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Review

Textile Fabrics as Electromagnetic Shielding Materials—A Review of Preparation and Performance

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Abstract: Shielding of instruments and humans from electromagnetic interference (EMI) has become increasingly important during the last decades due to more and more machines and devices radiating electromagnetic waves. While several applications can use rigid shields, more flexibility is enabled by developing bendable, drapable, ideally even stretchable EMI shielding. Textile fabrics can have these properties, combined with potentially good mechanical properties, depending on the textile structure and the chosen material. On the other hand, the necessary physical properties, especially conductivity and magnetic properties, cannot be taken for granted in normal textile fabrics. These properties have to be added by conductive yarn or layer coatings, integration of conductive or magnetic fibers, producing intrinsically conductive or magnetic fibers, etc. The article gives a critical comparison of the properties of materials typically used for this purpose, such as intrinsically conductive polymers, metal-coated fabrics and metal wires, MXene coatings, MXene fibers, carbon coatings, and fibers. The review concentrates on thematically suitable papers found in the Web of Science and Google Scholar from the last five years and shows that especially MXenes are highly investigated recently due to their high conductivity and EMI shielding effectiveness, while other conductive and magnetic coatings and fibers are nevertheless still interesting for the preparation of EMI shielding textile fabrics.

Keywords: shielding effectiveness; conductive coating; magnetic properties; porosity; cover factor

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1. Introduction

Electromagnetic interference (EMI) shielding materials are capable of protecting humans, instruments, etc. from electromagnetic (EM) irradiation by absorbing or reflecting the radiation, often combining both aspects [1,2]. EM shielding is used to minimize exposure by electromagnetic radiation, recently especially in the context of cyber security, i.e., protection of electronic equipment against the influence of external electromagnetic disturbances. For this purpose, textile fabrics are often taken into account since they are flexible, drapable, lightweight, and relatively thin.

Due to the secondary electromagnetic irradiation of reflection by conductive materials, absorption is often regarded as the ideal mechanism of EMI shielding [3,4]. Such EMI shielding is becoming more and more important due to an increasing number of emitters on the one hand and new standards, e.g., regarding medical electrical equipment, on the other hand [5]. Typical frequency ranges in which shielding materials are tested are 10^4–10^{12} Hz due to power lines, motors, or computers [6,7], while other experiments concentrate on low-frequency or quasistatic measurements, as occurring in magnetic resonance tomography, etc. [8,9]. These different frequency ranges necessitate different physical properties of the shielding materials, i.e., especially magnetic properties for shielding of static magnetic fields, grounded conductive materials for shielding static electric fields, and, again, conductive materials for high-frequency EM fields [10].

The shielding effectiveness *SE* is composed of shielding by reflection, absorption, and multiple-reflection inside the shielding material, and is measured as $SE = 20 \log T^{-1}$ or as $SE = 10 \log (P_0/P_t)$, with the transmission coefficient T, the power P_0 without shielding, and the power P_t with shielding [11,12]. For detailed calculations based on calculation theory and Schelkunoff theory, the reader is referred to [2]. A recent overview of potential shielding mechanisms as well as measurement techniques for electromagnetic shielding and related parameters is given in our previous review of EMI shielding by electrospun nanofiber mats [13]. Here, we concentrate on common "macroscopic" textiles, excluding nanofibers. Textile-based EMI shielding has been investigated more deeply recently, as Figure 1 shows, with this strongly increased interest being based on the introduction of new materials classes into EMI shielding textile coatings, such as MXenes and 1D or 2D carbon modifications. Especially for researchers starting in this emerging field of research, this overview will be supportive.

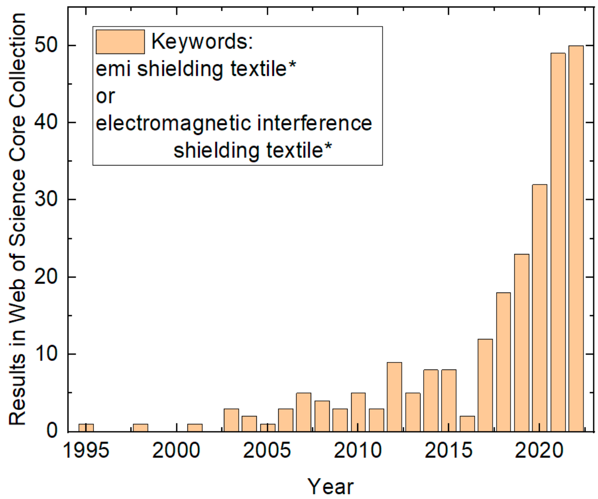

Figure 1. Numbers of results in the Web of Science Core Collection for the keywords given in the inset, counted on 12 January 2023.

We explain the physical properties related to EMI shielding in brief, followed by a broad overview of recent studies increasing the EMI shielding properties of differently functionalized textile fabrics.

2. Physical Properties and Their Measurements

As explained above, EMI shielding is based of reflection, absorption, and multiple reflections inside the shielding fabric [11]. Thus, electrical and magnetically conductive materials are advantageous due to large reflection losses, while absorption losses necessitate electric or magnetic dipoles in the material and are supported by high electrical conductivity and magnetic permeability. The fabric thickness, porosity, and amount of conductive, magnetic, and dielectric materials naturally influence the EMI shielding properties of textiles. Multiple reflections must be also taken into account for thin shielding layers, with a thickness similar to the skin depth [14]. Mathematically, the transmission coefficient of an electromagnetic wave is defined by

$$T = \frac{E_t}{E_0} = \frac{H_t}{H_0} \quad (1)$$

where E_0 (H_0) denotes the electric (magnetic) field intensity without shielding, and the values E_t (H_t) with shielding, respectively [12]. The shielding effectiveness SE is usually calculated by

$$SE = 20\log\frac{1}{T} = 20\log\frac{E_0}{E_t} = 20\log\frac{H_0}{H_t} = 10\log\frac{P_0}{P_t} \quad (2)$$

with P_0 (P_t) being defined as the power for the measurement without (with) shielding [12]. The shielding effectiveness SE is composed of shielding due to reflection (R), absorption (A), and multiple reflections (M) [11]:

$$SE = SE_R + SE_A + SE_M \quad (3)$$

As for the high-frequency properties of good shielding materials, they are determined by the electrical conductivity and thickness of the material. Measuring the conductivity of textile fabrics necessitates a more sophisticated setup than measuring the conductivity of a metal sheet or the like due to the problematic contact between the textile fabric and the measurement equipment which can be overcome, e.g., by four-probe measurements, well-fitting contact clamps exerting a standard pressure, additional solder lines on the textile fabrics, etc. [15–17]. Conductive properties of textile fabrics are useful in many smart textile applications and thus are often measured and consequently improved [18–20].

Magnetic properties are important in the context of shielding low-frequency or static magnetic fields. Magnetic properties are usually performed by superconducting quantum interference device (SQUID), alternating gradient magnetometer (AGM), vibrating sample magnetometer (VSM), or the like [21–24], while magneto-optical measurements (e.g., magneto-optic Kerr effect, MOKE) are highly challenging on rough surfaces and recently not available for textile materials [25]. Magnetic properties of textile fabrics are less often investigated since they are correlated with fewer applications.

For investigations of the EMI shielding of different materials, several methods are defined, which can be subdivided into open-field (free-space) methods, shielded-box methods, shielded-room methods, and coaxial transmission-line methods (e.g., according to ASTM D4935 standard), which can be applied in different frequency ranges and necessitate different amounts of time and equipment [26]. Geetha et al. describe the methods briefly as follows [26]:

- With coaxial transmission lines, planar specimens are investigated. Sample preparation needs to be done carefully; measurements necessitate reference measurements which makes them time-consuming, necessitating minutes to hours for each spectrum. This technique is usually applied in the frequency range from 10 kHz to 1 GHz.
- In the open field (free space) method, a large distance (30 m) is applied between the device and the receiving antenna. Differences in product assembly may lead to large differences in the results, reducing the reproducibility of these measurements.
- The shielded box method uses a metal box with a sample port in one wall. The receiving antenna is inside the box, the transmitting antenna outside. The electrical contact between the test specimens and the shielded box is difficult to establish; besides, the frequency range is limited to approximately 500 MHz. Reproducibility was shown to be low, comparing investigations in different laboratories.
- The shielded room method is similar to the shielded box method. An anechoic chamber, usually with a ground area 2.5 m^2, is used for this test, resulting in the necessity to use large test specimens to investigate shielding between the transmitting and the receiving antenna, making this method unsuitable for specimens which can only be produced in small sizes [26].

For a more detailed discussion of the effect of these physical properties of EMI shielding materials and their measurements, the reader is referred to [13].

3. MXene

While many approaches to prepare textile fabrics with EMI shielding properties are based on metal or carbon coatings or fibers, one new approach is more and more often found in the literature, using MXenes to prepare conductive coatings and sometimes even fibers. This section describes which materials belong to MXenes and how they can be used to prepare EMI shielding textile fabrics.

3.1. Different MXenes and Their Preparation

MXenes are two-dimensional layered materials containing early transition metal carbides, nitrides, and carbonitrides [27]. They are prepared by starting from so-called three-dimensional MAX phases, where MAX is the abbreviation of $M_{n+1}AX_n$ with (n = 1, 2, 3), and M denotes an early *d*-block transition metal (i.e., Ti, Sc, V, Cr, Ta, Nb, Zr, Mo, or Hf), A means a main group *sp* element especially from the groups 13 and 14, and X represents C and/or N [28]. By etching the *sp* element layers out of the MAX phases, two-dimensional MXenes (without the "A") remain [29]. MXenes have additional terminated functional groups (e.g., -OH, -O, -F) named "T", resulting in their general formula $M_{n+1}X_nT_x$ [30].

More than 60 of these MXenes have been found, yet with different metal or ceramic properties, depending on the chemical constitution [31]. One of the problems of MXenes is their susceptibility to oxidation in humid or aqueous environments, necessitating either excluding water vapor to reach them or increasing their stability against oxidation [32].

3.2. MXene Coatings

Due to their two-dimensional nature, MXenes are mostly applied in the form of coatings on textile fabrics, either solely or together with intrinsically conductive polymers, metals, or carbon-based fillers. Li et al. reported electromagnetic interference shielding combined with the potential applications of photothermal conversion and solar water evaporation, using a layer-by-layer assembly method on a textile fabric [33]. They combined SiO_2 nanoparticles/poly(dimethylsiloxane) (PDMS) and 1*H*,1*H*,2*H*,2*H*-perfluorooctyltriethoxysilane (PFOTES) to reach superhydrophobicity (i.e., a water contact angle larger than 160°) as well as MXene to reach a high conductivity of 1200 S/m, resulting in an EMI shielding of 36 dB.

Zheng et al. prepared bark-shaped MXene/textiles which showed not only high EMI shielding, but also good Joule heating and good piezoresistive sensing [34]. The bark-shape was suggested to enhance multiple interfaces scattering of EM waves to improve the EMI shielding effectiveness. To reach this shape, the authors used the pad-drying technology normally used in fabric dyeing to apply MXene flakes on a cellulose nonwoven. In their study, they synthesized $Ti_3C_2T_x$ MXene sheets, immersed a cellulose nonwoven into an aqueous MXene solution and used a padder to remove the excess water before drying, repeating this cycle 1–9 times. This process is depicted in Figure 2. By increasing the number of pad-drying cycles from 3–9, the EMI shielding effectiveness could be increased from 3.2 dB to 36.3 dB in a range from 8.2 GHz–12.4 GHz (X-band) due to improving single conductive paths towards a conductive network, which was also visible in the decreased sheet resistance for larger numbers of pad-drying cycles.

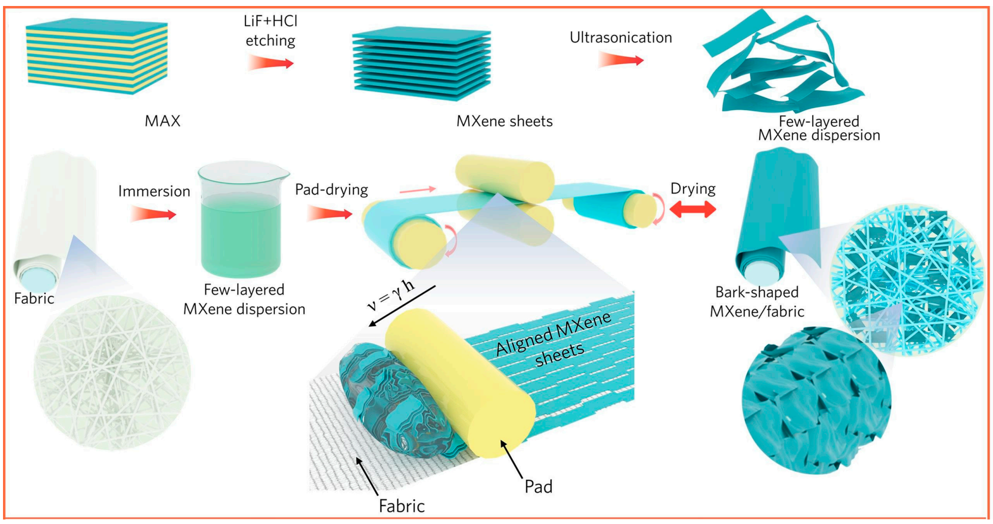

Figure 2. Illustration of the preparation of bark-like Mxene decorated cellulose fabrics. From [34], copyright (2022), with permission from Elsevier.

