-polyaniline nano-composites and ferrite-polyaniline deposited fabrics in X-band frequency range. *J. Alloy. Compd.* **2021**, *862*, 158331. [CrossRef]
67. Lee, C.; Song, H.; Jang, K.; Oh, E.; Epstein, A.; Joo, J. Electromagnetic interference shielding efficiency of polyaniline mixtures and multilayer films. *Synth. Met.* **1999**, *102*, 1346–1349. [CrossRef]
68. Pineda, E.G.; Azpeitia, L.; Presa, M.R.; Bolzán, A.; Gervasi, C. Benchmarking electrodes modified with bi-doped polypyrrole for sensing applications. *Electrochim. Acta* **2023**, *444*, 142011. [CrossRef]
69. Gahlout, P.; Choudhary, V. Tailoring of polypyrrole backbone by optimizing synthesis parameters for efficient EMI shielding properties in X-band (8.2–12.4 GHz). *Synth. Met.* **2016**, *222*, 170–179. [CrossRef]
70. Jani, R.K.; Patra, M.K.; Saini, L.; Shukla, A.; Singh, C.P.; Vadera, S.R. Tuning of Microwave Absorption Properties and Electromagnetic Interference (EMI) Shielding Effectiveness of Nanosize Conducting Black-Silicone Rubber Composites over 8–18 GHz. *Prog. Electromagn. Res.* **2017**, *58*, 193–204. [CrossRef]
71. Kulkarni, G.; Kandesar, P.; Velhal, N.; Phadtare, V.; Jatratkar, A.; Shinde, S.; Kim, D.-Y.; Puri, V. Exceptional electromagnetic interference shielding and microwave absorption properties of room temperature synthesized polythiophene thin films with double negative characteristics (DNG) in the Ku-band region. *Chem. Eng. J.* **2019**, *355*, 196–207. [CrossRef]
72. Ghosh, S.; Remanan, S.; Mondal, S.; Ganguly, S.; Das, P.; Singha, N.; Das, N.C. An approach to prepare mechanically robust full IPN strengthened conductive cotton fabric for high strain tolerant electromagnetic interference shielding. *Chem. Eng. J.* **2018**, *344*, 138–154. [CrossRef]
73. Rawat, N.K.; Panda, P. Microwave Synthesized Conducting Polymer-Based Green Nanocomposites as Smart Promising Materials. In *Integrating Green Chemistry and Sustainable Engineering*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2019; pp. 191–214.

74. Rawat, N.K.; Khatoon, H.; Kahtun, S.; Ahmad, S. Conducting polyborozirconia (o-toluidine) nanostructures: Effect of boron and zirconia doping on synthesis, characterization and their corrosion protective performance. *Compos. Commun.* **2019**, *16*, 143–149. [CrossRef]
75. Boroyevich, D.; Zhang, X.; Bishinoi, H.; Burgos, R.; Mattavelli, P.; Wang, F. Conducted EMI and systems integration. In Proceedings of the CIPS 2014, 8th International Conference on Integrated Power Electronics Systems, Nuremberg, Germany, 25–27 February 2014; pp. 1–14.
76. Bhattacharjee, Y.; Arief, I.; Bose, S. Recent trends in multi-layered architectures towards screening electromagnetic radiation: Challenges and perspectives. *J. Mater. Chem. C* **2017**, *5*, 7390–7403. [CrossRef]
77. Xu, W.; Wang, G.-S.; Yin, P.-G. Designed fabrication of reduced graphene oxides/Ni hybrids for effective electromagnetic absorption and shielding. *Carbon* **2018**, *139*, 759–767. [CrossRef]
78. Marka, S.K.; Sindam, B.; Raju, K.J.; Srikanth, V.V. Flexible few-layered graphene/poly vinyl alcohol composite sheets: Synthesis, characterization and EMI shielding in X-band through the absorption mechanism. *RSC Adv.* **2015**, *5*, 36498–36506. [CrossRef]
79. Patel, C.R.P.; Tripathi, P.; Singh, S.; Singh, A.P.; Dhawan, S.; Kotnala, R.; Gupta, B.K.; Srivastava, O. New emerging radially aligned carbon nano tubes comprised carbon hollow cylinder as an excellent absorber for electromagnetic environmental pollution. *J. Mater. Chem. C* **2016**, *4*, 5483–5490. [CrossRef]
80. Ameli, A.; Jung, P.; Park, C. Electrical properties and electromagnetic interference shielding effectiveness of polypropylene/carbon fiber composite foams. *Carbon* **2013**, *60*, 379–391. [CrossRef]
81. Xia, X.; Wang, Y.; Zhong, Z.; Weng, G.J. A theory of electrical conductivity, dielectric constant, and electromagnetic interference shielding for lightweight graphene composite foams. *J. Appl. Phys.* **2016**, *120*, 085102. [CrossRef]
82. Chen, Y.-J.; Li, Y.; Chu, B.; Kuo, I.-T.; Yip, M.; Tai, N. Porous composites coated with hybrid nano carbon materials perform excellent electromagnetic interference shielding. *Compos. Part B Eng.* **2015**, *70*, 231–237. [CrossRef]
83. Banerjee, S.; Sharma, R.; Kar, K.K. Nanocomposites Based on Carbon Nanomaterials and Electronically Nonconducting Polymers. In *Composite Materials*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 251–280.
