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RECEIVED 03 February 2026

REVISED 30 April 2026

ACCEPTED 04 May 2026

PUBLISHED 15 July 2026

### CITATION

Bandyopadhyay J and Ray SS (2026)  
Integrating conductivity in stealth and  
biomedicine: role of 3D printable  
polymers in next-generation  
technology.  
*Front. Mater.* 13:1803402.  
doi: 10.3389/fmats.2026.1803402

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# Integrating conductivity in stealth and biomedicine: role of 3D printable polymers in next-generation technology

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Recently, 3D printing has become a transformative force in manufacturing, especially for custom applications. It is reshaping industries like aerospace and healthcare. As technology advances, the demand for advanced functional materials suitable for 3D printing grows. This review focuses on electrically conductive polymers designed for 3D printing, especially fused deposition modeling. It discusses their use in stealth and medicine. The review thoroughly examines the necessary criteria for these applications and the polymers and composites with various fillers developed to meet them. Understanding the performance and cost implications is crucial for future material development across many applications, both known and yet-to-be-discovered. Additionally, a perspective on the future of this technology is offered.

### KEYWORDS

3D printing, conductive polymer materials, fused deposition modelling, medical fields, stealth

## 1 Introduction

3D printing is a relatively new process compared to traditional methods like injection molding. It offers significant advantages in on-demand manufacturing, custom design, quicker prototyping, reduced material waste, and easier access to spare parts. However, it currently does not match the efficiency of high-volume production techniques such as injection molding and is mainly suitable for niche products. Over time, 3D printing technology and functional polymeric materials have developed in parallel, but research remains limited, particularly regarding electrically conductive polymers and their applications in 3D printing. The pursuit of scalable production of multifunctional materials has driven the development of conductive polymers for additive manufacturing, including 3D and even 4D printing, to meet the required product performance (Sinha Ray et al., 2025). Over the years, a range of electrically conductive materials for 3D printing has been developed, with potential uses in stealth and medical fields. This study summarizes materials that possess the necessary properties for these applications, along with those already proven suitable for 3D printing. Offering a review from this perspective and insights into future trends is a novel approach.

Additive manufacturing fundamentally involves building 3D structures by adding material layer by layer (Pérez et al., 2020). The evolution of 3D printing began with

Dr. Hideo in the 1980s and has recently seen significant growth. Over time, various liquid-based technologies like stereolithography (SLA), multi-jet modeling (MJM), and digital light processing (DLP), as well as solid-based methods such as fused deposition modeling (FDM), direct ink writing (DIW), freeze form extrusion fabrication (FEF), and powder-based techniques like selective laser sintering (SLS), electron beam melting (EBM), and laser-engineered net shaping (LENS), have been developed. Among these processes, 3D printing stands out as an environmentally friendly option because it maximizes material efficiency and reduces waste, thus improving the buy-to-fly ratio. It also enables rapid production of large, complex geometries (Huang et al., 2013; Al-Makky and Mahmoud, 2016; Adeniran et al., 2022). Furthermore, it supports on-demand manufacturing, custom designs, shorter prototyping times, reduced material waste, and easier access to service parts (Adeniran et al., 2022). Information about the different categories of 3D printing processes, associated materials, and their possible applications is available elsewhere (Sinha Ray et al., 2025). Among various techniques, FDM is notable for its ability to print polymeric materials, offering many advantages. It uses inexpensive, environmentally safe materials. Printed parts are highly stable and do not need chemical post-processing. In FDM, a filament with desired properties is extruded through a heated nozzle that moves along the X/Y-axes and vertically along the Z-axis, depositing material layer by layer until the part is complete. In addition to part design and the FDM machine, factors affecting quality include print orientation, layer thickness, raster angle relative to the X-axis, bead width, air gaps between rasters and contours, contour path around curves (contour width), material properties like density and flow, and environmental conditions such as temperature and humidity.

The roots of conductive 3D printing date back to the early 2000s, when researchers began exploring how to incorporate conductive materials into additive manufacturing processes. At first, the emphasis was on creating a framework for conductive inks and pastes used in conventional printing methods (Patel). A significant advancement in the use of conductive polymers for 3D printing occurred in 2020, when Yuk et al. introduced a high-performance 3D-printable conducting polymer ink based on poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) (Yuk et al., 2020). In 2021, Mechnano introduced a CNT-containing polymer for producing electrostatic discharge (ESD)-grade materials using laser-based digital light processing (DLP) and liquid crystal display (LCD) 3D printing (Everett, 2021). Designing conductive polymers for 3D printing has led to the development of various carbon-based nanoparticles and their composites, which are promising functional materials with high electrical and mechanical properties. These materials are essential for applications such as stealth and shielding (Shirke et al., 2024; Ahmad et al., 2019). In context, material properties such as electrical conductivity, complex permeability, and complex permittivity become important alongside 3D printability when designing a component for the specified application.

Historically, radar warning systems, even before World War I (1914–1918), gave rise to stealth technology (Shirke et al., 2024). Originally, stealth technology was used primarily on aircraft and submarines to evade enemy radar. Radar technology was first developed in 1939, and by 1945, the United States had developed an iron-based radar-absorbent paint called MX-410

to reduce radar reflections. Throughout the early 1960s and 1970s, the US continued to develop various stealth prototypes. P. Ufimtsev, credited with inventing stealth technology, employed equations in 1991 to predict how electromagnetic (EM) waves could reflect from two- and three-dimensional surface objects (Ufimtsev, 1991). Extensive research on polymer composites aims to improve thermal and electrical conductivity and enhance electromagnetic interference (EMI) shielding. Vijayanath et al. examined the shielding mechanisms, influencing factors, and the use of conductive polymer composites for EMI shielding and electronic applications (VijayKashimatt et al., 2025; Vijayananth et al., 2025). Polymerization techniques, functional groups, and the strategic addition of dopants to lower band gaps, along with factors such as temperature, thickness, permeability, permittivity, porosity, and the formation of percolation networks in composite structures, all significantly enhance a material's electrical conductivity and shielding performance. Today, stealth technology is used not only in defense and warfare but also for civilian applications. Aerial vehicles, such as drones, employ systems including camera and sensor data transmission, GPS navigation, radio control, and telemetry. A 3D printable material can offer the added benefit of design flexibility.

Besides stealth, the need for conductive polymeric materials was also recognized for biomedical applications. Such materials with 3D printability can be extremely beneficial for on-demand manufacturing, custom designs, shorter prototyping times, reduced material waste, and easier access to service parts. Given the electrophysiological functions of the brain and nerve tissues, research has focused on electrically conductive materials, including metals, carbon-based materials, and conductive polymers, to mimic tissue-like environments for cells that stimulate and/or monitor signals from tissues effectively (Koo et al., 2018; Choi et al., 2020; Sanjuan-Alberte et al., 2022; Kim et al., 2023). However, a lack of flexibility, weak tissue adhesion, and low hydrophilicity prevented these materials from being compatible with the nervous tissues (Yuk et al., 2019; Sunwoo et al., 2020). The development of conductive hydrogels has gained considerable interest for applications in electroactive tissue engineering, tissue interfacing, tissue repair, soft bioelectronics and robotics, stimuli-responsive drug delivery systems, and wearable or implantable sensors due to their tissue-like mechanical properties and adjustable electrical characteristics (Sunwoo et al., 2020; Yuk et al., 2019; Wang et al., 2022b; Hsu et al., 2022; Liang et al., 2023; Xu et al., 2022; An et al., 2020). Meanwhile, advances in 3D/4D printing enabled the fabrication of artificial organs, prosthetics, and implants, with personalized dimensions (Kim et al., 2023; Zhu et al., 2021). There are still challenges, including biocompatibility, the ability to mimic various tissue characteristics, aesthetics, comfort, and the precision of 3D-printed articles, all of which require further development.