Using a spray-drying procedure, Zhang et al. reported good electrical conductivity and low sheet resistance of 5 Ω already for low MXene loading of 6 wt% on a woven cotton fabric, resulting in efficient EMI shielding and well-balanced Joule heating as well as the possibility of using this fabric as a strain sensor to detect human motion [35]. Besides EMI shielding and thermal heating, Yu et al. also mentioned bactericidal activity of their Mxene-decorated, polydopamine (PDA) modified cellulose nonwovens [36]. They reached an EMI shielding of 38.6 dB in the X-band, good heating performance, and a very high bactericidal efficacy of more than 99.99% against *E. coli* and *S. aureus*.

Working on basalt fiber fabrics, Yu et al. used multilayer spray-drying to coat $Ti_3C_2T_x$ nanosheets and $Ti_3C_2T_x$/natural rubber layers, the latter protecting the inner $Ti_3C_2T_x$ coating and additionally formed conductive connections between the conductively coated basalt fibers [37]. The Mxene phase was prepared by etching Al from commercially available Ti_3AlC_2 powder, using LiF, followed by exfoliation by ultrasonication in an ice bath under Ar flow. With this procedure, a sheet resistance of (5 ± 3) Ω was reached with the maximum tested $Ti_3C_2T_x$ amount of 4 mg/cm^2, resulting in EMI shielding up to 41 dB in the X-band.

Yao et al. also combined Mxene with a polymer network, here PDMS, to give a textile fabric EMI shielding, electro-thermal and photo-thermal conversion as well as pressure-sensing properties [38]. While different numbers of dip-coating cycles into a suspension of $Ti_3C_2T_x$ Mxene were examined, these coated textile fabrics were dipped into low cross-linked PDMS and thermally cured to reach adhesive properties. While samples without Mxene showed nearly no EMI shielding in the X-band, Mxene coated samples with 3–9 dip-coating cycles reached more than 30 dB along the whole X-band, mostly due to absorption.

Much higher EMI shielding values were even reported by Uzun et al. who used dip-coating of cotton and linen fabrics in $Ti_3C_2T_x$ Mxene dyes [39]. While 4 dip-coating cycles resulted in approx. 40 dB shielding in the X-band, 24 dip-coating cycles increased this value to approx. 80 dB. Interestingly, these values were decreased by only 8% and 13% for cotton and linen fabrics, respectively, after storing them for 2 years under ambient conditions.

Even higher values were reported from groups who combined Mxene coating with intrinsically conductive polymers, such as polyaniline (Pani), polypyrrole (Ppy), polythiophene, polyphenyl sulfide, polyacetylene, polyphenylene, polyphenylene vinylene, or poly (3,4-ethylene dioxythiophene) (PEDOT) [40]. Wang et al., e.g., applied Ppy-modified Mxene sheets on poly(ethylene terephthalate) (PET) textiles and subsequently coated them with silicone, resulting in high electrical conductivity around 1000 S/m and EMI shielding efficiency of approx. 90 dB as well as good Joule heating performance [41].

Combining Mxene with Pani nanowires on a carbon fiber fabric followed by PDMS coating resulted in a good conductivity of 325 S/m and EMI shielding effectiveness around 35 dB [42]. A 3D nanoflower structure from $Ti_3C_2T_x$/Pani was prepared by Li et al. by polymerization of aniline monomer on single-layer $Ti_3C_2T_x$ nanosheets, resulting in a shielding effectiveness of 52 dB in the X-band [43]. Previously, combining Mxenes and Pani in a layer-by-layer assembly, Yin et al. reached a conductivity of 25 S/m and an EMI shielding efficiency of 26 dB [44].

Other authors combined Mxene with metal, e.g., with Ag nanowires (Ag NWs), reaching an EMI shielding efficiency of 54 dB in the X-band [45], or with Fe_3O_4 hollow nanospheres, resulting in low sheet resistance of about 5 Ω and high EMI shielding effectiveness of 33 dB, enabling tuning the shielding mechanism between absorption and reflection [46]. Alternatively, combining MXene with carbon-based conductive materials is reported, e.g., a $Ti_3C_2T_x$/carbon nanotube (CNT) coated thermoplastic polyurethane nonwoven, leading to high EMI shielding around 43 dB [47].

As these examples show, there are many possibilities to apply MXene coatings on textile fabrics to prepare EMI shielding fabrics. However, only few reports about MXene fibers can be found in the literature. They are discussed in the next section.

3.3. MXene Fibers

One possibility to prepare MXene fibers is to use them as core or shell in coaxially spun fibers, as described by Liu et al. and depicted in Figure 3 [48]. The authors prepared a cellulose spinning solution by dissolving cotton linter pulp with LiOH solution, urea, and distilled water, and received regenerated cellulose after putting the cellulose dispersion into an acetic acid coagulation bath. $Ti_3C_2T_x$ MXene was mixed with graphene oxide (GO) to prepare the other spinning solution. Both solutions were coaxially spun into a rotating bath, with cellulose or MXene/GO building the core (Figure 3a). In this way, it was possible to prepare meter-long hollow fibers from regenerated cellulose and GO/MXene (Figure 3b) which could lift a mass of 100 g (Figure 3c). These fibers were found to have conductivities up to 10^5 S/m. The EMI shielding effectiveness depended on the mesh grid spacing of woven or sewn structures prepared from these fibers, showing values around 27–33 dB for a single layer with the smallest grid spacing and up to more than 100 dB for 3 layers, building an only 12 µm thick MXene film.

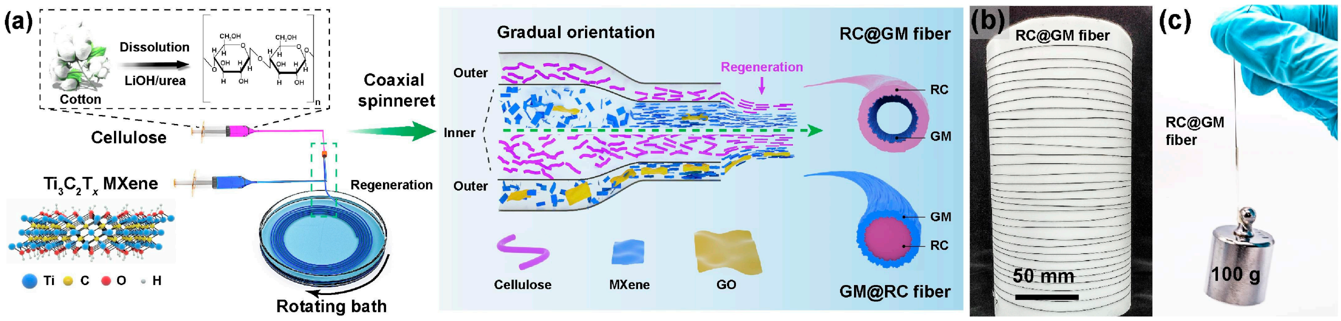

Figure 3. (**a**) Schematic illustration of coaxial spinning of hollow RC@GM fibers (upper) and solid GM@RC fibers (below); (**b**) meter-long hollow RC@GM fiber; (**c**) a single RC@GM fiber can sustain a mass of 100 g. From [48], copyright (2022), with permission from Elsevier.

The same group also showed coaxial spinning of core-shell fibers with MXene core and aramid nanofiber shell [49]. In this way, they reached a conductivity of 3×10^5 S/m and an EMI shielding efficiency of 83 dB.

Zhou et al. suggested preparing compact MXene fibers by combining wet spinning from a MXene-glutaraldehyde (GA) solution with thermal drawing, resulting in significantly increased tensile strength and toughness, conductivity around 8×10^5 S/m and EMI shielding effectiveness of 50–60 dB in the X-band [50].

Instead of these filament-based approaches, Xiong et al. used short MXene fibers, produced by wet-spinning, to produce a MXene nonwoven by wet-assembly [51]. In this way, a strong interfiber bonding was reached. This MXene nonwoven showed high conductivity around 70,000 S/m and an EMI shielding effectiveness of 75 dB in the X-band.

Another path was suggested by Zheng et al. who prepared a core–shell aerogel from reduced graphene oxide (rGO) with MXene by wet-spinning and freeze-drying [52]. In this way, they reached an EMI shielding effectiveness up to 83 dB which degraded by only 17% after 120 days.

As these few examples show, MXene fibers are challenging to produce and thus are less often prepared for EMI shielding applications. Carbon fibers and metal wires, on the other hand, are commercially available in diverse qualities and diameters; however, EMI shielding is nevertheless mostly reached by functionalizing textile fabrics with carbon or metal containing coatings, as the next sections will show.

4. Metals

Many metals, such as Cu, Al, or Ag, have very high conductivities. Lower conductivities are usually found in transition metals [53] as well as in thin films [54], limiting the range of materials as well as the expected conductivities for very thin coatings. Nevertheless, many attempts are made to produce EMI shielding coatings with metals included in the form of nanoparticles, nanowires or other shapes, partly taking advantage of the metals' magnetic properties.

4.1. Metal Coatings

Smart textiles often contain metal coatings on fabrics for diverse applications, such as strain sensors for human motion detection [55], electrodes for ECG monitoring [56], textile batteries and supercapacitors [57], textile-based solar cells [58], or more special systems such as metal-organic frameworks (MOFs) to hydrolyze organophosphonate-based nerve agents [59]. Correspondingly, a large number of research groups reported different possibilities to add EMI shielding properties to textile fabrics by coatings containing metals, either solely, e.g., in the form of a thin layer around the textile fibers, or combined with a binder, coating a full textile layer.

Hu et al., e.g., described copper-coating a polyester (PES) nonwoven by chemical surface activation of the fabric, followed by immersing in hydrochloric acid and then in a bath containing salt $CuSO_4$, before a reducing bath containing borohydride led to the formation of Cu nanoparticles on the fiber surfaces [60]. In this way, a dense copper layer was formed on the fibers, as depicted in Figure 4. The authors found volume resistivities between 1 Ωm and 5 Ωm and a shielding effectiveness, measured between 30 MHz and 1.5 GHz, between 42 dB and 63 dB, depending on the coating thickness (cf. Figure 4) and the frequency. For multi-layer systems, up to approx. 90 dB were reached with 3–5 layers of the Cu-coated nonwovens.

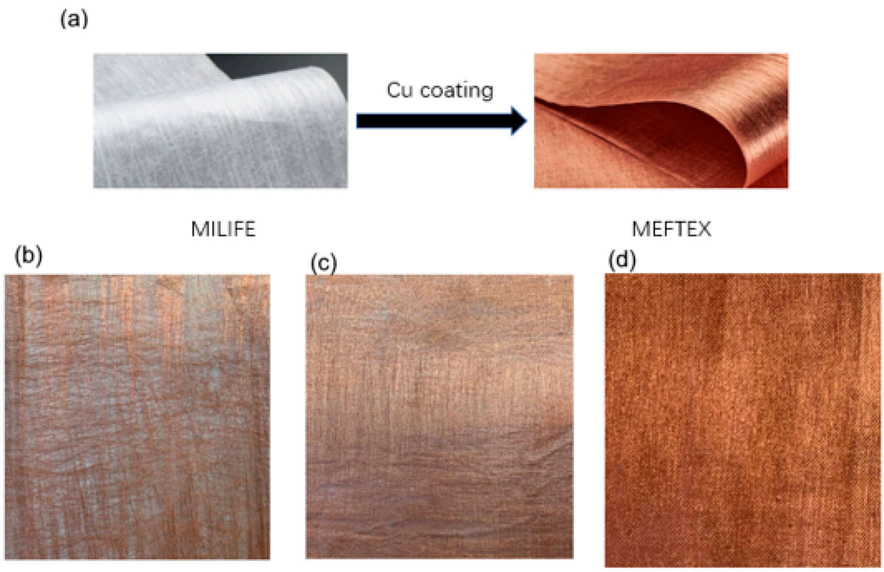

Figure 4. (**a**) Copper coating the PES fabric "MILIFE", resulting in "MEFTEX" sample; (**b**) MEFTEX from MILIFE sample with areal weight 10 g/m^2; (**c**) MEFTEX 20 g/m^2; (**d**) MEFTEX 30 g/m^2. Image sizes are 20 cm × 20 cm. From [60], copyright (2021), the authors.

The same base material was investigated after electroless plating of Cu particles on the PES nonwoven, using NaOH treatment before activation in tin(II) chloride and palladium(II) chloride solution, followed by electroless copper plating bath including $CuSO_4$ and other chemicals [61]. In this way, a shielding effectiveness between approx. 30 and 55 dB was reached in the frequency range of 0.5 GHz–1.5 GHz.

Another study based on Cu coating the same PES nonwoven used activation by hydrolysis or plasma treatment and metallization in a strong alkali bath, followed by silanization with different types of silane to stabilize the copper layer on the fibers [62]. Different silanes showed quite different effects on the EMI shielding effectiveness measured at a frequency of

1.5 GHz, either leaving the original value nearly unaltered, or nearly dividing it by a factor of 2, as well as nearly doubling it, depending on the chosen silane.