84. Tofighy, M.A.; Mohammadi, T. Barrier, Diffusion, and Transport Properties of Rubber Nanocomposites Containing Carbon Nanofillers. In *Carbon-Based Nanofiller and Their Rubber Nanocomposites*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 253–285.
85. Nagornaya, M.; Razdyakonova, G.; Khodakova, S.Y. The effect of functional groups of carbon black on rubber properties. *Procedia Eng.* **2016**, *152*, 563–569. [CrossRef]
86. Marquis, D.M.; Guillaume, E.; Chivas-Joly, C. Properties of nanofillers in polymer. In *Nanocomposites and Polymers with Analytical Methods*; IntechOpen: London, UK, 2011.
87. Jia, L.-C.; Zhang, G.; Xu, L.; Sun, W.-J.; Zhong, G.-J.; Lei, J.; Yan, D.-X.; Li, Z.-M. Robustly superhydrophobic conductive textile for efficient electromagnetic interference shielding. *ACS Appl. Mater. Interfaces* **2018**, *11*, 1680–1688. [CrossRef]
88. Yue, L.; Jayapal, M.; Cheng, X.; Zhang, T.; Chen, J.; Ma, X.; Dai, X.; Lu, H.; Guan, R.; Zhang, W. Highly dispersed ultra-small nano Sn-SnSb nanoparticles anchored on N-doped graphene sheets as high performance anode for sodium ion batteries. *Appl. Surf. Sci.* **2020**, *512*, 145686. [CrossRef]
89. Zhang, L.; Bi, S.; Liu, M. Lightweight electromagnetic interference shielding materials and their mechanisms. In *Electromagnetic Materials and Devices*; IntechOpen: London, UK, 2018; pp. 1–10.
90. Fang, Q.; Lafdi, K. Effect of nanofiller morphology on the electrical conductivity of polymer nanocomposites. *Nano Express* **2021**, *2*, 010019. [CrossRef]
91. Kausar, A.; Ahmad, S.; Salman, S.M. Effectiveness of polystyrene/carbon nanotube composite in electromagnetic interference shielding materials: A review. *Polym.-Plast. Technol. Eng.* **2017**, *56*, 1027–1042. [CrossRef]
92. Zhang, X.; Zhu, J.; Haldolaarachchige, N.; Ryu, J.; Young, D.P.; Wei, S.; Guo, Z. Synthetic process engineered polyaniline nanostructures with tunable morphology and physical properties. *Polymer* **2012**, *53*, 2109–2120. [CrossRef]
93. Youssef, A.; Mohamed, S.; Abdel-Aziz, M.; Abdel-Aziz, M.; Turky, G.; Kamel, S. Biological studies and electrical conductivity of paper sheet based on PANI/PS/Ag-NPs nanocomposite. *Carbohydr. Polym.* **2016**, *147*, 333–343. [CrossRef] [PubMed]
94. Bhardwaj, P.; Kaushik, S.; Gairola, P.; Gairola, S. Designing of nickel cobalt molybdate/multiwalled carbon nanotube composites for suppression of electromagnetic radiation. *SN Appl. Sci.* **2019**, *1*, 113. [CrossRef]
95. Joshi, A.; Bajaj, A.; Singh, R.; Anand, A.; Alegaonkar, P.; Datar, S. Processing of graphene nanoribbon based hybrid composite for electromagnetic shielding. *Compos. Part B Eng.* **2015**, *69*, 472–477. [CrossRef]
96. Modak, P.; Kondawar, S.B.; Nandanwar, D. Synthesis and characterization of conducting polyaniline/graphene nanocomposites for electromagnetic interference shielding. *Procedia Mater. Sci.* **2015**, *10*, 588–594. [CrossRef]
97. Yu, H.; Wang, T.; Wen, B.; Lu, M.; Xu, Z.; Zhu, C.; Chen, Y.; Xue, X.; Sun, C.; Cao, M. Graphene/polyaniline nanorod arrays: Synthesis and excellent electromagnetic absorption properties. *J. Mater. Chem.* **2012**, *22*, 21679–21685. [CrossRef]