Given the recent trend, there is a need for a comprehensive understanding of conductive polymeric materials, including those comprising micron-sized fillers and nanostructures, that are designed to meet the specific requirements of stealth and biomedical applications while remaining 3D printable. VijayKashimatt et al. have recently compiled a review of advances in polymer composites, elucidating their 3D printability, electrical conductivity, and EMI shielding effectiveness for electronic devices (VijayKashimatt et al., 2025). Some reviews highlight the potential applications of inherently conductive polymers, various conductive

fillers, and their combinations in 3D-printable energy devices and electronics (Jain and Waidi, 2025; Khan et al., 2025). In contrast, this review summarizes conductive polymeric materials, with a focus on stealth and medical applications that lack comprehensive research and further demonstration for 3D printing, particularly FDM.

Extensive research has been conducted on electrically conductive polymers and composites suitable for 3D printing via FDM. These materials have potential applications in advanced fields such as stealth and healthcare. The review primarily focuses on their use cases, essential requirements, and existing material knowledge, and emphasizes those that are also compatible with 3D printing. In addition to their performance and ability to meet key criteria for specific applications, challenges related to 3D printability, scalability, manufacturability, and cost are also discussed where relevant. The review concludes with insights into future research directions.

## 2 Conductive polymers for stealth applications

Stealth (low-observable) technology dates back to the Stone Age, when hunters used natural camouflage, such as leaves and plants, to conceal themselves (Ahmad et al., 2019). In modern times, it is used to camouflage vehicles and buildings from radar (Shirke et al., 2024). In addition to aircraft, uncrewed aerial systems (UAS) and unmanned aerial vehicles (UAVs), including those for civilian use, depend on technologies such as camera and sensor data transmission, GPS navigation, radio control, and telemetry. These systems are susceptible to radio frequency (RF) or EMI from both natural and human-made sources, which can cause control loss, navigation mistakes, data corruption, or system breakdown. Therefore, shielding against external RF/EMI is crucial to protect these systems from such issues. The critical factors affecting the stealth mechanism are described in the subsequent section.

### 2.1 Factors influencing the stealth mechanism

As devices miniaturize, EMI or RFI shielding for stealth becomes increasingly important to ensure reliable performance. EMI shielding is directly related to the reduction in skin depth. Skin depth is the distance into a material at which the EM wave intensity drops to  $1/e$  (~37%) of its value at the surface. Frequency, electrical conductivity, and the complex permeability of a material affect the skin depth. The skin depth ( $\delta$ ) can be determined from (Equation 1) (Matan, 2024) and is inversely proportional to the square root of the frequency ( $\omega$ ), electrical conductivity ( $\sigma$ ), and the complex permeability ( $\mu^*$ ). The imaginary part of the complex permeability ( $\mu''$ ), presented in (Equation 2) (Meena et al., 2010), represents magnetic losses within the material (e.g., hysteresis, eddy currents, domain-wall damping) that contribute to absorption. According to (Equation 3) (Keller, 2023) the skin depth is inversely related to the attenuation constant.

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu^*}} \quad (1)$$

$$\mu^* = \mu' - j\mu'' \quad (2)$$

$$\delta = 1/\alpha \quad (3)$$

$$\epsilon^* = \epsilon' - j\epsilon'' \quad (4)$$

$$\gamma = \alpha + j\beta \quad (5)$$

$$\alpha = \omega \sqrt{\frac{\mu\epsilon}{2} \left[ \sqrt{1 + \left(\frac{\sigma}{\omega\epsilon}\right)^2} - 1 \right]} \quad (6)$$

Another factor affecting EMI or RFI shielding is the complex permittivity ( $\epsilon^*$ ), as shown in (Equation 4) (Meena et al., 2010). Complex permittivity quantifies how a material polarizes in response to an electric field and is related to charge displacement, dipole alignment, and conduction. The propagation constant ( $\gamma$ ) depends on the attenuation constant and the phase constant, as presented in (Equations 5, 6) (Yasir, 2011).

Moreover, radar and infrared (IR) detection technologies also play essential roles in stealth (Zhou and Huang, 2021). In stealth technology, radar, infrared, and other detection methods account for approximately 60%, 30%, and 10%, respectively (Jin et al., 2024; Feng-Sheng et al., 2021). Figure 1 illustrates the schematic diagrams of different types of radar detection systems, and stealth against such detection is of utmost importance (Kulshreshtha and Al-Obaidi, 2020). Stealth technology decreases an object's radar visibility by minimizing reflections of infrared and acoustic waves with radar-absorbing materials and shielding against electromagnetic interference. Since radar beams are conical, a larger area is illuminated when the target is farther, resulting in less electromagnetic energy being reflected back to the radar system (Ahmad et al., 2019). Therefore, a small fraction of the reflected energy is detected by the specially designed antennas/receivers in the case of a long-range target.

The maximum detection range is influenced by several variables, including the transmitter's effective radiated power, beamwidth, antenna aperture size, receiver processing capability, and the object's radar cross-section (RCS), among others (Ahmad et al., 2019). The RCS of an object is defined as the ratio of the power reflected or backscattered per unit solid angle in the direction of the radar to the total power intercepted by the target, as shown in (Equations 7, 8) (Ahmad et al., 2019).

$$\begin{aligned} \text{RCS}(\sigma) &= \frac{\text{Power reflected to the receiver per solid angle}}{\text{Incident power} \frac{\text{density}}{4\pi}} \\ &= \lim_{R \rightarrow \infty} \frac{4\pi R^2 \cdot \text{Power density in the scattered field}}{\text{Power density of the incident plane wave}} \quad (7) \end{aligned}$$

In terms of decibel square meter, RCS is expressed as,

$$\sigma_{(dBsm)} = 10 \log_{10} \frac{\sigma}{\sigma_R} \quad (8)$$

where  $\sigma_R$  represents the RCS of a reference object with an area of  $1 \text{ m}^2$ . A lower RCS indicates reduced detectability, while a higher RCS signifies greater detectability. For example, a smaller RCS value makes it more challenging for an aircraft, UAS, or UAV to be detected (Gaowei et al., 2024). RCS can be reduced by adopting a stealth design, using stealth materials (e.g., coatings and structural components), and employing both passive (impedance loading) and

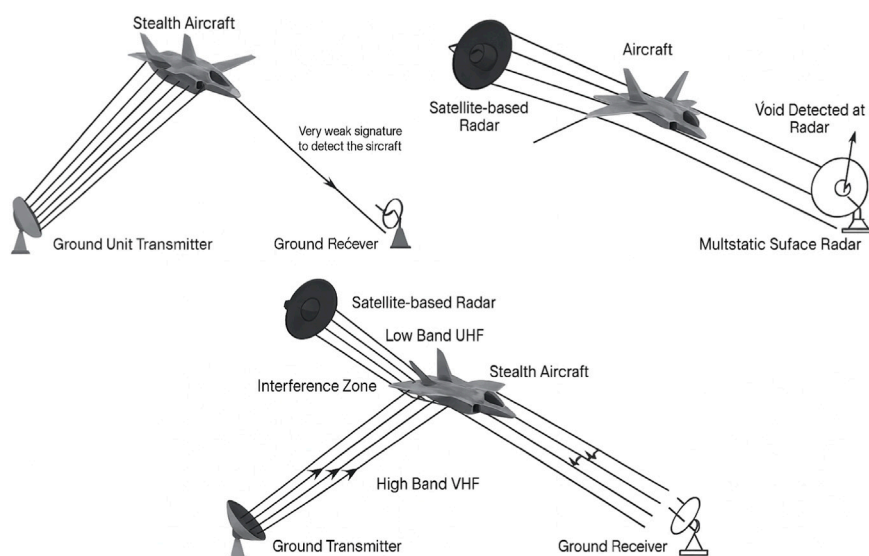


FIGURE 1  
Schematic diagram of Bistatic radar system (top left), void detection system (top right), and cross wave interference (bottom).  
Adapted from (Kulshreshtha and Al-Obaidi, 2020).

active cancellation (Yuzcelik, 2003). Typical shape design principles include (Gaowei et al., 2024): (i) Eliminating configurations that could create corner reflectors is crucial. The shape should not produce strong radar reflections. For example, the RCS is high and fluctuates for small spheres, whereas it remains constant for cylindrical shapes. (ii) Angled design involves transforming reflecting or backscattering surfaces into non-backscattering ones by tilting the surfaces. For example, in “boxy” structures like ships and ground vehicles, dihedral and trihedral corners, as well as “top hats” (right circular cylinders with axes perpendicular to a flat surface), significantly contribute to RCS. This effect can be minimized by positioning intersecting surfaces at acute or obtuse angles (Yuzcelik, 2003). (iii) Shielding design involves hiding one component behind another, like dorsal intakes that are concealed by the fuselage and wings. (iv) Parallel design involves aligning all wing surface edges along a few non-critical directions (more than  $40^\circ$  from directly ahead), which causes radar reflection spikes to align and reduces the occurrence of strong spikes.