Another important metal, often chosen to reach high conductivity in coatings, is silver. Hong et al. oxidized a cellulose textile surface, thus converting hydroxymethyl to carboxyl moieties under sonochemical activation, before Ag nanoparticles were generated directly on the oxidized cellulose [63]. These textiles had a low sheet resistance of 1 Ω and a high EMI shielding efficiency of 47 dB for a single layer or 69 dB for a triple-layer system.

Combining Ag nanowires with Fe_3O_4 nanoparticles, Zong et al. produced an EMI shielding fiber coating [64]. The authors impregnated a cotton fabric, cleaned with NaOH solution, in a commercially available Ag nanowire solution in isopropyl alcohol (IPA), using different numbers of dip-coating cycles. Afterwards, a Fe_3O_4/ethanol solution was sprayed onto the Ag nanowire-coated cotton fabric, before the fabric was dip-coated in silicone oligomer/n-hexane solution to reach a PDMS coating which increased the adhesion of Ag nanowires and Fe_3O_4 nanoparticles on the cotton fabric. In this way, shielding efficiencies around 60 dB in the X-band were reached for a single fabric and up to approx. 100 dB for three fabric layers.

A similar mixture of Ag nanowires with CNTs, poly(tetrafluoroethylene) (PTFE) nanoparticles, and fluoroacrylic polymer was suggested by Jia et al. who reached more than 51 dB EMI shielding in the as-prepared functionalized fabric, which was mostly retained after 5000 stretching-releasing cycles, ultrasonic treatment for 60 min, peeling tests up to 100 cycles, and introduction in strong acidic/alkaline solutions and various organic solvents, thus showing high robustness against mechanical and chemical impact [65].

Nickel belongs to the metals which are not only conductive, but also ferromagnetic. Moazzenchi and Montazer placed a PES woven fabric in nickel acetate solution with hydrazine hydrate, leading to formation of Ni nanoparticles on the fabric surface [66]. By this, a resistivity less than 2 Ω and ferromagnetic properties with a coercivity around 100 Oe were found as well as an EMI shielding effectiveness around 32 dB.

Duan and Lu firstly plated acetate fabrics with nickel and then coated them with carbon nanotubes from a silk sericin dispersion, resulting in abundant nickel ions being adsorbed on the CNT surfaces, leading to an EMI shielding effectiveness larger than 30 dB [67].

Bai et al. used electroless deposition of the ternary alloy Ni-W-P on a polyamide (PA) fabric to reach an EMI shielding effectiveness of 44 dB within the range of 2 GHz–12.5 GHz [68]. They also reported good durability of this effect after heating to 180 °C, ultrasonication, and repetitive peeling tests.

To reach this stability against mechanical, thermal, and chemical impact, many researchers combined metal coatings with protective polymer layers or embedded metal nanoparticles or nanowires in polymeric coatings. Liu et al., e.g., embedded Ag nanowires in polyvinyl butyral (PVB) ethanol solution in which they immersed a textile fabric, resulting in an EMI shielding effectiveness of 59 dB in the range of 5–18 GHz [69]. Ag nanowires integrated in a polyurethane (PU) protective layer, Jia et al. prepared an EMI shielding textile with shielding effectiveness of 64 dB, which was retained to 89% after 20 machine washing cycles and to 82% after 5000 stretching cycles, making this coated fabric useful for garments or other applications where textiles have to be washed [70].

Additional flame-retardant properties are reported by Zhang et al. who used dip-coating of a cotton fabric alternatingly into a cationic polyethylenimine (PEI) solution and an anionic phytic acid solution, before they were dipped into an Ag nanowire/ethanol suspension, as depicted in Figure 5 [71]. This multi-layer approach led to immediately extinguishing the flame in vertical flame tests after removing the fire source, as well as electrical conductivity up to 2400 S/m and shielding effectiveness between 20 dB and 35 dB in the X-band, depending on the amount of Ag nanowires adsorbed on the samples.

It should be mentioned that commercially available yarns containing silver-coated fibers or filaments are scarcely mentioned in studies on EMI shielding textiles in spite of reasonable EMI shielding effectiveness values around 25–50 dB [72–74], possibly due to oxidation during handling and washing [75–77].

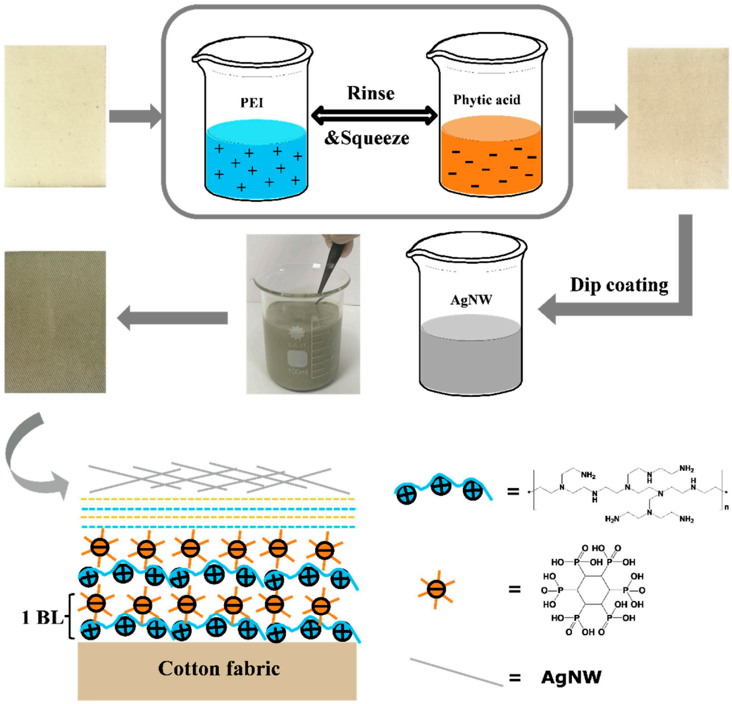

Figure 5. Illustration of layer-by-layer treatment and dip-coating method on cotton fabrics. From [71], copyright (2019), with permission from Elsevier.

In addition to these conventional metals in the form of nanowires or nanoparticles, some researchers reported more special materials, such as liquid metals, i.e., metals with low melting points such as Pb, In, Ga, Sn or Bi [78], e.g., in the form of liquid metal/PDMS coating which reached an EMI shielding efficiency of 73 dB in relaxed state and 52 dB at 50% strain as well as high retention after 5000 stretching cycles [79].

Besides textile coatings, metals can also be inserted in their macroscopic form, i.e., as wires, as described in the next section.

4.2. Metal Wires

Similar to silver-coated polyamide filament yarns, there are also yarns containing stainless steel fibers or filaments commercially available, often used for diverse smart textile applications [80–84]. It should be mentioned that stainless steel fibers are often magnetic and thus may be well-suitable for EMI shielding applications [85,86]. These commercially available yarns, however, are rarely reported in studies on EMI shielding textile fabrics [87,88]. Instead, some groups report about self-spun yarns including different stainless steel wires.

Gupta et al., e.g., prepared a ring-spun composite yarn from stainless steel (20 wt%) and polyester fibers which they used as the core of a sheath core yarn with PET fibers as sheath material [89]. Fabrics woven from this yarn reached EMI shielding effectiveness of 31–35 dB in the range of 8.2–18.0 GHz.

A wrap yarn with stainless steel filament core and carbon helical yarns as wrapping threads was prepared by Krishnasamy et al. who reported EMI shielding effectiveness values around 5–28 dB for different wrapping densities in the frequency range of 4–8 GHz [90].

Li et al. prepared composites from warp-knitted stainless steel meshes and thermoplastic polyurethane (TPU) with CNTs and found a high conductivity of 1348 S/m and an EMI shielding effectiveness of 22 dB in the X-band which was more than doubled, compared with the pure warp-knitted mesh [91].

Most studies on metal wires used to prepare EMI shielding textiles, however, were published several years ago [92–94], which may be attributed to the relatively low EMI shielding effectiveness reached with these approaches, as compared to the previously described metal-containing coatings or MXene coatings.

5. Carbon

Another well-known method to make textile fabrics conductive, namely by carbon coatings or carbon fibers, has been investigated more deeply during the last years.

Carbon-based coatings are very often used on textiles, e.g., to produce batteries and supercapacitors [95], garment-integrated sensors [96], photocatalytic degradation of dyes and organic pollutants [97,98], and more applications in the area of smart and electronic textiles [99–101]. On the other hand, carbon yarns are commercially available and thus often used in diverse applications. However, due to the fragility of macroscopic carbon fibers, they are most often embedded in a resin or in cement to form a composite [102–104]. Carbon exists in diverse shapes, from carbon quantum dots [105] to graphene [106] and CNTs [107], from carbon black [108] to graphite [109]. Depending on their dimensionality, i.e., whether they are zero-dimensional (0D), one-dimensional (1D), two- or three-dimensional (2D or 3D) as well as their crystallography, carbon can have quite different conductivities [110]; however, many of these modifications are highly conductive and thus are well suited for EMI shielding applications, as described in the next sub-sections.

5.1. Carbon Coatings

Carbon coatings on textile fabrics, applied to improve the EMI shielding effectiveness of a fabric, often contain carbon nanotubes. Due to their one-dimensional shape and the correspondingly highly anisotropic conductivity, the orientation of such carbon nanotubes significantly influences their effect on EMI shielding properties. Lan et al. thus describe a new approach to reach high axial alignment of CNTs along cotton fibers, based on spontaneous capillary-driven self-assembly [111]. By this technique, EMI shielding effectiveness values of 21.5 dB in the X-band and 20.8 dB in the Ku band were reached, which was nearly two orders of magnitude higher than the values for disordered CNT microstructure. Besides, they reported a high stability against bending, scratching, and washing, making this coating suitable for portable and wearable electronics. Without such special techniques to reach a defined orientation of the CNTs, Moonlek et al. reported an EMI shielding effectiveness of 8 dB or 19 dB for relatively thick silk fabric/natural rubber latex/CNT composites of 2 mm or 8 mm thickness, respectively [112].

Another possibility to increase the EMI shielding effectiveness of CNT coatings is based on adding other carbon fillers, such as graphene. Dai et al. added 80% CNT and 20% graphene to waterborne PU and dipped a PES/cotton woven fabric into this dispersion [4]. Besides high hydrophobicity, they found a conductivity of 64 S/m for 3% mixed filler, which is higher than 50 S/m for the textile with 3% CNT containing coating and 7.7 S/m for the textile with 3% graphene containing coating. Correspondingly, a relatively high EMI shielding effectiveness around 35 dB in the X-band was reached by these samples.

Another way to increase the EMI shielding effectiveness was suggested by Gupta et al. who added highly dielectric ZnO nanoparticles to reduced graphene oxide (rGO) in a textile coating [113]. In this way, they reached a shielding effectiveness of 55 dB which was mostly (82%) based on absorption, as it is desired in most shielding applications.

On the other hand, several groups investigated textile coatings with combinations of carbon and metal fillers to reach high conductivity. Xu et al. prepared a CNT film by chemical vapor deposition, followed by metallization with a Cu nanolayer, using electron beam evaporation [114]. To prepare a sandwich textile, both sides were covered by PA6 nanofibers, electrospun on them, as depicted in Figure 6 [114]. In this way, they reached an EMI shielding effectiveness around 50–55 dB in the frequency range of 1.7–5.85 GHz, which was higher than the value of the pure CNT film, which was approx. 40 dB, indicating the importance of the additional metal deposition.

Besides Cu, Ag nanowires or nanoparticles are often used in combination with graphene or other carbon fillers. Sim et al. prepared silver nanowire/graphene oxide (GO) coated textile fabrics, reaching an EMI shielding effectiveness of 72 dB at 8.2 GHz, which was mostly retained after cracking and subsequent self-healing [115]. Using Ag nanoparticle-decorated rGO sheets, applied on a textile fabric by non-ionic polymer adhesive, Ghosh et al. reached

EMI shielding effectiveness of 27 dB in the X-band, combined with high conductivity and bactericidal effect against *E. coli* [116]. Combining CNTs with nickel ferrite ($NiFe_2O_4$) instead of Ag nanoparticles in a PDMS coating on a textile fabric, Wang et al. reached a much higher EMI shielding effectiveness of 84 dB in the X-band as well as good thermal conductivity and improved structural stability due to the coating [117].