98. Gyergyek, S.; Pahovnik, D.; Žagar, E.; Mertelj, A.; Beković, M.; Jagodič, M.; Hofmann, H.; Makovec, D. Nanocomposites comprised of homogeneously dispersed magnetic iron-oxide nanoparticles and poly (methyl methacrylate). *Beilstein J. Nanotechnol.* **2018**, *9*, 1613–1622. [CrossRef]
99. Biswas, S.; Panja, S.S.; Bose, S. Tailored distribution of nanoparticles in bi-phasic polymeric blends as emerging materials for suppressing electromagnetic radiation: Challenges and prospects. *J. Mater. Chem. C* **2018**, *6*, 3120–3142. [CrossRef]
100. Pal, R.; Goyal, S.L.; Rawal, I. Lightweight graphene encapsulated with polyaniline for excellent electromagnetic shielding performance in X-band (8.2–12.4 GHz). *Mater. Sci. Eng. B* **2021**, *270*, 115227. [CrossRef]

101. Khasim, S. Polyaniline-Graphene nanoplatelet composite films with improved conductivity for high performance X-band microwave shielding applications. *Results Phys.* **2019**, *12*, 1073–1081. [CrossRef]
102. Zhang, Y.; Qiu, M.; Yu, Y.; Wen, B.; Cheng, L. A novel polyaniline-coated bagasse fiber composite with core–shell heterostructure provides effective electromagnetic shielding performance. *ACS Appl. Mater. Interfaces* **2017**, *9*, 809–818. [CrossRef] [PubMed]
103. Saini, P.; Choudhary, V.; Singh, B.; Mathur, R.; Dhawan, S. Polyaniline–MWCNT nanocomposites for microwave absorption and EMI shielding. *Mater. Chem. Phys.* **2009**, *113*, 919–926. [CrossRef]
104. Sundara, R.; Srinivasan, S.K. Nerve Guide Conduit Containing Carbon Nanotubes. U.S. Patent US9327054B2, 3 May 2016.
105. Mei, J.F.; Jia, X.Y.; Lai, J.C.; Sun, Y.; Li, C.H.; Wu, J.H.; Cao, Y.; You, X.Z.; Bao, Z. A highly stretchable and autonomous self-healing polymer based on combination of Pt··· Pt and π–π interactions. *Macromol. Rapid Commun.* **2016**, *37*, 1667–1675. [CrossRef] [PubMed]
106. Gu, H.; Guo, J.; He, Q.; Jiang, Y.; Huang, Y.; Haldolaarachige, N.; Luo, Z.; Young, D.P.; Wei, S.; Guo, Z. Magnetoresistive polyaniline/multi-walled carbon nanotube nanocomposites with negative permittivity. *Nanoscale* **2014**, *6*, 181–189. [CrossRef] [PubMed]
107. Hu, W. The physics of polymer chain-folding. *Phys. Rep.* **2018**, *747*, 1–50. [CrossRef]
108. Yun, J.; Kim, H.-I. Electromagnetic interference shielding effects of polyaniline-coated multi-wall carbon nanotubes/maghemite nanocomposites. *Polym. Bull.* **2012**, *68*, 561–573. [CrossRef]
109. Fagbayigbo, B.; Opeolu, B.; Fatoki, O. Adsorption of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) from water using leaf biomass (*Vitis vinifera*) in a fixed-bed column study. *J. Environ. Health Sci. Eng.* **2020**, *18*, 221–233. [CrossRef]
110. Saini, P.; Choudhary, V.; Singh, B.; Mathur, R.; Dhawan, S. Enhanced microwave absorption behavior of polyaniline-CNT/polystyrene blend in 12.4–18.0 GHz range. *Synth. Met.* **2011**, *161*, 1522–1526. [CrossRef]
111. Duan, Y.; Liu, W.; Song, L.; Wang, T. A discrete structure: FeSiAl/carbon black composite absorption coatings. *Mater. Res. Bull.* **2017**, *88*, 41–48. [CrossRef]
112. Peymanfar, R.; Rahmanisaghieh, M. Preparation of neat and capped $BaFe_2O_4$ nanoparticles and investigation of morphology, magnetic, and polarization effects on its microwave and optical performance. *Mater. Res. Express* **2018**, *5*, 105012. [CrossRef]