For some scattering sources that cannot be fully mitigated through shape adjustments, radar-absorbing materials (RAM) can be used to absorb electromagnetic waves and convert them into internal energy (Gaowei et al., 2024). UAV and UAS are detected by their signatures as follows (Carter et al., 2019).

- Acoustics (20–16,000 Hz) – Noise from motors and propellers can be reduced by using quieter propulsion systems and flight patterns.
- Optical (0.4–0.7  $\mu\text{m}$ ): Visual stealth involves camouflage, low-reflectivity coatings, and flying at altitudes or times that minimize visibility.
- IR (0.75  $\mu\text{m}$ –1 mm): Thermal emissions are mitigated using heat-dissipating materials and shielding.
- Radar (3 mm<sup>-3</sup> cm, or  $\sim 10$ –100 GHz): Radar stealth requires appropriate shape/design and materials for low RCS.

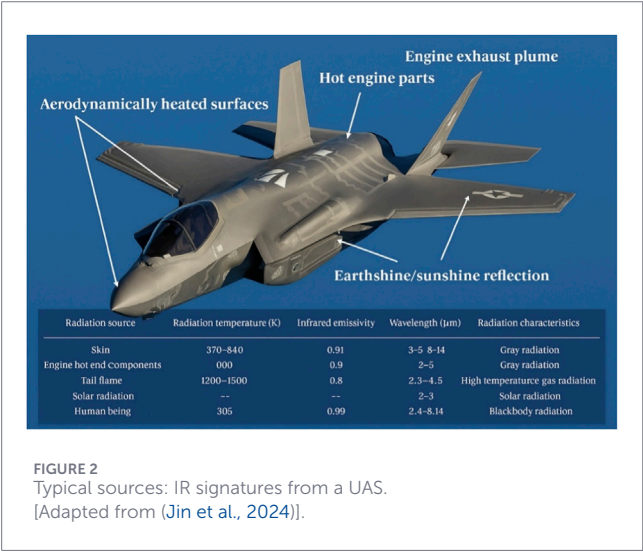
To decrease their detectability, it is essential to lower the reflection of waves that have frequencies or wavelengths below the threshold (Austin, 2011; Carter et al., 2019). Typical frequencies and wavelengths for different applications are summarized in Table 1. Stealth in the C and X bands appears vital for reducing the radar signature.

Figure 2 illustrates common sources of IR signatures. Because wavelengths in the 2–5  $\mu\text{m}$  and 8–14  $\mu\text{m}$  ranges can pass through Earth's atmosphere, stealth strategies are most effective in these spectral ranges. Designing outer-surface materials with low IR emissions can offer both radar and IR stealth (Jin et al., 2024). Nonetheless, the overall effectiveness of stealth depends on balancing EMI/RFI signals, radar, and IR concealment. Radar stealth involves minimizing radar reflections and maximizing microwave absorption, whereas IR stealth requires high reflection and low emission (Wu et al., 2023). Excessive radar reflection can convert microwave energy into heat, reducing IR stealth. Design solutions include spectral-selective radiation canopies, honeycomb stealth inlets, and wave-absorbing thermal structures (Jin et al., 2024). Materials such as quartz, fiber-reinforced resin, carbon fiber-reinforced resin, and aramid honeycomb are suitable for use in canopies, inlets, radomes, wings, and other parts; whereas, for nozzles, ceramics based on silicon-boron-carbon nitride (Si(B)C(N)) and their composites are preferred.

An active cancellation involves modifying and retransmitting the received radar signal (Yuzcelik, 2003). In a fully active process, the cancellation network receives, amplifies, and retransmits the threat signal out of phase with the target's static RCS. Passive cancellation, also known as impedance loading, involves introducing a secondary scatterer to cancel the reflection from a primary target (Yuzcelik, 2003). The core concept involves adding an echo source with adjustable amplitude and phase to counteract the original echo. A port can be cut into the body, and the interior cavity's dimensions and shape can be optimized to match the

TABLE 1 Typical frequency and wavelength for different applications.

| Band | Frequency range (GHz) | Wavelength (approx.) (cm) | Applications                                            |
|------|-----------------------|---------------------------|---------------------------------------------------------|
| L    | 1–2                   | 15–30                     | GPS, Mobile phone, aircraft surveillance radar          |
| S    | 2–4                   | 7.5–15                    | Wi-Fi (2.4 GHz), weather radar, satellite communication |
| C    | 4–8                   | 3.75–7.5                  | Radar, Satellite TV, long-distance radio                |
| X    | 8–12                  | 2.5–3.75                  | Military, marine, and weather monitoring radar          |
| Ku   | 12–18                 | 1.7–2.5                   | Satellite communication, broadcasting                   |
| Ka   | 26.5–40               | 0.75–1.1                  | High-resolution radar, satellite internet, 5G backhaul  |



aperture impedance. However, even with simple bodies, creating the necessary frequency-dependent impedance behavior of this built-in system remains challenging. Another approach for passive cancellation could be the utilization of RAM. Research on RAM began in the 1930s, focusing on maximizing EM wave absorption across a wide frequency spectrum. These materials decrease radar reflections by absorbing energy through mechanisms linked to their dielectric or magnetic properties. The absorbed energy typically converts into heat, though the temperature increase is usually minimal. For RCS reduction, a RAM must have a suitable frequency response, support two orthogonal polarizations, and meet specific aspect-angle criteria (Yuzcelik, 2003). Traditional RAM consists of an insulating binder (matrix) and magnetic or conductive fillers (reinforcement) (Ahmad et al., 2019). It can produce internal reflections of the received signals and hinder their reflection from the outer surface. Impedance matching is crucial for this purpose. The reflection coefficient of a surface is presented by (Equation 9):

$$r = \frac{\eta_M - \eta_o}{\eta_M + \eta_o} = \frac{Z_M - Z_o}{Z_M + Z_o} \tag{9}$$

Where  $r$ ,  $\eta_m$ ,  $\eta_o$ ,  $Z_m$ , and  $Z_o$  denote the reflection coefficient, the admittance of the reflecting substrate, the admittance of the incident medium, the intrinsic impedance of the reflecting substrate, and the intrinsic impedance of the incident medium, respectively,

and  $Z = 1/\eta$ . For  $\eta_m = \eta_o$  and  $r = 0$ , this condition represents impedance matching.

The intrinsic coefficient of the free space is presented by (Ahmad et al., 2019) in (Equation 10).

$$Z_{free\ space} = \frac{E}{H} = \sqrt{\frac{\mu_0}{\epsilon_0}} \approx 377\ \Omega \tag{10}$$

E, H,  $\mu_0$ , and  $\epsilon_0$  represent the electric field factor, magnetic field factor, permeability of free space, and permittivity of free space, respectively. Reflection from a substrate is zero if its intrinsic impedance is about 377  $\Omega$ , as in impedance-matched RAM (Saville, 2005). Since the impedance of a metallic aircraft is nearly zero, much of the incident signal is reflected. Applying RAM (ferritic, magnetic, or dielectric) to the metal surface allows rapid absorption of electromagnetic waves as they pass through. The absorption depends on the coating thickness (Yuzcelik, 2003), the angle of incidence (Säily and Räisänen, 2003), and material properties (Folgueras et al., 2014). RAM can be a nonmetallic mesh or a thin layer with embedded carbon or ferrite particles. Broadband radar systems use multiple layers of different materials to create a dielectric gradient.