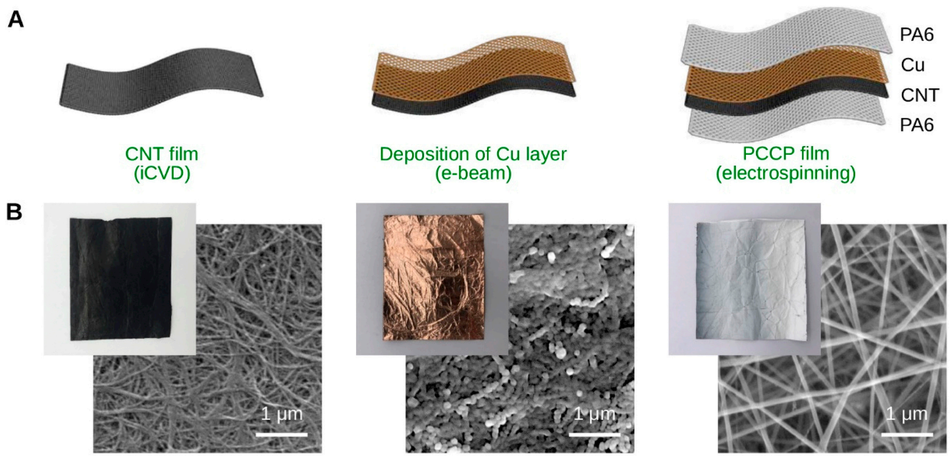

Figure 6. (**A**) Schematic of the fabrication of PCCP composite textile; (**B**) photos (10 cm × 10 cm) and SEM images of the CNT film, Cu layer and PA6 surface of PCCP textile. From [114], copyright (2020), with permission from Elsevier.

Combinations of carbon materials can not only be found with metal fillers as partners, but also common with intrinsically conductive polymers. Zou et al., e.g., showed that PANI polymerized on CNTs could improve the CNT distribution on a cotton woven fabric, obtained by dip-coating [118]. In this way, the sheet resistance was reduced by approx. a factor 5, as compared to pure CNT and PANI coatings, and the EMI shielding effectiveness was improved from around 5–6 dB for the single-material coatings to 23 dB for the composite coating.

Besides these carbon-based coatings, there are also several recent studies based on carbon fibers, either used solely or combined with metal fibers or metal coatings, as shown in the next sub-section.

5.2. Carbon Fibers and Filaments

Since carbon fibers are increasingly used in lightweight constructions nowadays, the carbon fiber waste is also increasing. Pakdel et al. addressed this problem by investigating how carbon fiber waste could be re-used in EMI shielding hybrid nonwovens [119]. For this, they combined carbon fiber scraps with a defined length of 100 mm with nylon (PA6) fibers of 75 mm length to form a nonwoven by needle-punching from carding webs with different carbon:nylon ratios, as depicted in Figure 7. While these nonwovens showed conductivities from 0.4–34 S/m, the EMI shielding effectiveness was found to be between approx. 25 dB and 80 dB, depending on the carbon fraction, the number of carding cycles and the thickness of the samples.

Hu et al. also worked with recycled carbon fibers recovered from composite waste and formed a felt by adding polymeric binder and applying a paper-making process to the fibers [120]. In this way, they reached conductivities between 17 S/m and 140 S/m, depending on the polymeric binder as well as the sample thickness, and an EMI shielding effectiveness around 30–70 dB, mostly based on reflection due to high electrical conductivity and impedance mismatch between the shielding and the neighboring air.

Besides such nonwovens, many authors investigated carbon fiber composites. Lin et al. prepared composites from different TPUs and long-fiber carbon reinforcement in the core and used these composite yarns as weft yarns in woven fabrics with polyester fiber yarns in the warp [121]. With these woven fabrics, EMI shielding effectiveness values around 8 dB–40 dB in the range of 30–3000 MHz, depending on the frequency and the fabric thickness. Similarly, Duan et al. reached up to 73 dB shielding effectiveness for a carbon fiber/TPU composite and suggested it due to its flexibility and robustness for aerospace applications [122]. Another approach was suggested by Jia et al. who carbonized a cotton fabric and coated it with nano-sized carbon black as well as PDMS, in this way reaching a shielding effectiveness of 43 dB combined with superhydrophobic properties [123].

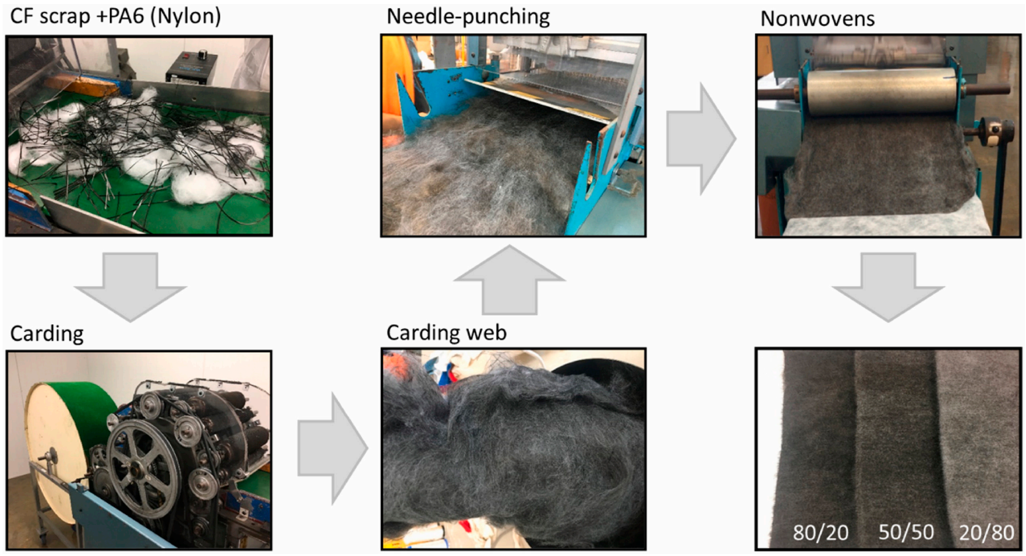

Figure 7. Production of carbon fiber/PA5 nonwovens. From [119], copyright (2021), with permission from Elsevier.

As seen before in the case of carbon-based coatings, combing carbon with metals may further improve the EMI shielding effectiveness of a textile fabric. Similarly, carbon fibers can either be coated with metal layers or nanoparticles, or additional metal nanoparticles can be embedded in the matrix or a carbon composite. Zhu et al. used the first of these methods and coated carbon fiber fabrics by electroless plating with nickel to increase their conductivity [124]. After polymerization of dopamine on the fabric to improve the interlaminar shear strength with an epoxy matrix, the composite showed not only good mechanical properties, but also an EMI shielding effectiveness of 30–35 dB in the X-band.

Abdelal stitched carbon fiber laminates with copper, titanium, Kevlar metallic and non-conductive threads, and investigated the composites after vacuum-assisted infusion, finding EMI shielding effectiveness values around 40–47 dB in the X-band, with slightly larger values for copper threads, but generally a significant increase in shielding effectiveness due to the compacter fiber arrangement in the stitched multi-layer composites [125].

Spray-coating a woven carbon fiber fabric with a highly conductive silver film, Liu and Kang reported up to 81 dB shielding effectiveness after 100 spraying cycles [126]. Adding magnetic Fe_3O_4 particles in the matrix of a carbon composite, Tang et al. reached an EMI shielding effectiveness of 38 dB in the X-band, mostly due to absorption [127].

Finally, it should be mentioned that combinations of carbon fibers with MXenes can also be found in the literature. Duan et al., e.g., prepared a composite from $Ti_3C_3T_x$ MXene, deposited on a carbon fiber fabric by electrohydrodynamic atomization, in a TPU matrix [128]. By this procedure, they reached EMI shielding effectiveness values up to 40 dB, depending on the MXene fraction, mostly based on absorption.

Besides the previously describe methods to make isolating textile fibers or textile fabrics conductive by adding conductive nanoparticles, nanowires, or blending them with metal wires or carbon fibers, another possibility to add conductive properties is coating textiles with intrinsically conductive polymers. Approaches to prepare EMI shielding textiles based on such conductive polymers are described in the next section.

6. Intrinsically Conductive Polymers

Opposite to most polymers which are isolating, some conductive polymers exist, such as poly(3,4-ethylenedioxythiophene):polystyrenesulfonic acid (PEDOT:PSS), PEDOT, polyaniline (PANI), polypyrrole (PPy), or polythiophene (PTh) [129]. Their π-conjugated orbital structure allows electron transport, resulting in a tailorable conductivity [130]. Conductive polymers are often used as coatings on yarns and textiles [131], e.g., for energy storage applications [132], in smart textiles [133], or biosensors [134]. Naturally, they are also used for EMI shielding coatings on textile fabrics, as described here.

Conductive polymers can be used solely, i.e., without other conductive materials, to provide shielding properties to a textile fabric. Rybicki et al. tested PANI as well as PPy on poly(acrylonitrile) (PAN) fabrics [135]. The conductive polymers were deposited on the woven PAN fabric by an oxidizing inkjet printing of aniline hydrochloride or pyrrole with ammonium peroxodisulfate, where one nozzle sprayed the aqueous solution of aniline hydrochloride or pyrrole, respectively, followed by the second nozzle spraying the aqueous solution of ammonium peroxodisulfate, in this way polymerizing the material. Depending on the number of PANI or PPy layers, shielding effectiveness values between 5 dB and 22 dB were found for PANI and values between 2.25 dB and 7 dB for PPy, using 1–5 layers of the conductive polymers.

By adding a thin protective layer of 1*H*,1*H*,2*H*,2*H*-perfluorooctyltriethoxysilane (POTS) on a PPy-coated fabric Zou et al. reached self-healing properties of the EMI shielding effect by microwave heating for a few seconds [136]. The functionalization process involved dip-coating into a Py monomer solution for 5 min, immersion in $FeCl_3$ aqueous solution for polymerization of PPy, repeating this process if desired, followed by washing and finally dip-coating in a POTS/ethanol solution, as depicted in Figure 8. In this way, sheet resistances of 350 Ω for 1 PPy deposition cycle down to 34 Ω after six deposition cycles were reached. The long-term stability against mechanical impact was found to be much better for the POTS-coated fibers than for pure PPy coated fabrics. The EMI shielding effectiveness was always slightly smaller for the POTS-coated fabrics than for pure PPy coatings, but reached values around 25 dB in the X-band after six deposition cycles in both cases. After mechanical impact, such as bending, twisting, or stripping, however, the POTS-coated samples showed nearly unaltered shielding properties, while those of the purely PPy coated samples were reduced to around 20 dB.

A similar PPy deposition method was investigated by Yu et al. who modified the PPy concentration in the dipping solution, followed by in situ polymerization of poly(N-isopropylacrylamide) (PNIPAAm) on the PPy-coated cotton fabrics [137]. In this way, they reached an EMI shielding effectiveness around 40 dB in the X-band, mostly based on absorption.

Gahlout and Choudhary tested PPy on different fabrics from cotton, PES, nylon and cotton/Lycra with 1–4 impregnation cycles [138]. They added sodium lauryl sulphate as a dopant to the Py solution before polymerization in $FeCl_3$ solution. The authors reported conductivities increasing with increasing numbers of impregnation cycles, reaching max. 4000 S/m on the cotton/Lycra sample and values below 10 S/m for the others. Correspondingly, the cotton/Lycra fabrics showed the highest EMI shielding effectiveness of 19 dB in the X-band, which could be increased to 25 dB by stacking two layers of this sample.

Another approach was suggested by Ghosh et al. who prepared a dip-coating suspension from PEDOT:PSS pellets and poly(ethylene glycol) (PEG) and dipped a cotton fabric for up to 25 times [139]. The conductivity for 20 dip-coating cycles reached 5000 S/m and survived bending and twisting, resulting in up to 47 dB shielding effectiveness, as compared to around 15 dB for a cotton fabric coated with pure PEDOT:PSS.

Besides these examples of EMI shielding coatings from conductive polymers without additional conductive fillers, several groups combined conductive polymers with different metals. Riaz et al. dip-coated cotton fabrics by with PEDOT:PSS/PEG for 5 cycles and afterwards removed the PSS by introducing them in H_2SO_4, followed by electroless plating with copper and silver, as depicted in Figure 9 [140]. The metallic nanofillers were additionally coupled to the fibers by a silane coupling agent to improve the durability of the coating. Measuring the EMI shielding effectiveness in the range of 100 MHz to 13.6 GHz, they found values around 6 dB for the PEDOT/PEG coated samples, increased to about 32 dB for an additional Cu layer and to about 42 dB for an additional Ag layer, measured at 8 GHz.