113. Zhao, J.; Lu, Y.; Ye, W.; Wang, L.; Liu, B.; Lv, S.; Chen, L.; Gu, J. Enhanced wave-absorbing performances of silicone rubber composites by incorporating C-SnO_2-MWCNT absorbent with ternary heterostructure. *Ceram. Int.* **2019**, *45*, 20282–20289. [CrossRef]
114. Mondal, S.; Das, P.; Ganguly, S.; Ravindren, R.; Remanan, S.; Bhawal, P.; Das, T.K.; Das, N.C. Thermal-air ageing treatment on mechanical, electrical, and electromagnetic interference shielding properties of lightweight carbon nanotube based polymer nanocomposites. *Compos. Part A Appl. Sci. Manuf.* **2018**, *107*, 447–460. [CrossRef]
115. Kaur, A.; Dhawan, S. Tuning of EMI shielding properties of polypyrrole nanoparticles with surfactant concentration. *Synth. Met.* **2012**, *162*, 1471–1477. [CrossRef]
116. Ebrahimi, I.; Gashti, M.P. Chemically reduced versus photo-reduced clay-Ag-polypyrrole ternary nanocomposites: Comparing thermal, optical, electrical and electromagnetic shielding properties. *Mater. Res. Bull.* **2016**, *83*, 96–107. [CrossRef]
117. Ebrahimi, I.; Gashti, M.P. Polypyrrole-MWCNT-Ag composites for electromagnetic shielding: Comparison between chemical deposition and UV-reduction approaches. *J. Phys. Chem. Solids* **2018**, *118*, 80–87. [CrossRef]
118. Aghvami-Panah, M.; Wang, A.; Panahi-Sarmad, M.; Esfahani, S.A.S.; Seraji, A.A.; Shahbazi, M.; Ghaffarian, R.; Jamalpour, S.; Xiao, X. A comparison study on polymeric nanocomposite foams with various carbon nanoparticles: Adjusting radiation time and effect on electrical behavior and microcellular structure. *Int. J. Smart Nano Mater.* **2022**, *13*, 504–528. [CrossRef]
119. Yu, D.; Wang, Y.; Hao, T.; Wang, W.; Liu, B. Preparation of silver-plated polyimide fabric initiated by polyaniline with electromagnetic shielding properties. *J. Ind. Text.* **2018**, *47*, 1392–1406. [CrossRef]
120. Fang, F.; Li, Y.-Q.; Xiao, H.-M.; Hu, N.; Fu, S.-Y. Layer-structured silver nanowire/polyaniline composite film as a high performance X-band EMI shielding material. *J. Mater. Chem. C* **2016**, *4*, 4193–4203. [CrossRef]
121. Yu, L.; Yang, Q.; Liao, J.; Zhu, Y.; Li, X.; Yang, W.; Fu, Y. A novel 3D silver nanowires@ polypyrrole sponge loaded with water giving excellent microwave absorption properties. *Chem. Eng. J.* **2018**, *352*, 490–500. [CrossRef]
122. Chen, J.-J.; Liu, S.-L.; Wu, H.-B.; Sowade, E.; Baumann, R.R.; Wang, Y.; Gu, F.-Q.; Feng, Z.-S. Structural regulation of silver nanowires and their application in flexible electronic thin films. *Mater. Des.* **2018**, *154*, 266–274. [CrossRef]
123. Mindemark, J.; Lacey, M.J.; Bowden, T.; Brandell, D. Beyond PEO—Alternative host materials for Li+-conducting solid polymer electrolytes. *Prog. Polym. Sci.* **2018**, *81*, 114–143. [CrossRef]
124. Bora, P.J.; Vinoy, K.; Ramamurthy, P.C.; Madras, G. Electromagnetic interference shielding efficiency of MnO_2 nanorod doped polyaniline film. *Mater. Res. Express* **2017**, *4*, 025013. [CrossRef]
125. Bora, P.J.; Vinoy, K.; Ramamurthy, P.C.; Madras, G. Electromagnetic interference shielding effectiveness of polyaniline-nickel oxide coated cenosphere composite film. *Compos. Commun.* **2017**, *4*, 37–42. [CrossRef]
126. Raicheff, R.; Mladenov, M.; Stoyanov, L.; Boshkov, N.; Bachvarov, V. Novel current collector and active mass carrier of the zinc electrode for alkaline nickel-zinc batteries. *Bulg. Chem. Commun.* **2016**, *48*, 61–65.