In summary, this stealth mechanism relies on the interplay between EMI/RFI shielding and the concealment of a device's radar and IR signatures. While properties like high electrical conductivity, complex permeability, and permittivity affect EMI/RFI shielding, factors such as proper design, impedance loading, and the addition of RAM can alter radar and IR signatures. Therefore, to develop materials that achieve optimal performance, further investigation into their material properties—discussed in the following sections—is essential. Additionally, advancements in 3D printing technology offer design flexibility that can be leveraged to maximize performance and promote business and environmental sustainability.

2.2 Evolution of materials for stealth applications

Different types of electrically conductive materials and RAMs have been developed over time, and they are interconnected. Figure 3 shows a classification table and a schematic of RAM. In pyramidal RAM, EM wave attenuation occurs through multiple reflections inside the pyramids. Each pyramid's size, being larger than the wavelength of the incident wave, causes its faces to reflect the wave, absorbing some energy with each reflection (Hasnain

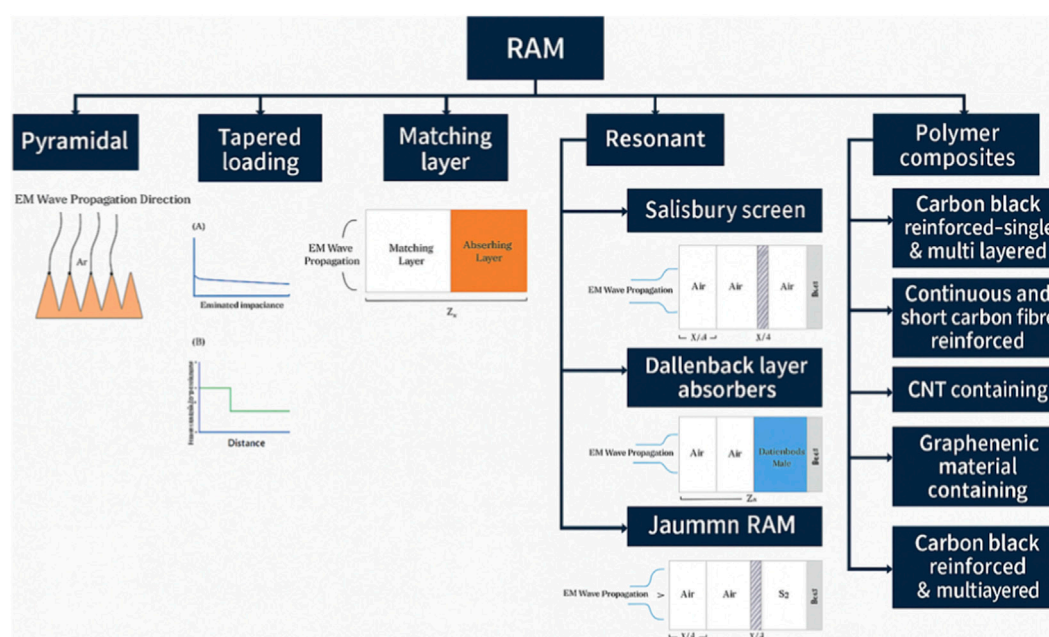


FIGURE 3  
Different types of RAM [pictures are adapted from (Ahmad et al., 2019)].

et al., 2007). Its usage is limited by its thickness and fragility (Yuzcelik, 2003). Tapered loading RAM combines lossy and low-loss materials, usually in a slab structure with a uniform lossy material layer parallel to the incident surface and an impedance gradient that increases with depth—examples include 3D plastic nets or open-cell foam created through dipping, spraying, or drainage, followed by drying. It is thinner than pyramidal RAM but less effective. A matching layer-RAM is placed between the incident surface and the absorber to match the medium impedance with that of the layered materials, controlled by the matching layer's thickness. These three RAM types have narrow bandwidths. Resonant RAM involves reflection and transmission at destructive interference points, with reflected waves undergoing a  $180^\circ$  phase reversal, and transmitted waves passing through and reflecting off a metal backing for the second reversal (Ahmad et al., 2019). Types include Salisbury screens, Dallenbach-layer absorbers, and Jaumann RAM. Salisbury screens consist of a resistive sheet placed at a quarter-wavelength distance in front of a conducting surface, often separated by an air gap or high-permittivity material. Dallenbach absorbers are homogeneous dielectric layers backed by a conductor. Their bandwidth is expanded by stacking multiple layers, such as silicon rubber loaded with titanium dioxide, carbon black, and silicon carbide. For example, a 4.6 mm ferrite-resin layer achieves over  $-20$  dB attenuation up to  $45^\circ$  across 8–12 GHz (Hatakeyama and Inui, 1984). Jaumann RAM uses multiple resistive layers separated by spacers before a metal backing, increasing bandwidth—such as a six-layer device, which reduced reflectivity by about 30 dB from 7 to 15 GHz (Tong, 2016). To develop lightweight RAM with broad frequency operation and design flexibility, researchers also investigated various polymer composites with different carbon-based fillers, which is discussed in detail in the following section.

It is evident that the material's inherent properties and design aspects cannot be considered separately when designing RAM to attenuate EMI/RFI signals and thereby improve devices' stealth performance. By selecting appropriate 3D-printing parameters, such as the infill pattern and layer height, a balance between conductive pathways and dielectric properties can be achieved; the extent to which this balance can be achieved remains an open question.

## 2.3 Polymer composites and their role in shielding and stealth technology

Polymer composites with different fillers are essential for creating lightweight, 3D-printable materials tailored for specific uses. These composites can be employed in RAM to provide EMI/RFI shielding. Composites with carbon fillers primarily provide shielding through their electrical conductivity, whereas ceramic nanoparticle-based composites improve heat dissipation, enhancing stealth against IR heating. Both features are discussed here.

Shielding and attenuating an incident electromagnetic wave involves absorption, reflection, and multiple internal reflections (Abedi et al., 2022). EM waves comprise electric and magnetic fields that oscillate perpendicular to each other. Therefore, shielding material's ability to reduce EM waves depends mainly on its electrical and magnetic properties, through reflection and absorption. In reflection-dominated EMI/RFI shielding—common when many charge carriers are present—the impedance mismatch causes the incident EM wave to reflect. As the EM field interacts with free electrons at the surface, an opposing field is generated inside the material. This results in reflection-based shielding, especially in metals, where EM wave penetration is limited to a shallow surface layer called the skin depth, where the field diminishes to  $1/e$  of

its original strength. Some of the transmitted waves are absorbed, while a small part may reflect internally between the front and back surfaces, creating multiple internal reflections. In absorption-dominated shielding, EM waves penetrate the entire thickness of the shield because there are fewer free charge carriers at the surface (Gupta and Tai, 2019). The material then dissipates the absorbed EM energy through dielectric losses, including conductive and polarization losses (Wang et al., 2021). The overall shielding effectiveness, as expressed by Abedi et al. (2022), is given by (Equation 11).

$$\text{shielding effectiveness} = 10 \log \frac{P_T}{P_I} = SE_a + SE_r + SE_m \quad (11)$$

where  $SE_a$ ,  $SE_r$ , and  $SE_m$  are the shielding effectiveness due to absorption, reflection, and multiple reflection, respectively.  $SE_m$  is negligible as it decreases with an increase in the  $SE_a$ . The literature indicates that numerous reflection effects in EMI/RFI shielding become significant only when  $SE_a$  is below 15 dB (Zhang et al., 2011).