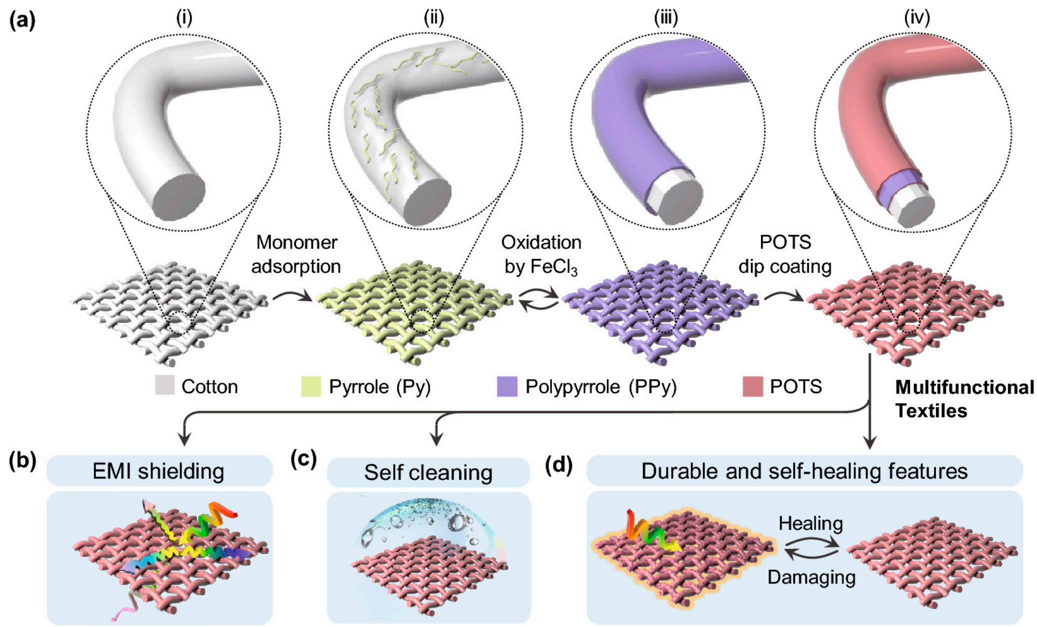

Figure 8. Preparation of PPy*n*@POTS fabrics. (**a**) Fabrication process of PPy*n*@POTS fabrics via a dip-coating approach. The desired number of PPy coating layers can be obtained by repeating the adsorption-oxidation process before the final protection layer coating of POTS. (**b**–**d**) Resulting multifunctionality of the coated fabric with high EMI shielding (PPy), self-cleaning (POTS), and durable performance assisted by near-instantaneously self-healing capability. From [136], copyright (2021), the authors. (i–iv) denote subsequent steps of the fabrication process.

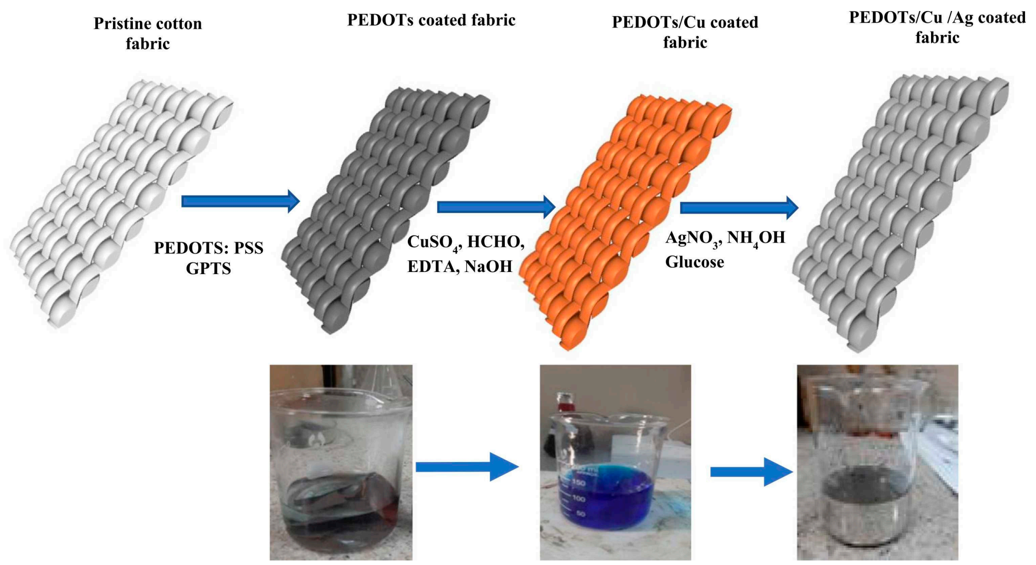

Figure 9. Preparation of Cu/Ag/PEDOT coated fabric. From [140], copyright (2022), with permission from Elsevier.

Combining PPy, Ag nanoparticles, and PEDOT:PSS, Siavashani et al. reached a similar EMI shielding effectiveness of 40 dB, nearly twice the value than with PPy/Ag nanoparticle coating, which they explained by the PEDOT:PSS filling gaps in the PPy/Ag nanoparticle coating [141]. Wang et al. used L-cysteine as a binder for Ag nanoparticles on a cotton fabric, followed by PEDOT:PSS coating to improve fixation of the Ag nanoparticles on the fabric [142]. By this technique, they reached a sheet resistance of 9 Ω and EMI shielding of 27 dB, which was nearly unaltered after stretching, bending or folding the fabric.

Instead of silver, Liu et al. performed Ni plating after PPy polymerization on warp-knitted and nonwoven PET fabrics [143]. By this technique, they reached a conductivity of 9632 S/m and an EMI shielding effectiveness of 78 dB in the X-band for the nonwoven and slightly reduce values for the warp-knitted fabric.

Finally, it should be mentioned that not only the coating and its conductivity, but also the textile structure influences the EMI shielding effectiveness, as Duan et al. showed using PPy and GO [144].

7. Summary and Discussion

As the previous sections showed, many approaches can be used to prepare textiles fabrics with EMI shielding properties. Here, we give an exemplary overview of materials, manufacturing technologies, thickness, electrical and magnetic (E/M) properties, frequency range, measured values of shielding efficiency, potentially additional properties (mechanical, thermal, waterproof, etc.) in Table 1. Most measurements were performed in the X-band, resulting in a shielding effectiveness around 30–90 dB, based on specimens with a thickness often below 1 mm.

Table 1. Comparison of textile fabrics with EMI shielding properties. E/M: electrical and magnetic; f: frequency; R_S: sheet resistance; R_V: volume resistivity; EC: electrical conductivity; H_C: coercive field; SE: shielding effectiveness (max. value).

Material	Manufact.	Thickness	E/M Properties	f	SE/dB	Other Properties	Ref.
MXene	Coating	0.62 mm	R_S = 2.2 Ω, EC = 890 S/m	X-band	35	Joule heating, pressure sensing	[34]
	Coating	0.33 mm	R_S = 5 Ω	X-band	39	Joule heating, bactericidal	[36]
	Wet-spun fibers	0.5 mm	EC = 11,360 S/cm	X-band	75	Joule heating	[50]
Metals	Cu coating	0.112 mm	R_V = 1 Ωm … 5 Ωm	30 MHz–1.5 GHz	55	Air permeability	[60]
	Ni coating	Not given	R_S < 2 Ω, H_C ~ 100 Oe	X-band	32	Not reported	[66]
Carbon	CNT/graphene coating	0.35 mm	EC = 64 S/m	X-band	35	Superhydrophobicity	[113]
	Carbon/PA6 nonwoven	4.48 mm	EC = 34 S/m	X-band	85	Sound absorption	[120]
Conduct. polymers	PANI/PPy coating	80 μm/56 μm	R_S = 20 Ω/96 Ω	2.5–18 GHz	22/7	Not reported	[135]
	PPy dip-coating	0.37 mm	EC = 1.5 S/m	X-band	40	Joule heating	[137]

These shielding effectiveness values are comparable to those found for EMI shielding by electrospun nanofiber mats [13]. Here, however, sample preparation is often easier and possible with common textile technologies, and macroscopic textiles are more robust against mechanical forces, while the sample thickness of freestanding nanofiber mats is significantly lower. Thus, both kinds of EMI shielding fabrics, macroscopic textiles, and nanofibrous mats, have their own fields of applications, due to their advantages and disadvantages.

8. Conclusions

EMI shielding belongs to the strongly investigated topics in the research area of smart textiles. The necessary physical properties, such as electrical and/or magnetic conductivity, can be added to common textile fabrics by coatings with conductive polymers, carbon- or metal-based coatings as well as with the new material class of MXenes. Besides, developing yarns with conductive metal wires or using conductive carbon fibers are potential approaches to produce EMI shielding textile fabrics.

Our review of the most recent developments in this field of research presents suitable production methods by different coating and spinning techniques and gives an overview of the shielding effectiveness which can be reached by the different methods, e.g., approx. 80 dB for a combined coating from conductive polymer and a metal layer [143], around 47 dB for a PEDOT:PSS/PEG coating [139], 73 dB for a carbon fiber/TPU composite [123], 72 dB for a Ag nanowire/(GO) coating [116], 55 dB for an rGO/ZnO coating [114], 100 dB for 3 layers of an Ag nanowire/Fe_3O_4 nanoparticle coated fabric [64], or more than 100 dB for 3 layers of a very thin fabric from GO/MXene hollow fibers [48]. As these examples show, many approaches can be used to reach high EMI shielding effectiveness, typically measured in the technologically relevant X-band, but also in other frequency ranges. We hope our review will stimulate more researchers to start working in this highly interesting research area.

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References

1. Wang, H.; Li, S.N.; Liu, M.Y.; Zhou, Y. Review on Shielding Mechanism and Structural Design of Electromagnetic Interference Shielding Composites. *Macromol. Mater. Eng.* **2021**, *306*, 2100032. [CrossRef]
2. Peng, M.Y.; Qin, F.X. Clarification of basic concepts for electromagnetic interference shielding effectiveness. *J. Appl. Phys.* **2021**, *130*, 225108. [CrossRef]
3. Guan, H.T.; Chung, D.D.L. Absorption-dominant radio-wave attenuation loss of metals and graphite. *J. Mater. Sci.* **2021**, *56*, 8037–8047. [CrossRef]
4. Dai, M.W.; Zhai, Y.H.; Zhang, Y. A green approach to preparing hydrophobic, electrically conductive textiles based on waterborne polyurethane for electromagnetic interference shielding with low reflectivity. *Chem. Eng. J.* **2021**, *421*, 127749. [CrossRef]
5. Mocha, J.; Wójcik, D.; Surma, M. Immunity of medical electrical equipment to radiated RF disturbances. *Proc. SPIE* **2018**, *10715*, 1071507.
6. Wu, J.H.; Chung, D.D.L. Increasing the electromagnetic interference shielding effectiveness of carbon fiber polymer–matrix composite by using activated carbon fibers. *Carbon* **2002**, *40*, 445–467. [CrossRef]
7. Roh, J.-S.; Chi, Y.-S.; Kang, T.J. Electromagnetic shielding effectiveness of multifunctional metal composite fabrics. *Text. Res. J.* **2008**, *78*, 825–835. [CrossRef]
8. Ren, S.; Guo, S.; Liu, X.; Liu, Q. Shielding effectiveness of double-layer magnetic shield of current comparator under radial disturbing magnetic field. *IEEE Trans. Magn.* **2016**, *52*, 9401907. [CrossRef]
9. Blachowicz, T.; Ehrmann, A.; Malczyk, M.; Stasiak, A.; Osadnik, R.; Paluch, R.; Koruszowic, M.; Pawlyta, J.; Lis, K.; Lehrich, K. Plant growth in microgravity and defined magnetic field. In Proceedings of the International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), Mauritius, East Africa, 7–8 October 2021; pp. 1–8.
10. Yao, Y.Y.; Jin, S.H.; Zou, H.M.; Li, L.J.; Ma, X.L.; Lv, G.; Gao, F.; Lv, X.J.; Shu, Q.H. Polymer-based lightweight materials for electromagnetic interference shielding: A review. *J. Mater. Sci.* **2021**, *56*, 6549–6580. [CrossRef]
11. Duan, Y.P.; Liu, S.H.; Guan, H.T. Investigation of electrical conductivity and electromagnetic shielding effectiveness of polyaniline composite. *Sci. Technol. Adv. Mater.* **2005**, *6*, 513–518.
12. Liang, R.R.; Cheng, W.J.; Xiao, H.; Shi, M.W.; Tang, Z.H.; Wang, N. A calculating method for the electromagnetic shielding effectiveness of metal fiber blended fabric. *Text. Res. J.* **2018**, *88*, 973–986. [CrossRef]
13. Blachowicz, T.; Hütten, A.; Ehrmann, A. Electromagnetic Interference Shielding with Electrospun Nanofiber Mats—A Review of Production, Physical Properties and Performance. *Fibers* **2022**, *10*, 47. [CrossRef]
14. Chung, D.D.L. Electromagnetic interference shielding effectiveness of carbon materials. *Carbon* **2001**, *39*, 279–285. [CrossRef]
15. Knittel, D.; Schollmeyer, E. Electrically high-conductive textiles. *Synth. Met.* **2009**, *159*, 1433–1437. [CrossRef]
16. Kacprzyk, R. Measurement of the volume and surface resistance of textile materials. *Fibres Text. East. Eur.* **2011**, *19*, 47–49.
17. Meding, J.T.; Tuvshinbayar, K.; Döpke, C.; Tamoue, F. Textile electrodes for bioimpedance measuring. *Commun. Dev. Assem. Text. Prod.* **2021**, *2*, 49–60. [CrossRef]