127. Tian, Z.; Zhao, Z.; Yang, K.; Peng, K.; Zong, C.; Lai, Y. Communication—Solvothermal Synthesis of Bi_2O_3@ ZnO Spheres for High-Performance Rechargeable Zn-Ni Battery. *J. Electrochem. Soc.* **2019**, *166*, A208–A210. [CrossRef]
128. Phang, S.W.; Tadokoro, M.; Watanabe, J.; Kuramoto, N. Synthesis, characterization and microwave absorption property of doped polyaniline nanocomposites containing TiO_2 nanoparticles and carbon nanotubes. *Synth. Met.* **2008**, *158*, 251–258. [CrossRef]

129. Petrovski, S.; Bouchet, F.; Petrovski, A. Data-driven modelling of electromagnetic interferences in motor vehicles using intelligent system approaches. In Proceedings of the 2013 IEEE INISTA, Albena, Bulgaria, 19–21 June 2013; pp. 1–7.
130. Ram, R.; Rahaman, M.; Khastgir, D. Electromagnetic interference (EMI) shielding effectiveness (SE) of polymer-carbon composites. In *Carbon-Containing Polymer Composites*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 339–368.
131. Shahzad, F.; Alhabeb, M.; Hatter, C.B.; Anasori, B.; Hong, S.M.; Koo, C.M.; Gogotsi, Y. Electromagnetic interference shielding with 2D transition metal carbides (MXenes). *Science* **2016**, *353*, 1137–1140. [CrossRef]
132. Ghosh, S.; Ganguly, S.; Das, P.; Das, T.K.; Bose, M.; Singha, N.K.; Das, A.K.; Das, N.C. Fabrication of reduced graphene oxide/silver nanoparticles decorated conductive cotton fabric for high performing electromagnetic interference shielding and antibacterial application. *Fibers Polym.* **2019**, *20*, 1161–1171. [CrossRef]
133. Mondal, S.; Ganguly, S.; Das, P.; Khastgir, D.; Das, N.C. Low percolation threshold and electromagnetic shielding effectiveness of nano-structured carbon based ethylene methyl acrylate nanocomposites. *Compos. Part B Eng.* **2017**, *119*, 41–56. [CrossRef]
134. Burger, N.; Laachachi, A.; Ferriol, M.; Lutz, M.; Toniazzo, V.; Ruch, D. Review of thermal conductivity in composites: Mechanisms, parameters and theory. *Prog. Polym. Sci.* **2016**, *61*, 1–28. [CrossRef]
135. Abbasi, H.; Antunes, M.; Velasco, J.I. Recent advances in carbon-based polymer nanocomposites for electromagnetic interference shielding. *Prog. Mater. Sci.* **2019**, *103*, 319–373. [CrossRef]
136. Wu, G.; Jia, Z.; Zhou, X.; Nie, G.; Lv, H. Interlayer controllable of hierarchical MWCNTs@ C@ FexOy cross-linked composite with wideband electromagnetic absorption performance. *Compos. Part A Appl. Sci. Manuf.* **2020**, *128*, 105687. [CrossRef]
137. Yu, L.; Lan, X.; Wei, C.; Li, X.; Qi, X.; Xu, T.; Li, C.; Li, C.; Wang, Z. MWCNT/NiO-Fe_3O_4 hybrid nanotubes for efficient electromagnetic wave absorption. *J. Alloy. Compd.* **2018**, *748*, 111–116. [CrossRef]