The extent of EM wave attenuation arising from absorption or reflection can be quantified from the scattering parameters (S-parameters), which describe the behavior of a two-port network (Pupalaikis, 2020). A single S-parameter,  $S_{ij}$ , represents the ratio of the EM wave reflected at port  $i$  to the wave incident on port  $j$ .  $SE_a$  and  $SE_r$  can be obtained from S-parameters measured as follows (Yin et al., 2019):

$$SE_a = -10 \log \frac{|S_{21}|^2}{1 - |S_{11}|^2} \quad (12)$$

$$SE_r = -10 \log (1 - |S_{11}|^2) \quad (13)$$

where  $S_{21}$  and  $S_{11}$  are the transmission and reflection coefficients, respectively. Typically, electrical conductivity, overall EMI shielding effectiveness, and S-parameters are used to gauge the stealth performance of a material or component made from it.

In addition to electrically conductive polymers, most conventional thermoplastics suitable for part, component, or device manufacturing are electrically resistive and thermally insulating. Therefore, various conductive fillers are incorporated into these polymers to enhance electrical conductivity and complex permeability, thereby affecting skin depth and, consequently, shielding performance. However, incorporating conductive fillers into a matrix is not limited to electrically resistive polymers or to thermoplastics. Polymer composites, particularly those comprising micron- or nanoscale carbon fillers, have garnered significant attention for their design flexibility. The dispersion and distribution of carbon fillers within a matrix, their degree of alignment (particularly in asymmetric structures such as fibers or carbon CNTs), and their concentration all affect the effective conductive networks formed within the matrix and, consequently, the shielding effectiveness (Huang et al., 2020; Chung, 2001; Abedi et al., 2022). The absorption characteristics of a composite can be influenced by altering its geometry, morphology, and composition. When a composite contains carbon fillers, its shielding effectiveness can increase because charge carriers can transfer *via* electron hopping or tunneling once the percolation threshold is reached. This threshold is the critical filler concentration at which electrical resistivity drops sharply, indicating a transition of the polymer composite into a

conductive state. At sufficiently high carbon filler levels, direct contact between fillers forms a continuous conductive network that enhances charge transport.

Table 3 summarizes the effect of different fillers on the composite's microwave and RF absorption and transmission. Wu et al. have reported that in epoxy composites comprised of 30 wt.% carbon black coated with polyaniline, −40 dB reflection loss can be achieved in the frequency range of 9–13 GHz, whereas the widest bandwidth obtained with 20 wt.% carbon black loading with −12 dB reflection loss in the frequency range of 18–40 GHz (Wu et al., 2008). The improved electrical conductivity of PANI at high carbon black loadings explains the observed performance. The authors noted that PANI's electrical conductivity increases from 0.1997 S/cm to 0.6323 S/cm at 20 wt.% carbon black and to 0.8452 S/cm at 30 wt.%. Additionally, Oh et al. reported a maximum absorption of 32 dB across the 2.7 GHz bandwidth and the X-band (8–12 GHz) in a glass/epoxy composite containing 6% (vol.) carbon black (Oh et al., 2004). A radar-absorbing layer was developed by layering composites with 5 wt.% and 7 wt.% carbon black. The optimal composite thickness is 1.9 mm for 5 wt.% and 0.6 mm for 7 wt.%—is vital to balance shielding efficiency with mechanical strength. However, the report does not explicitly detail the relationship between mechanical properties and the optimal layering thickness. Studies indicate that EM wave absorption in carbon-black-filled composites can be enhanced by catalyzing carbon black particles with carbonyl iron powder (Liu et al., 2010; Shen et al., 2009). Many high-speed communication systems are transitioning to the terahertz frequency range to meet the growing demand for more efficient data transmission. In this context, Zeranska-Chudek et al. developed ethylene co-butyl acrylate/carbon black composites with various carbon black loadings (Zeranska-Chudek et al., 2021). They achieved an 80 dB shielding effectiveness at 0.9 THz in a 1 mm-thick sample containing 14.44 vol% carbon black (Zeranska-Chudek et al., 2021). Carbon black exhibits  $sp^2$  hybridization due to its graphitic microstructure; thus, when percolation networks form in a polymer composite, the electrical conductivity and EMI/RF shielding efficiency (*via* internal reflection) of the polymer are enhanced (Rahaman, 2023). Interfacial polarization and dielectric permittivity can also influence the absorption of EM waves (Zeranska-Chudek et al., 2021). When filler distribution reaches percolation, electrical conductivity increases, thereby limiting tunneling and reducing polarizability and dielectric loss. This is important for EMI shielding. Carbon black-filled polymer composites are suitable for EMI shielding because of their improved electrical conductivity; however, they may not be effective for IR stealth. Generally, the high absorptivity and emissivity of carbon black can be limiting factors in applications that require IR stealth. Low-emissivity topcoats (Kelly, 2020), IR reflecting pigments (like titanium dioxide or zinc oxide), paint, IR-absorbing materials, and multi-layered architectures can be used to adjust emissivity and IR stealth (Dutta et al., 2022). However, emissivity can also be used for camouflage if the background has a similar characteristic. The key point is that these materials lack a report on their 3D printability. Wang et al. reported that a PLA composite filled with 25 wt.% carbon black can be extruded, and the extrudate (without the proper filament required for FDM printing) was used to 3D print using a homemade setup (Wang et al., 2022a). Therefore, the scalability of filament processing and, subsequently,

the effect of such high filler loading on the FDM printing process require further investigation. The material's viscosity, the risk of inconsistent filament diameter disrupting continuous printing, and the abrasiveness due to the high filler concentration remain to be realized. However, the authors studied the effect of carbon black concentration on the composites' absorption performance using a vector network analyzer and found that the minimum reflection loss was  $-45.47$  dB at  $13.68$  GHz, corresponding to an effective absorption bandwidth of  $5.36$  GHz. The improved electrical conductivity of the PLA composite, up to  $0.02576$  S/cm at a carbon black concentration of  $25$  wt.%, together with the synergistic effects of polarization relaxation loss, conduction loss, and absorption, accounts for the observed shielding behavior.

Among carbon-based fillers, polymer composites with graphite have been created for shielding purposes. Krueger and King found that a nylon 6,6 composite containing  $30$  wt.% graphite had an SE of  $2.63$  dB over the  $0.3$ – $0.8$  GHz frequency range. In comparison, synthetic graphite in polycarbonate showed a higher SE of  $5.44$  dB, likely due to better filler dispersion (Krueger and King, 2003). Panwar and Mehra later created graphite-filled HDPE composites, achieving about  $33$  dB shielding effectiveness in the X-band ( $8$ – $12$  GHz), primarily due to reflection (Panwar and Mehra, 2008). Similarly, Sachdev et al. showed that adding more graphite to ABS improved both reflection and absorption losses, leading to an SE of up to  $60$  dB for a  $15$  wt.% graphite/ABS composite in the  $8$ – $12$  GHz range (Sachdev et al., 2011). High filler concentration can also limit the FDM printability, which has yet to be verified.