18. Schwarz-Pfeiffer, A.; Obermann, M.; Weber, M.O.; Ehrmann, A. Smarten up garments through knitting. *IOP Conf. Ser. Mater. Sci. Eng.* **2016**, *141*, 012008. [CrossRef]
19. Pakdel, E.; Wang, J.F.; Kashi, S.; Sun, L.; Wang, X.G. Advances in photocatalytic self-cleaning, superhydrophobic and electromagnetic interference shielding textile treatments. *Adv. Coll. Interf. Sci.* **2020**, *277*, 102116. [CrossRef]
20. Ehrmann, G.; Blachowicz, T.; Homburg, S.V.; Ehrmann, A. Measuring biosignals with single circuit boards. *Bioengineering* **2022**, *9*, 84. [CrossRef]
21. Schneider, V.; Reinholdt, A.; Kreibig, U.; Weirich, T.; Güntherodt, G.; Beschoten, B.; Tillmanns, A.; Krenn, H.; Rumpf, K.; Granitzer, P. Structural and magnetic properties of Ni/NiOxide- and Co/CoOxide core/shell nanoparticles and their possible use for ferrofluids. *Z. Phys. Chem.* **2006**, *220*, 173–187. [CrossRef]
22. Blachowicz, T.; Tillmanns, A.; Fraune, M.; Beschoten, B.; Güntherodt, G. Exchange-bias in (110)-oriented CoO/Co bilayers with different magnetocrystalline anisotropies. *Phys. Rev. B* **2007**, *75*, 054425. [CrossRef]
23. Regtmeier, A.; Meyer, J.; Mill, N.; Peter, M.; Weddemann, A.; Mattay, J.; Hütten, A. Influence of nanoparticular impurities on the magnetic anisotropy of self-assembled magnetic co-nanoparticles. *J. Magn. Magn. Mater.* **2013**, *326*, 112–115. [CrossRef]
24. Wang, L.; Dong, X.; Gai, G.; Zhao, L.; Xu, S.; Xiao, X. One-pot facile electrospinning construct of flexible Janus nanofibers with tunable and enhanced magnetism-photoluminescence bifunctionality. *J. Nanopart. Res.* **2015**, *17*, 91. [CrossRef]
25. Blachowicz, T.; Ehrmann, A.; Mahltig, B. Magneto-optic measurements on uneven magnetic layers on cardboard. *AIP Adv.* **2017**, *7*, 045306. [CrossRef]
26. Geetha, S.; Kumar, K.K.S.; Rao, C.R.K.; Vijayan, M.; Trivedi, D.C. EMI Shielding: Methods and Materials—A Review. *J. Appl. Polym. Sci.* **2009**, *112*, 2073–2086. [CrossRef]
27. Naguib, M.; Mochalin, V.N.; Barsoum, M.W.; Gogotsi, Y. MXenes: A new family of two-dimensional materials. *Adv. Mater.* **2014**, *26*, 992–1005. [CrossRef]
28. Barsoum, M.W. The $M_{n+1}AX_n$ phases: A new class of solids. *Prog. Solid State Chem.* **2000**, *28*, 201–281. [CrossRef]
29. Sinha, A.; Dhanjai; Zhao, H.M.; Huang, Y.J.; Lu, X.B.; Chen, J.P.; Jain, R. MXene: An emerging material for sensing and biosensing. *TrAC Trends Anal. Chem.* **2018**, *105*, 424–435. [CrossRef]
30. Zhang, C.; McKeon, L.; Kremer, M.P.; Park, S.-H.; Ronan, O.; Seral-Ascasco, A.; Barwich, S.; Coileáin, C.Ó.; McEvoy, N.; Nerl, H.C.; et al. Additive-free MXene inks and direct printing of micro-supercapacitors. *Nat. Commun.* **2019**, *10*, 1795. [CrossRef]
31. Naguib, M.; Mashtalir, O.; Carle, J.; Presser, V.; Lu, J.; Hultman, L.; Gogotsi, Y.; Barsoum, M.W. Two dimensional transition metal carbides. *ACS Nano* **2012**, *6*, 1322–1331. [CrossRef]
32. Lee, Y.H.; Kim, S.J.; Kim, Y.-J.; Lim, Y.H.; Chae, Y.J.; Lee, B.J.; Kim, Y.-T.; Han, H.; Gogotsi, Y.; Ahn, C.W. Oxidation-resistant titanium carbide MXene films. *J. Mater. Chem. A* **2020**, *8*, 573–581. [CrossRef]
33. Li, E.; Pan, Y.M.; Wang, C.F.; Liu, C.T.; Shen, C.Y.; Pan, C.F.; Liu, X.H. Asymmetric Superhydrophobic Textiles for Electromagnetic Interference Shielding, Photothermal Conversion, and Solar Water Evaporation. *ACS Appl. Mater. Interfaces* **2021**, *13*, 28996–29007. [CrossRef]
34. Zheng, X.H.; Wang, P.; Zhang, X.S.; Hu, Q.L.; Wang, Z.Q.; Nie, W.Q.; Zou, L.H.; Li, C.L.; Han, X. Breathable, durable and bark-shaped MXene/textiles for high-performance wearable pressure sensors, EMI shielding and heat physiotherapy. *Compos. A Appl. Sci. Manuf.* **2022**, *152*, 106700. [CrossRef]
35. Zhang, X.S.; Wang, X.F.; Lei, Z.W.; Wang, L.L.; Tian, M.W.; Zhu, S.F.; Xiao, H.; Tang, X.N.; Qu, L.J. Flexible MXene-Decorated Fabric with Interwoven Conductive Networks for Integrated Joule Heating, Electromagnetic Interference Shielding, and Strain Sensing Performances. *ACS Appl. Mater. Interfaces* **2020**, *12*, 14459–14467. [CrossRef] [PubMed]
36. Yu, Z.C.; Deng, C.; Seidi, F.; Yong, Q.; Lou, Z.C.; Meng, L.C.; Liu, J.W.; Huang, C.; Liu, Y.Q.; Wu, W.B.; et al. Air-permeable and flexible multifunctional cellulose-based textiles for bio-protection, thermal heating conversion, and electromagnetic interference shielding. *J. Mater. Chem. A* **2022**, *10*, 17452–17463. [CrossRef]
37. Yu, J.; Cui, Z.L.; Lu, J.Y.; Zhao, J.L.; Zhang, Y.; Fan, G.Q.; Liu, S.Y.; He, Y.B.; Yu, Y.H.; Qi, D.M. Integrated hierarchical macrostructures of flexible basalt fiber composites with tunable electromagnetic interference (EMI) shielding and rapid electrothermal response. *Compos. B Eng.* **2021**, *224*, 109193. [CrossRef]
38. Yao, D.J.; Tang, Z.H.; Liang, Z.H.; Zhang, L.; Sun, Q.-J.; Fan, J.M.; Zhong, G.K.; Liu, Q.-X.; Jiang, Y.-P.; Tang, X.-G.; et al. Adhesive, multifunctional, and wearable electronics based on MXene-coated textile for personal heating systems, electromagnetic interference shielding, and pressure sensing. *J. Coll. Interface Sci.* **2023**, *630*, 23–33. [CrossRef] [PubMed]
39. Uzun, S.; Han, M.K.; Strobel, C.J.; Hantanasirisakul, K.; Goad, A.; Dion, G.; Gogotsi, Y. Highly conductive and scalable $Ti_3C_2T_x$-coated fabrics for efficient electromagnetic interference shielding. *Carbon* **2021**, *174*, 382–389. [CrossRef]
40. Taghizadeh, A.; Taghizadeh, M.; Jouyandeh, M.; Khodadadi Yazdi, M.; Zarrintaj, P.; Saeb, M.R.; Lima, E.C.; Gupta, V.K. Conductive polymers in water treatment: A review. *J. Mol. Liq.* **2020**, *312*, 113447. [CrossRef]
41. Wang, Q.-W.; Zhang, H.-B.; Liu, J.; Zhao, S.; Xie, X.; Liu, L.X.; Yang, R.; Koratkar, N.; Yu, Z.-Z. Multifunctional and Water-Resistant MXene-Decorated Polyester Textiles with Outstanding Electromagnetic Interference Shielding and Joule Heating Performances. *Adv. Funct. Mater.* **2019**, *29*, 1806819. [CrossRef]
42. Yin, G.; Wang, Y.; Wang, W.; Qu, Z.J.; Yu, D. A Flexible Electromagnetic Interference Shielding Fabric Prepared by Construction of PANI/MXene Conductive Network via Layer-by-Layer Assembly. *Adv. Mater. Interfaces* **2021**, *8*, 2001893. [CrossRef]
43. Li, J.; Li, Y.X.; Yang, L.Y.; Yin, S.G. $Ti_3C_2T_x$/PANI/Liquid Metal Composite Microspheres with 3D Nanoflower Structure: Preparation, Characterization, and Applications in EMI Shielding. *Adv. Mater. Interfaces* **2022**, *9*, 2102266. [CrossRef]

44. Yin, G.; Wang, Y.; Wang, W.; Yu, D. Multilayer structured PANI/MXene/CF fabric for electromagnetic interference shielding constructed by layer-by-layer strategy. *Coll. Surf. A Physicochem. Eng. Asp.* **2020**, *601*, 125047. [CrossRef]
45. Liu, L.-X.; Chen, W.; Zhang, H.-B.; Wang, Q.-W.; Guan, F.L.; Yu, Z.-Z. Flexible and Multifunctional Silk Textiles with Biomimetic Leaf-Like MXene/Silver Nanowire Nanostructures for Electromagnetic Interference Shielding, Humidity Monitoring, and Self-Derived Hydrophobicity. *Adv. Funct. Mater.* **2019**, *29*, 1905197. [CrossRef]
46. Zheng, X.H.; Tang, J.H.; Cheng, L.Z.; Yang, H.W.; Zou, L.H.; Li, C.L. Superhydrophobic hollow magnetized Fe_3O_4 nanospheres/MXene fabrics for electromagnetic interference shielding. *J. Alloy. Comp.* **2023**, *934*, 167964. [CrossRef]
47. Zhang, D.B.; Yin, R.; Zheng, Y.J.; Li, Q.M.; Liu, H.; Liu, C.T.; Shen, C.Y. Multifunctional MXene/CNTs based flexible electronic textile with excellent strain sensing, electromagnetic interference shielding and Joule heating performances. *Chem. Eng. J.* **2022**, *438*, 135587. [CrossRef]
48. Liu, L.-X.; Chen, W.; Zhang, H.-B.; Zhang, Y.; Tang, P.P.; Li, D.Y.; Deng, Z.M.; Ye, L.X.; Yu, Z.-Z. Tough and electrically conductive $Ti_3C_2T_x$ MXene–based core–shell fibers for high–performance electromagnetic interference shielding and heating application. *Chem. Eng. J.* **2022**, *430*, 133074. [CrossRef]
49. Liu, L.-X.; Chen, W.; Zhang, H.-B.; Ye, L.X.; Wang, Z.G.; Zhang, Y.; Min, P.; Yu, Z.-Z. Super-Tough and Environmentally Stable Aramid. Nanofiber@MXene Coaxial Fibers with Outstanding Electromagnetic Interference Shielding Efficiency. *Nano-Micro Lett.* **2022**, *14*, 111. [CrossRef]
50. Zhou, T.Z.; He, Y.Z.; He, B.; Wang, Z.; Xiong, T.; Wang, Z.X.; Liu, Y.T.; Xin, J.W.; Qi, M.; Zhang, H.Z.; et al. Ultra-compact MXene fibers by continuous and controllable synergy of interfacial interactions and thermal drawing-induced stresses. *Nat. Commun.* **2022**, *13*, 4564. [CrossRef]
51. Xiong, J.H.; Zheng, H.W.; Ding, R.J.; Li, P.Y.; Liu, Z.L.; Zhao, X.; Xue, F.H.; Chen, Z.; Yan, Q.; Peng, Q.Y.; et al. Multifunctional non-woven fabrics based on interfused MXene fibers. *Mater. Des.* **2022**, *223*, 111207. [CrossRef]
52. Zheng, X.H.; Tang, J.H.; Wang, P.; Wang, Z.Q.; Zou, L.H.; Li, C.L. Interfused core-shell heterogeneous graphene/MXene fiber aerogel for high-performance and durable electromagnetic interference shielding. *J. Coll. Interface Sci.* **2022**, *628*, 994–1003. [CrossRef] [PubMed]
53. Mott, N.F. The electrical conductivity of transition metals. *Proc. R. Soc. A* **1936**, *153*, 699–717.
54. Laman, N.; Grischkowsky, D. Terahertz conductivity of thin metal films. *Appl. Phys. Lett.* **2008**, *93*, 051105. [CrossRef]
55. Wang, J.L.; Lu, C.H.; Zhang, K. Textile-Based Strain Sensor for Human Motion Detection. *Energy Environ. Mater.* **2020**, *3*, 80–100. [CrossRef]
56. Pani, D.; Achilli, A.; Bonfiglio, A. Survey on Textile Electrode Technologies for Electrocardiographic (ECG) Monitoring, from Metal Wires to Polymers. *Adv. Mater. Technol.* **2018**, *3*, 1800008. [CrossRef]
57. Wang, Z.N.; Wang, H.X.; Ji, S.; Wang, H.; Brett, D.J.L.; Wang, R.F. Design and synthesis of tremella-like Ni–Co–S flakes on co-coated cotton textile as high-performance electrode for flexible supercapacitor. *J. Alloy. Comp.* **2020**, *814*, 151789. [CrossRef]
58. Ehrmann, A.; Blachowicz, T. Recent coating materials for textile-based solar cells. *AIMS Mater. Sci.* **2019**, *6*, 234–251. [CrossRef]
59. Ma, K.K.; Islamoglu, T.; Chen, Z.J.; Li, P.; Wasson, M.C.; Chen, Y.W.; Wang, Y.F.; Peterson, G.W.; Xin, J.H.; Farha, O.K. Scalable and Template-Free Aqueous Synthesis of Zirconium-Based Metal–Organic Framework Coating on Textile Fiber. *J. Am. Chem. Soc.* **2019**, *141*, 15626–15633. [CrossRef]
60. Hu, S.; Wang, D.; Periyasamy, A.P.; Kremenakova, D.; Militky, J.; Tunak, M. Ultrathin Multilayer Textile Structure with Enhanced EMI Shielding and Air-Permeable Properties. *Polymers* **2021**, *13*, 4176. [CrossRef]
61. Hu, S.; Wang, D.; Kyosev, Y.; Kremenakova, D.; Militky, J. The novel approach of EMI shielding simulation for metal coated nonwoven textiles with optimized textile module. *Polym. Test.* **2022**, *114*, 107706. [CrossRef]
62. Periyasamy, A.P.; Yang, K.; Xiong, X.M.; Venkataraman, M.; Militky, J.; Mishra, R.; Kremenakova, D. Effect of silanization on copper coated milife fabric with improved EMI shielding effectiveness. *Mater. Chem. Phys.* **2020**, *239*, 122008. [CrossRef]
63. Hong, S.W.; Yoo, S.S.; Lee, J.Y.; Yoo, P.J. Sonochemically activated synthesis of gradationally complexed Ag/TEMPO-oxidized cellulose for multifunctional textiles with high electrical conductivity, super-hydrophobicity, and efficient EMI shielding. *J. Mater. Chem. C* **2020**, *8*, 13990–13998. [CrossRef]
64. Zong, J.-Y.; Zhou, X.-J.; Hu, Y.-F.; Yang, T.-B.; Yan, D.-X.; Lin, H.; Lei, J.; Li, Z.-M. A wearable multifunctional fabric with excellent electromagnetic interference shielding and passive radiation heating performance. *Comp. B Eng.* **2021**, *225*, 109299. [CrossRef]
65. Jia, L.-C.; Zhang, G.Q.; 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* **2019**, *11*, 1680–1688. [CrossRef] [PubMed]
66. Moazzenchi, B.; Montazer, M. Click electroless plating of nickel nanoparticles on polyester fabric: Electrical conductivity, magnetic and EMI shielding properties. *Colloids Surf. A Physicochem. Eng. Asp.* **2019**, *571*, 110–124. [CrossRef]
67. Duan, Q.Y.; Lu, Y.X. Silk Sericin as a Green Adhesive to Fabricate a Textile Strain Sensor with Excellent Electromagnetic Shielding Performance. *ACS Appl. Mater. Interfaces* **2021**, *13*, 28832–28842. [CrossRef]
68. Bai, Y.; Qin, F.; Lu, Y.X. Multifunctional Electromagnetic Interference Shielding Ternary Alloy (Ni–W–P) Decorated Fabric with Wide-Operating-Range Joule Heating Performances. *ACS Appl. Mater. Interfaces* **2020**, *12*, 48016–48026. [CrossRef]
69. Liu, J.C.; Lin, S.; Huang, K.; Jia, C.; Wang, Q.M.; Li, Z.W.; Song, J.N.; Liu, Z.L.; Wang, H.Y.; Lei, M.; et al. A large-area AgNW-modified textile with high-performance electromagnetic interference shielding. *NPJ Flex. Electron.* **2020**, *4*, 10. [CrossRef]
70. Jia, L.-C.; Ding, K.-Q.; Ma, R.-J.; Wang, H.-L.; Sun, W.-J.; Yan, D.-X.; Li, B.; Li, Z.-M. Highly Conductive and Machine-Washable Textiles for Efficient Electromagnetic Interference Shielding. *Adv. Mater. Technol.* **2019**, *4*, 1800503. [CrossRef]

71. Zhang, Y.; Tian, W.X.; Liu, L.X.; Cheng, W.H.; Wang, W.; Liew, K.M.; Wang, B.; Hu, Y. Eco-friendly flame retardant and electromagnetic interference shielding cotton fabrics with multi-layered coatings. *Chem. Eng. J.* **2019**, *372*, 1077–1090. [CrossRef]
72. Rybicki, T. EMI Shielding and Reflection From Textile Mesh Grids Compared With Analytic Models. *EEE Trans. Electromagn. Compat.* **2019**, *61*, 372–380. [CrossRef]
73. Radulescu, I.R.; Surdu, L.; Scarlat, R.; Constantin, C.; Mitu, B.; Morari, C.; Costea, M. Modelling the Woven Structures with Inserted Conductive Yarns Coated with Magnetron Plasma and Testing Their Shielding Effectiveness. *Textiles* **2021**, *1*, 4–20. [CrossRef]
74. Onder, E.; Noyan, E.C.B.; Duru, S.C.; Candan, C.; Paker, S.; Sayar, R. Smart Protective Clothing for Aircraft Crew. In *Advances in Sustainable Aviation*; Karakoç, T., Colpan, C., Şöhret, Y., Eds.; Springer: Cham, Switzerland, 2018; pp. 221–235.
75. Vahle, D.; Böttjer, R.; Heyden, K.; Ehrmann, A. Conductive polyacrylonitrile/graphite textile coatings. *AIMS Mater. Sci.* **2018**, *5*, 551–558. [CrossRef]
76. Isaia, C.; McMaster, S.; McNally, D. The effect of washing on the electrical performance of knitted textile strain sensors for quantifying joint motion. *J. Industr. Text.* **2022**, *51*, 8528S–8548S. [CrossRef]
77. Böhnke, P.R.C.; Winger, H.; Wieczorek, F.; Warncke, M.; Lüneburg, L.M.; Kruppke, I.; Nocke, A.; Häntzsche, E.; Cherif, C. Protective Coating for Electrically Conductive Yarns for the Implementation in Smart Textiles. *Solid State Phenom.* **2022**, *333*, 11–20. [CrossRef]
78. Daeneke, T.; Khoshmanesh, K.; Mahmood, N.; de Castro, I.A.; Esrafilzadeh, D.; Barrow, S.J.; Dickey, M.D.; Kalantar-zadeh, K. Liquid metals: Fundamentals and applications in chemistry. *Chem. Soc. Rev.* **2018**, *47*, 4073–4111. [CrossRef]
79. Jia, L.-C.; Jia, X.-X.; Sun, W.-J.; Zhang, Y.-P.; Du, L.; Yan, D.-X.; Su, H.-J.; Li, Z.-M. Stretchable Liquid Metal-Based Conductive Textile for Electromagnetic Interference Shielding. *ACS Appl. Mater. Interfaces* **2020**, *12*, 53230–53238. [CrossRef]
80. Ehrmann, G.; Ehrmann, A. Electronic textiles. *Encyclopedia* **2021**, *1*, 115–130. [CrossRef]
81. Atalay, O.; Kalaoglu, F.; Bahadir, S.K. Development of textile-based transmission lines using conductive yarns and ultrasonic welding technology for e-textile applications. *J. Eng. Fibers Fabr.* **2019**, *14*, 1558925019856603. [CrossRef]
82. Nigusse, A.B.; Mengistie, D.A.; Malengier, B.; Tseghai, G.B.; van Langenhove, L. Wearable Smart Textiles for Long-Term Electrocardiography Monitoring—A Review. *Sensors* **2021**, *21*, 4174. [CrossRef]
83. Blachowicz, T.; Ehrmann, G.; Ehrmann, A. Textile-Based Sensors for Biosignal Detection and Monitoring. *Sensors* **2021**, *21*, 6042. [CrossRef] [PubMed]
84. Simegnaw, A.A.; Malengier, B.; Tadesse, M.G.; van Langenhove, L. Development of Stainless Steel Yarn with Embedded Surface Mounted Light Emitting Diodes. *Materials* **2022**, *15*, 2892. [CrossRef]
85. Weber, M.O.; Akter, F.; Ehrmann, A. Shielding of static magnetic fields by textiles. *Ind. Text.* **2013**, *64*, 184–187.
86. He, S.J.; Liu, Z.; Wang, H.Y.; Wang, X.C. Effect of needle loops on shielding effectiveness of electromagnetic shielding knitted fabrics. *Text. Res. J.* **2022**, *93*, 691–700. [CrossRef]
87. Rubežienė, V.; Abraitienė, A.; Baltušnikaitė-Guzaitienė, J.; Varnaitė-Žuravliova, S.; Sankauskaitė, A.; Kancleris, Ž.; Ragulis, P.; Šlekas, G. The influence of distribution and deposit of conductive coating on shielding effectiveness of textiles. *J. Text. Inst.* **2018**, *109*, 358–367. [CrossRef]
88. Mikinka, E.; Siwak, M. Experimental characterisation and prediction of shielding effectiveness for multilayer carbon fibre reinforced composite materials with varying configurations. *Mater. Today Commun.* **2022**, *32*, 104039. [CrossRef]
89. Gupta, K.K.; Abbas, S.M.; Abhyankar, A.C. Effect of yarn composition and fabric weave design on microwave and EMI shielding properties of hybrid woven fabrics. *J. Text. Inst.* **2022**, *113*, 1862–1877. [CrossRef]
90. Krishnasamy, J.; Ramasamy, A.; Das, A.; Basu, A. Electromagnetic absorption behaviour of carbon helical/coiled yarn woven and knitted fabrics and their composites. *J. Thermoplast. Comp. Mater.* **2018**, *32*, 357–382. [CrossRef]
91. Li, J.; Shao, H.Q.; Shao, G.W.; Su, C.L.; Yu, Q.H.; Huang, Y.L.; Chen, N.L.; Jiang, J.H. Flexible Warp-Knitted Metal Mesh-Based Composites: An Effective EMI Shielding Material with Efficient Joule Heating. *ACS Appl. Polym. Mater.* **2022**, *4*, 7025–7041. [CrossRef]
92. Shyr, T.-W.; Shie, J.-W. Electromagnetic shielding mechanisms using soft magnetic stainless steel fiber enabled polyester textiles. *J. Magn. Magn. Mater.* **2012**, *324*, 4127–4132. [CrossRef]
93. Huang, C.-H.; Lin, J.-H.; Yang, R.-B.; Lin, C.-W.; Lou, C.-W. Metal/PET composite knitted fabrics and composites: Structural design and electromagnetic shielding effectiveness. *J. Electron. Mater.* **2012**, *41*, 2267–2273. [CrossRef]
94. Allaer, K.; De Baere, I.; Lava, P.; Van Paepegem, W.; Degrieck, J. On the in-plane mechanical properties of stainless steel fibre reinforced ductile composites. *Compos. Sci. Technol.* **2014**, *100*, 34–43. [CrossRef]
95. Gao, Y.; Xie, C.; Zheng, Z.J. Textile Composite Electrodes for Flexible Batteries and Supercapacitors: Opportunities and Challenges. *Adv. Energy Mater.* **2021**, *11*, 2002838. [CrossRef]
96. Sadi, M.S.; Pan, J.J.; Xu, A.C.; Cheng, D.S.; Cai, G.M.; Wang, X. Direct dip-coating of carbon nanotubes onto polydopamine-templated cotton fabrics for wearable applications. *Cellulose* **2019**, *26*, 7569–7579. [CrossRef]
97. Yao, C.K.; Yuan, L.L.; Zhang, H.H.; Li, B.X.; Liu, J.Y.; Xi, F.N.; Dong, X.P. Facile surface modification of textiles with photocatalytic carbon nitride nanosheets and the excellent performance for self-cleaning and degradation of gaseous formaldehyde. *J. Coll. Interface Sci.* **2019**, *533*, 144–153. [CrossRef]
98. Khan, J.; Ilyas, S.; Akram, B.; Ahmad, K.; Hafeez, M.; Siddiq, M.; Ashraf, M.A. Zno/NiO coated multi-walled carbon nanotubes for textile dyes degradation. *Arab. J. Chem.* **2018**, *11*, 880–896. [CrossRef]
99. Lund, A.; van der Velden, N.M.; Persson, N.-K.; Hamedi, M.M.; Müller, C. Electrically conducting fibres for e-textiles: An open playground for conjugated polymers and carbon nanomaterials. *Mater. Sci. Eng. R Rep.* **2018**, *126*, 1–29. [CrossRef]