Another well-known carbon filler widely used in polymer composites is carbon fiber. At high carbon fiber concentrations ( $60$ – $70$  vol.), carbon fiber-reinforced polymer composites exhibit quasi-reflective properties and are suitable for EMI shielding, but they are ineffective for microwave absorption (Ahmad et al., 2019). Kim et al. studied the microwave absorption of a two-layer composite laminate, consisting of a carbon black-impregnated rubber sheet (with  $10$ – $40$  vol.% carbon black) attached to a carbon fiber-epoxy panel, and found reflection losses ranging from  $-2$  dB at  $4$  GHz to  $-3.5$  dB at  $12$  GHz (Kim and Kim, 2018). Tuning the dielectric property is crucial for designing radar-absorbing structures or microwave-absorbing materials. Mehdipour et al. studied the performance of carbon fiber-reinforced epoxy with multi-walled CNTs (MWCNTs) for antenna uses. They found that the reflection coefficient stayed below  $-10$  dB between  $4.9$  and  $10$  GHz (Mehdipour et al., 2012). However, the key point to address is fiber orientation, as electrical conductivity and reflection coefficients depend on it. Perpendicular fiber orientation relative to the ground forces current to flow up the center of the radiating element, thus reducing electrical conductivity and *vice versa*. Orientation-dependent electrical conductivity in the carbon fiber-reinforced polymer is well documented and discussed in this section. For example, Li et al. reported that the average effective conductivities in the parallel and orthogonal directions can reach  $37.2$  S/m and  $17$  S/m, respectively, over  $8$ – $12$  GHz (Li et al., 2019). Consequently, in a carbon fiber epoxy composite laminate, the least reflection happens in the orthogonal case with around six plies, each approximately  $0.125$  mm thick, resulting in a maximum power absorption of  $84\%$  (Li et al., 2019). To enhance shielding effectiveness, Morales et al. prepared a multifunctional composite

comprising a carbon-fiber-reinforced polymer with additional copper-mesh layers (Morales et al., 2023). Carbon-fiber-reinforced polymer layers mainly provide absorption-based shielding, while copper mesh relies on reflection. Combining these materials enhances shielding effectiveness over a broader frequency range than alone, due to complementary trends: absorption loss increases in the polymer and reflection loss decreases in the copper mesh as frequency rises. Overall, shielding effectiveness ranges from  $60\%$  to  $80\%$  within  $50$  MHz to  $10$  GHz. Figure 4 presents the layering sequence of carbon-fiber-reinforced polymer and copper mesh, and Figure 5 shows how these layered structures influence shielding performance. The authors also note that the placement of copper mesh has little effect on overall shielding, as polymer absorption dominates in the tested frequency range. The electrical conductivity of the carbon fiber-reinforced polymer varies with orientation, as mentioned earlier. The authors have reported high electrical conductivities of  $4 \times 10^4$  S/m in the y-direction and  $8$  S/m in the x- and z-directions. Consequently, the incident EM wave components in the x- and y-directions could only be dissipated in the y-direction, resulting in lower SE. In another context, Luo et al. and Chang and Eddib used hot-pressing to produce high-loading continuous carbon fiber-reinforced epoxy and polyamide six composites (Luo and Chung, 1999; Chung and Eddib, 2019). The shielding efficiency of the epoxy composite was  $124$  dB over  $0.3$ – $1.5$  GHz, while that of the polyamide six composite was  $66.9$  dB over  $0.1$ – $1$  GHz. The observed shielding efficiency is associated with the directional electrical conductivities in the carbon fiber-reinforced polymer (Table 2). Although Luo and Chung did not report electrical conductivity values, the reduction in resistivity, and hence a significant (approximately an order-of-magnitude) reduction in attenuation upon reflection at a thickness of  $1.9$  mm, is the leading cause of the achieved EMI shielding (Luo and Chung, 1999). Polypropylene foam reinforced with  $10$  vol.% carbon fibers achieves a shielding effectiveness of  $24.9$  dB at  $8$ – $12$  GHz (Ameli et al., 2013). Cell growth during the foaming process enhances the probability that preferentially oriented fibers will redistribute, thereby increasing the chance of interconnectivity. As a result, above the percolation threshold (in this case, around  $7.5$  vol.%), the electrical conductivity of foam structures is in the order of  $10^{-5}$  S/cm and is independent of frequency. Further increase in the filler loading to  $10$  vol.% allows an increase in electrical conductivity to the order of  $10^{-3}$  S/cm and in shielding effectiveness to  $24.9$  dB at  $8$ – $12$  GHz. For 3D-printed polylactic acid (PLA) reinforced with  $6.41$  vol.% carbon fiber, the shielding effectiveness is  $78.9$  dB at  $8$ – $12$  GHz (Yin et al., 2019). Abedi et al. achieved a shielding effectiveness of  $52.11$  dB across the  $8.2$ – $12.4$  GHz range using a robotic 3D-printed low-melt polyaryletherketone engineered with continuous carbon reinforcement fiber (Abedi et al., 2022). As with carbon black, the inherent properties of carbon fibers and percolation networks are essential to overall electrical conductivity and, consequently, to shielding effectiveness. Not only does filler concentration affect the percolation networks, but the 3D printing process also impacts on the properties of the printed objects. For example, factors such as the number of layers, hatch spacing (the distance between adjacent deposited composite lines), which influences the content and distribution of carbon fibers), and fill angles are crucial for overall performance, including EMI shielding and mechanical properties (Yin et al., 2019). Studies showed that by

adjusting the number of layers (2–12), hatch spacing (1.6–0.8 mm), and filling angle (90°–0°), a shielding effectiveness of 25.1–69.9 dB, 51.1–75.6 dB, and 6.8–78.9 dB can be achieved in continuous carbon fiber reinforced PLA. The authors also reported the maximum tensile and flexural strengths of the composites as 111.0 and 152.9 MPa, respectively. The interfaces between the carbon fibers and the polymer cause polarization loss and energy dissipation *via* internal reflections, which increases shielding efficiency as the layer count rises. The shielding efficiency improves with reduced hatch spacing, likely because of more contact points between the fibers. This allows several free charge carriers to contribute to electric loss and increases the number of interfaces involved in polarization loss. Conversely, shielding efficiency decreases with higher infill angles. Although there are only a few conductive paths within the cross-section of the carbon fiber bundle, a significant conductive path exists along the axial direction. Therefore, the likelihood of current flow is higher in the axial direction. Considering the angle  $\theta$  between the electric field ( $E$ ) and the oriented fibers, the electric field decomposes into  $E_{\perp}$  ( $E_{\perp} = E \sin \theta$ ) and  $E_{\parallel}$  ( $E_{\parallel} = E \cos \theta$ ), with the fibers aligned along  $E_{\parallel}$ . Thus, a lower  $\theta$  increases both the current density and the shielding efficiency. Additionally, the authors observed that the shielding efficiency increased from 52.9 dB to 69.6 dB as the thickness of the 3D-printed carbon fiber-reinforced PLA increased from 3 to 6 mm. 3D-printed continuous carbon fiber-reinforced polymer shows promise for applications across various sectors, including lightweight structures in automotive, aerospace, robotics, and prosthetics. Despite advancements in 3D printing techniques for continuous fiber-reinforced polymers using multi-nozzle systems or in-nozzle impregnation, manufacturability remains limited. These composite fibers face the same challenges as carbon black in IR stealth, and the same solutions apply. As discussed above, polymer composites containing fillers such as carbon black, graphite, and carbon fibers require a high filler concentration for effective shielding; however, their application for IR stealth can be limited due to their high emissivity. It can also adversely affect mechanical properties, which are critical for any product/part/component. Moreover, high filler loading may cause frequent damage to the printing nozzles, making 3D printing, particularly the scalable FDM process, challenging.

In contrast to conventional micron-sized fillers such as graphite, carbon black, and short or continuous carbon fibers, carbon nanostructures offer a high aspect ratio value and enable achieving the desired performance at lower concentrations. In this family, the tubular structure of CNTs, with their dominant axial electrical conductivity, is a promising candidate for providing highly conductive polymeric materials, as required for stealth applications. The effect of CNT concentration across various matrices has been investigated for this purpose. This section first delves into the extent of improvement in electrical conductivity and its influence on the stealth mechanism in various polymer composites containing CNTs, and, where applicable, their 3D printability. Research indicates that segregated CNT networks enhance the SE of CNT/polypropylene composites (2.2 mm thick) up to 48.3 dB (Wu et al., 2018). Chizari et al. produced a PLA/CNT composite *via* ball milling and compression molding, reporting a shielding efficiency of 55 dB across 8.2–12.4 GHz for the compression-molded sample containing 30 wt.% of CNT (Chizari et al., 2017). The report shows an asymptotic increase in electrical conductivity with

rising CNT concentration up to 40 wt.%, which also enhances EMI shielding effectiveness. As the CNT concentration increased from 0 to 40 wt.%, the electrical conductivity of the nanocomposites rose from approximately  $1.4 \times 10^{-14}$  to about  $1.7 \times 10^{-4}$  S/m. There is a possibility of agglomeration at high filler levels; however, the process still positively impacts the samples' electrical conductivity, even at very high CNT loadings. Consequently, EMI shielding effectiveness increased to about 47 and 55 dB at CNT concentrations of 20 and 30 wt.%, respectively. In addition to CNT concentration, the authors investigated electrical conductivity and EMI shielding as functions of interfilament spacing, layer number, and printing pattern. Results indicated that the number of layers has a greater influence on EMI shielding than interfilament spacing, as the overall sample thickness increases. Additionally, CNT-PLA-Dichloromethane (DCM) ink used in solvent casting for 3D printing produces scaffold structures. Schmitz et al. studied EMI shielding of ABS with 5 wt.% CNT, poly(acrylonitrile-co-butadiene-co-styrene) (ABS) with 5 wt.% carbon black, and a hybrid with a total additive of 5 wt.% and a CNT-to-carbon black ratio of 75:25 (Schmitz et al., 2021). They analyzed how 3D printing orientations—horizontal concentric (HC), perpendicular concentric (PC), and  $\pm 45^\circ$  (H 45)—affect electrical conductivity (refer to Figure 6) and EMI shielding (refer to Figure 7). According to Figure 6, electrical conductivity increases with carbon black, CNT, and especially with CNT alone, mirroring the shielding effectiveness pattern. Figure 7 shows the EMI shielding results for the PC-Horizontal, PC-Vertical, and H45 layers at a thickness of 0.1 mm. The data reveal that shielding decreases with thinner layers, mainly due to void formation, which can occur if flow rate, nozzle pressure, or interlayer adhesion are not optimized. Such gaps may arise from rapid crystallization in thinner layers. In applications such as antennas, soft materials with EMI shielding are preferred. A hybrid filler system, a combination of CNT with ceramic nanostructures such as boron nitride, was investigated to leverage the inherent electrical conductivity of CNT and the high thermal conductivity of boron nitride, which is critical for absorption-dominated stealth and IR stealth. Zhan et al. demonstrated that layering CNTs and hexagonal boron nitride flakes alternately on natural rubber (NR) latex yields 32.5 dB of shielding, attributed to a segregated, anisotropic network (Zhan et al., 2020). The increase in electrical conductivity with CNT loading up to 8 wt.% results from the formation of a more effective conductive network facilitated by the surfactant used during sample preparation. This, in turn, improves the shielding performance. The authors reported that the rubber material reinforced with 8 wt.% CNT and 8 wt.% boron nitride has an electrical conductivity of 0.98 S/cm, whereas that containing 4 wt.% graphene, 4 wt.% CNT, and 8 wt.% boron nitride measures 0.234 S/cm, and the material with 8 wt.% graphene and 8 wt.% boron nitride has a conductivity of  $3.98 \times 10^{-5}$  S/cm. The inherent thermal conductivity and specific heat capacity of these fillers further enhance thermal diffusivity through thermal phonon exchange, due to the densification of the three-dimensional filler network and increased particle overlap. Improved thermal conductivity helps dissipate heat, minimizes hot spots, and maintains background temperature, making such material potentially useful for IR stealth. Similarly, polyetherimide/CNT composite foam with segregated structures achieved a high shielding effectiveness (SE) of 32.8 dB across 8.2–12.4 GHz at 4.0 wt.% CNT loading (Feng et al., 2019). Xie et al. observed 44.2 dB of

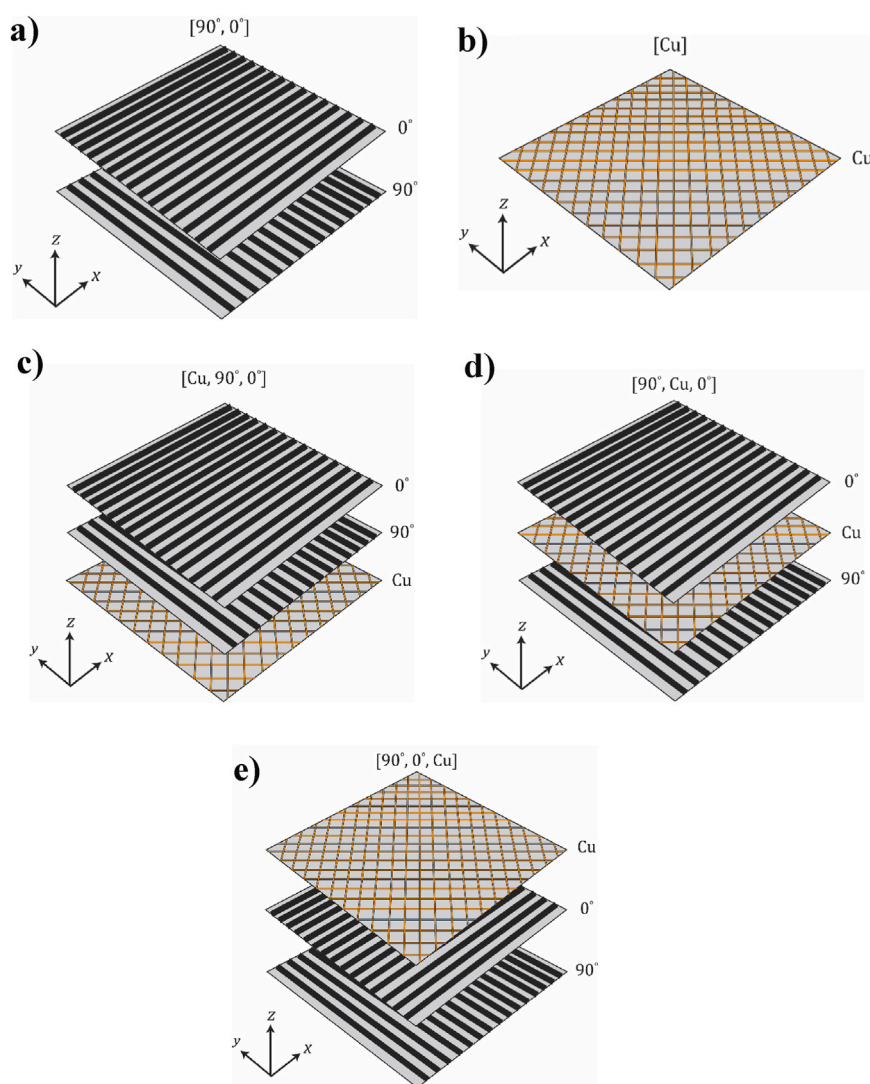


FIGURE 4

Fabrication of layer structures: (a) lay-up  $[90^\circ, 0^\circ]$ , (b) the copper mesh, (c) the lay-up  $[\text{Copper}, 90^\circ, 0^\circ]$ , (d) the lay-up  $[90^\circ, \text{Copper}, 0^\circ]$ , and (e) the lay-up  $[90^\circ, 0^\circ, \text{Copper}]$ . Adapted from (Morales et al., 2023).

shielding in CNT-reinforced (2.04 vol.%) natural rubber latex foam, due to the synergistic effects of the segregated network and porous foam structure (Xie et al., 2022). During foaming, the formation of the interconnected CNT network enhances overall electrical conductivity and, consequently, EMI shielding. The specific porous foam can be used to create insulating EMI shielding. Its thermal conductivity is reported as 0.048 W/mK. Extensive research also covers EMI shielding in polymer composites with graphene or reduced graphene oxide (rGO). The shielding effectiveness depends on the matrix-filler interaction (e.g., between MWCNT and various polymers), filler content, and thickness (Zhang et al., 2007; Al-Saleh, 2015; Yim and Park, 2015; Al-Saleh et al., 2013; Al-Saleh and Sundararaj, 2009). It is relatively easier to form interconnected networks with CNTs than with other fillers, which is key to improving electrical conductivity and, consequently, EMI shielding effectiveness. In this context, Zhang et al. observed a nearly constant low resistivity at CNT loadings

of approximately 4 wt.% (Zhang et al., 2007). A similar trend was reported by Al-Saleh et al. (2013). However, the percolation threshold varies in a high-density PE matrix. Electrical conductivity increases even at a CNT loading of 18 wt.%, which is the maximum concentration investigated by the authors (Yim and Park, 2015). The highest EMI shielding effectiveness in the composites was about 58 dB at 18 wt.% CNT loading and 1.4 GHz. Free volume, processing methods, and conditions play a critical role in controlling viscosity and shear, which in turn affect CNT distribution while maintaining aspect ratio. As a result, the percolation threshold can differ between polymers. In addition to multiple reflections and absorption, quantum tunneling between nearby CNT nanoparticles enables electron hopping before the percolation threshold is reached (Lu et al., 2020). To elucidate further on the types and dimensions of fillers, Al-Saleh et al. compared ABS composites containing carbon black, carbon nanofibers, and CNTs at various filler concentrations (Al-Saleh et al., 2013). Notably, the percolation threshold and