100. Müller, S.; Wieschollek, D.; Juhász Junger, I.; Schwenzfeier-Hellkamp, E.; Ehrmann, A. Back electrodes of dye-sensitized solar cells on textile fabrics. *Optik* **2019**, *198*, 163243. [CrossRef]
101. Wang, C.Y.; Xia, K.L.; Wang, H.M.; Liang, X.P.; Yin, Z.; Zhang, Y.Y. Advanced Carbon for Flexible and Wearable Electronics. *Adv. Mater.* **2019**, *31*, 1801072. [CrossRef]
102. Hengstermann, M.; Hasan, M.M.D.; Scheffler, C.; Abdkader, A.; Cherif, C.J. Development of a new hybrid yarn construction from recycled carbon fibres for high-performance composites. Part III: Influence of sizing on textile processing and composite properties. *Thermoplast. Comp. Mater.* **2019**, *34*, 409–430. [CrossRef]
103. Gong, T.; Heravi, A.A.; Alsous, G.; Curosu, I.; Mechtcherine, V. The Impact-Tensile Behavior of Cementitious Composites Reinforced with Carbon Textile and Short Polymer Fibers. *Appl. Sci.* **2019**, *9*, 4048. [CrossRef]
104. Zhang, M.; Deng, M.K. Tensile behavior of textile-reinforced composites made of highly ductile fiber-reinforced concrete and carbon textiles. *J. Build. Eng.* **2022**, *57*, 104824. [CrossRef]
105. Alaghmandfard, A.; Sedighi, O.; Rezaei, N.T.; Abedini, A.A.; Khachatourian, A.M.; Toprak, M.S.; Seifalian, A. Recent advances in the modification of carbon-based quantum dots for biomedical applications. *Mater. Sci. Eng. C* **2021**, *120*, 111756. [CrossRef]
106. Tiwari, S.K.; Sahoo, S.; Wang, N.; Huczko, A. Graphene research and their outputs: Status and prospect. *J. Sci. Adv. Mater. Devices* **2020**, *5*, 10–29. [CrossRef]
107. Li, B.M.; Yildiz, O.; Mills, A.C.; Flewwellin, T.J.; Bradford, P.D.; Jur, J.S. Iron-on carbon nanotube (CNT) thin films for biosensing E-Textile applications. *Carbon* **2020**, *168*, 673–683. [CrossRef]
108. Hu, J.S.; Yu, J.S.; Li, Y.; Liao, X.Q.; Yan, X.W.; Li, L. Nano Carbon Black-Based High Performance Wearable Pressure Sensors. *Nanomaterials* **2020**, *10*, 664. [CrossRef]
109. Schäl, P.; Juhász Junger, I.; Grimmelsmann, N.; Ehrmann, A. Development of graphite-based conductive textile coatings. *J. Coat. Technol. Res.* **2018**, *15*, 875–883. [CrossRef]
110. Li, Y.C.; Huang, X.R.; Zeng, L.J.; Li, R.F.; Tian, H.F.; Fu, X.W.; Wang, Y.; Zhong, W.-H. A review of the electrical and mechanical properties of carbon nanofiller-reinforced polymer composites. *J. Mater. Sci.* **2019**, *54*, 1036–1076. [CrossRef]
111. Lan, C.T.; Guo, M.; Li, C.L.; Qiu, Y.P.; Ma, Y.; Sun, J.Q. Axial Alignment of Carbon Nanotubes on Fibers To Enable Highly Conductive Fabrics for Electromagnetic Interference Shielding. *ACS Appl. Mater. Interfaces* **2020**, *12*, 7477–7485. [CrossRef]
112. Moonlek, B.; Wimolmala, E.; Markpin, T.; Sombatsompop, N.; Saenboonruang, K. Enhancing electromagnetic interference shielding effectiveness for radiation vulcanized natural rubber latex composites containing multiwalled carbon nanotubes and silk textile. *Polym. Compos.* **2020**, *41*, 396–4009. [CrossRef]
113. Gupta, S.; Chang, C.; Anbalagan, A.K.; Lee, C.-H.; Tai, N.-H. Reduced graphene oxide/zinc oxide coated wearable electrically conductive cotton textile for high microwave absorption. *Compos. Sci. Technol.* **2020**, *188*, 107994. [CrossRef]
114. Xu, C.L.; Zhao, J.N.; Chao, Z.; Wang, J.J.; Wang, W.L.; Zhang, X.H.; Li, Q.W. Developing thermal regulating and electromagnetic shielding textiles using ultra-thin carbon nanotube films. *Compos. Commun.* **2020**, *21*, 100409. [CrossRef]
115. Sim, H.J.; Lee, D.W.; Kim, H.S.; Jang, Y.W.; Spinks, G.M.; Gambhir, S.; Officer, D.L.; Wallace, G.G.; Kim, S.J. Self-healing graphene oxide-based composite for electromagnetic interference shielding. *Carbon* **2019**, *155*, 499–505. [CrossRef]
116. 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]
117. Wang, Y.; Wang, W.; Qi, Q.B.; Xu, N.; Yu, D. Layer-by-layer assembly of PDMS-coated nickel ferrite/multiwalled carbon nanotubes/cotton fabrics for robust and durable electromagnetic interference shielding. *Cellulose* **2020**, *27*, 2829–2845. [CrossRef]
118. Zhou, L.H.; Lan, C.T.; Yang, L.; Xu, Z.Z.; Chu, C.L.; Liu, Y.C.; Qiu, Y.P. The optimization of nanocomposite coating with polyaniline coated carbon nanotubes on fabrics for exceptional electromagnetic interference shielding. *Diam. Relat. Mater.* **2020**, *104*, 107757. [CrossRef]
119. Pakdel, E.; Kashi, S.; Baum, T.; Usman, K.A.S.; Razal, J.M.; Varley, R.; Wang, X.G. Carbon fibre waste recycling into hybrid nonwovens for electromagnetic interference shielding and sound absorption. *J. Clean. Prod.* **2021**, *315*, 128196. [CrossRef]
120. Hu, Q.L.; Duan, Y.F.; Zheng, X.H.; Nie, W.Q.; Zou, L.H.; Xu, Z.Z. Lightweight, flexible, and highly conductive recycled carbon fiber felt for electromagnetic interference shielding. *J. Alloys Comp.* **2023**, *935*, 168152. [CrossRef]
121. Lin, M.-C.; Lin, J.-H.; Bao, L.M. Applying TPU blends and composite carbon fibers to flexible electromagnetic-shielding fabrics: Long-fiber-reinforced thermoplastics technique. *Compos. A Appl. Sci. Manuf.* **2020**, *138*, 106022. [CrossRef]
122. Duan, N.M.; Shi, Z.Y.; Wang, J.L.; Wang, G.L.; Zhang, X.Z. Strong and Flexible Carbon Fiber Fabric Reinforced Thermoplastic Polyurethane Composites for High-Performance EMI Shielding Applications. *Macromol. Mater. Eng.* **2020**, *305*, 1900829. [CrossRef]
123. Jia, L.-C.; Nie, R.-P.; Xu, L.; Yan, D.-X.; Lei, J.; Li, Z.-M. Carbonized cotton textile with hierarchical structure for superhydrophobicity and efficient electromagnetic interference shielding. *Compos. A Appl. Sci. Manufact.* **2021**, *149*, 106555. [CrossRef]
124. Zhu, S.; Shi, R.J.; Qu, M.C.; Zhou, J.F.; Ye, C.H.; Zhang, L.Y.; Cao, H.J.; Ge, D.T.; Chen, Q.J. Simultaneously improved mechanical and electromagnetic interference shielding properties of carbon fiber fabrics/epoxy composites via interface engineering. *Compos. Sci. Technol.* **2021**, *207*, 108696. [CrossRef]
125. Abdelal, N. Electromagnetic interference shielding of stitched carbon fiber composites. *J. Ind. Text.* **2020**, *49*, 773–790. [CrossRef]
126. Liu, C.Y.; Kang, Z.X. Facile fabrication of conductive silver films on carbon fiber fabrics via two components spray deposition technique for electromagnetic interference shielding. *Appl. Surf. Sci.* **2019**, *487*, 1245–1252. [CrossRef]

127. Tang, X.R.; Lin, G.; Liu, C.C.; Cao, T.; Xia, Y.Q.; Yi, K.Y.; Zhang, S.; Liu, X.B. Lightweight and tough multilayered composite based on poly(aryl ether nitrile)/carbon fiber cloth for electromagnetic interference shielding. *Coll. Surf. A Physicochem. Eng. Asp.* **2022**, *650*, 129578. [CrossRef]
128. Duan, N.M.; Shi, Z.Y.; Wang, Z.H.; Zou, B.; Zhang, C.P.; Wang, J.L.; Xi, J.R.; Zhang, X.S.; Zhang, X.Z.; Wang, G.L. Mechanically robust $Ti_3C_2T_x$ MXene/Carbon fiber fabric/Thermoplastic polyurethane composite for efficient electromagnetic interference shielding applications. *Mater. Des.* **2022**, *214*, 110382. [CrossRef]
129. Wang, Y.Q.; Ding, Y.; Guo, X.L.; Yu, G.H. Conductive polymers for stretchable supercapacitors. *Nano Res.* **2019**, *12*, 1978–1987. [CrossRef]
130. Peng, Q.Y.; Chen, J.S.; Wang, T.; Peng, X.W.; Liu, J.F.; Wang, X.G.; Wang, J.M.; Zeng, H.B. Recent advances in designing conductive hydrogels for flexible electronics. *InfoMat* **2020**, *2*, 843–865. [CrossRef]
131. Onggar, T.; Kruppke, I.; Cherif, C. Techniques and Processes for the Realization of Electrically Conducting Textile Materials from Intrinsically Conducting Polymers and Their Application Potential. *Polymers* **2020**, *12*, 2867. [CrossRef]
132. Salado, M.; Lanceros-Mendez, S.; Lizundia, E. Free-standing intrinsically conducting polymer membranes based on cellulose and poly(vinylidene fluoride) for energy storage applications. *Eur. Polym. J.* **2021**, *144*, 110240. [CrossRef]
133. Grancaric, A.M.; Jerkovic, I.; Koncar, V.; Cochrane, C.; Kelly, F.M.; Soulat, D.; Legrand, X. Conductive polymers for smart textile applications. *J. Ind. Text.* **2018**, *48*, 612–642. [CrossRef]
134. Prajapati, D.G.; Kandasubramanian, B. Progress in the Development of Intrinsically Conducting Polymer Composites as Biosensors. *Macromol. Chem. Phys.* **2019**, *220*, 1800561. [CrossRef] [PubMed]
135. Rybicki, T.; Stempien, Z.; Karbownik, I. EMI Shielding and Absorption of Electroconductive Textiles with PANI and PPy Conductive Polymers and Numerical Model Approach. *Energies* **2021**, *14*, 7746. [CrossRef]
136. Zou, L.H.; Zhang, S.L.; Zheng, X.H.; Xu, Z.Z.; Li, C.L.; Yang, L.; Ruan, F.T.; Tan, S.C. Near-Instantaneously Self-Healing Coating toward Stable and Durable Electromagnetic Interference Shielding. *Nano-Micro Lett.* **2021**, *13*, 190. [CrossRef]
137. Yu, Z.C.; Zhao, Y.H.; Liu, J.R.; Wang, Y.S.; Qin, Y.; Zhu, Z.Y.; Wu, C.; Peng, J.C.; He, H.L. Advancement in cellulose-based multifunctional high conductive PNIPAAm/PPy hydrogel/cotton composites for EMI shielding. *Cellulose* **2022**, *29*, 6963–6981. [CrossRef]
138. Gahlout, P.; Choudhary, V. Microwave shielding behaviour of polypyrrole impregnated fabrics. *Compos. B Eng.* **2019**, *175*, 107093. [CrossRef]
139. Ghosh, Y.; Ganguly, S.; Remanan, S.; Das, N.C. Fabrication and investigation of 3D tuned PEG/PEDOT: PSS treated conductive and durable cotton fabric for superior electrical conductivity and flexible electromagnetic interference shielding. *Compos. Sci. Technol.* **2019**, *181*, 107682. [CrossRef]
140. Riaz, S.; Naz, S.; Younus, A.; Javid, A.; Akram, S.; Nosheen, A.; Ashraf, M. Layer by layer deposition of PEDOT, silver and copper to develop durable, flexible, and EMI shielding and antibacterial textiles. *Colloids Surf. A Physicochem. Eng. Asp.* **2022**, *650*, 129486. [CrossRef]
141. Siavashani, V.S.; Gursoy, N.C.; Montazer, M.; Altay, P. Stretchable Electromagnetic Interference Shielding Textile Using Conductive Polymers and Metal Nanoparticles. *Fibers Polym.* **2022**, *23*, 2748–2759. [CrossRef]
142. Wang, P.; Wang, Y.; Xu, Q.B.; Chen, Q.; Zhang, Y.Y.; Xu, Z.Z. Fabrication of durable and conductive cotton fabric using silver nanoparticles and PEDOT:PSS through mist polymerization. *Appl. Surf. Sci.* **2022**, *592*, 153314. [CrossRef]
143. Liu, Q.Z.; Yi, C.; Chen, J.H.; Xia, M.; Lu, Y.; Wang, Y.D.; Liu, X.; Li, M.F.; Liu, K.; Wang, D. Flexible, breathable, and highly environmental-stable Ni/PPy/PET conductive fabrics for efficient electromagnetic interference shielding and wearable textile antennas. *Compos. B Eng.* **2021**, *215*, 108752. [CrossRef]
144. Duan, M.H.; Hou, Y.J.; Guo, M.; Li, X.P.; Li, X.; Wang, J.L.; Ma, Y. Tailoring Electromagnetic Interference Shielding Performance of Conductive Nanocomposite Coating Using Textile Substrates. *Adv. Mater. Interfaces* **2021**, *8*, 2101089. [CrossRef]