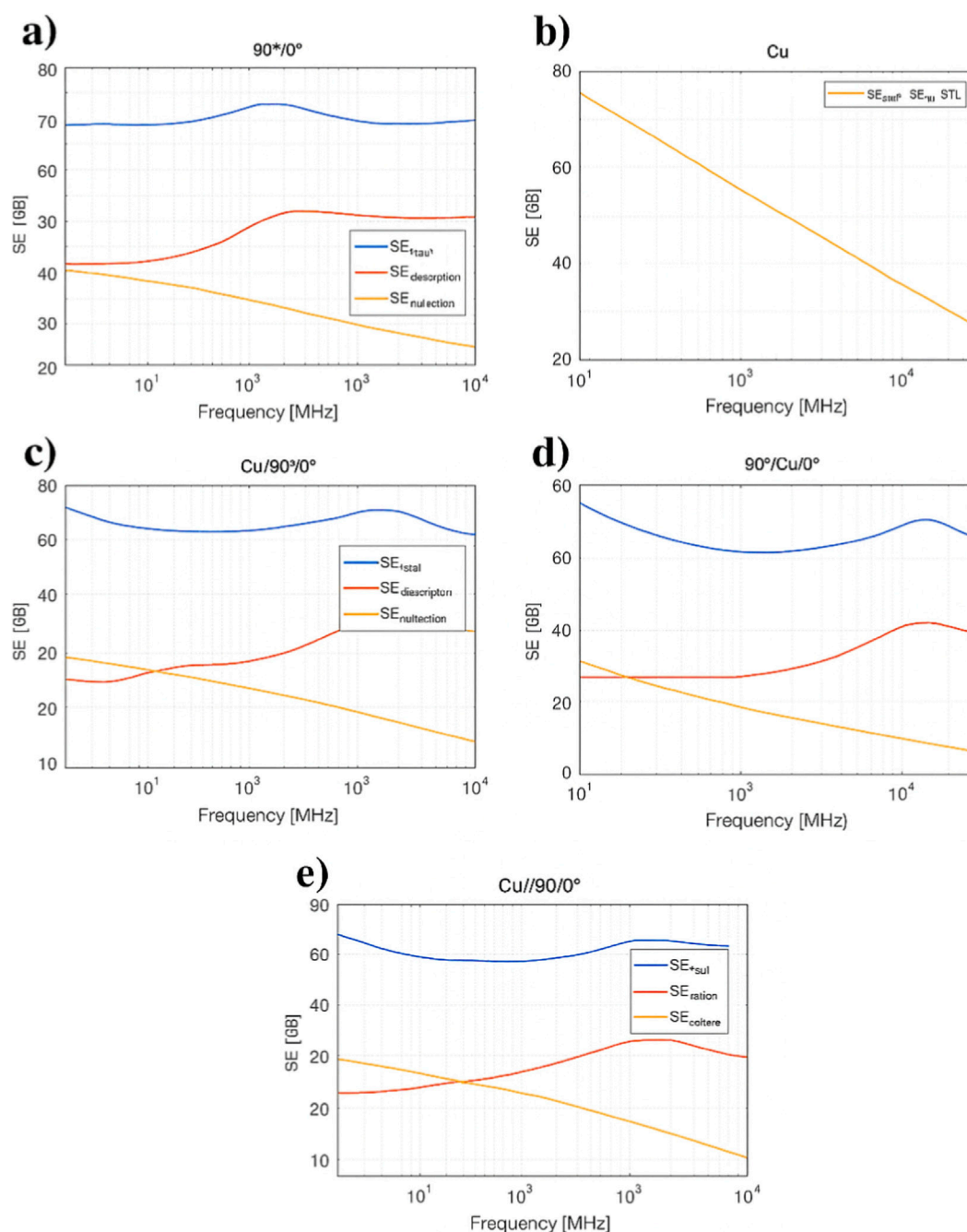


FIGURE 5

Calculated shielding effectiveness in (a) the carbon fiber-reinforced polymer composites with the lay-up [90°, 0°], (b) the copper mesh, (c) the lay-up [Copper, 90°, 0°], (d) the lay-up [90°, Copper, 0°], and (e) the lay-up [90°, 0°, Copper]. Graphs are adapted from (Morales et al., 2023).

low-volume resistivity can be achieved at much lower CNT concentrations than those of other fillers studied, leading to high EMI shielding at relatively low CNT content. Therefore, CNT-based composites are well-suited for the fabrication of lightweight EMI shielding materials. As shown in Table 2, EMI shielding effectiveness also depends on the polymer type and whether it is amorphous or semicrystalline. The distribution of fillers and the achievement of the percolation threshold are easier in amorphous polymers like ABS (due to free volume) than in semicrystalline polymers like PP.

Research indicates that CNTs can be used to develop resin-based composites for RAM. (Yilmaz Atay and Bilgiç, 2024; Munir, 2017). Most of the absorption results from magnetic and dielectric losses. Impedance matching can be improved in hybrid filler systems, such as combining CNT with reduced graphene oxide (Kong et al., 2014) or metal oxides (Ghosh et al., 2023). Hybrid fillers can enhance EM absorption. Filler concentration and viscosity control are critical for 3D printing, such as FDM. Although the 3D printability of the materials discussed here has not been reported, higher filler contents

TABLE 2 Effect of filler type and concentration in the polymer composites designed for microwave and RF absorption and reflection.

| Filler       | Composite                                                                                                                                                    | EMI shielding                                                                                                                                                                                                                                                                                 | Electrical conductivity                                 | Mechanical properties | FDM printability | References                          |
|--------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------|-----------------------|------------------|-------------------------------------|
| Carbon black | Carbon black coated with polyaniline in epoxy matrix                                                                                                         | Microwave absorption for the frequency range of 9–13 GHz (X-band) with –40 dB in reflection loss in a composite containing 30 wt% carbon black coated with polyaniline. Widest bandwidth obtained with 20 wt% filler loading with –12 dB reflection loss in the frequency range of 18–40 GHz. | 0.2057–0.4852 S/cm at a loading of 5–30 wt.% of fillers | —                     | —                | <a href="#">Wu et al. (2008)</a>    |
|              | Carbon black in glass/epoxy matrix                                                                                                                           | 32 dB microwave reflection loss for the 2.7 GHz                                                                                                                                                                                                                                               | —                                                       | —                     | —                | <a href="#">Oh et al. (2004)</a>    |
|              | Carbon black in epoxy matrix in the presence of carbonyl-iron powder                                                                                         | –17.5 dB reflection loss of microwave in the composite comprised of 20 wt.% carbon black and 25 wt.% carbonyl-iron powder.                                                                                                                                                                    | —                                                       | —                     | —                | <a href="#">Liu et al. (2010)</a>   |
|              | Carbon black in LLDPE matrix in the presence of carbonyl—iron powder                                                                                         | –17.8 dB reflection loss at 6.2 GHz and –16.39 dB at 13.4 GHz                                                                                                                                                                                                                                 | —                                                       | —                     | —                | <a href="#">Shen et al. (2009)</a>  |
|              | PLA composite comprising carbon black                                                                                                                        | –47.5 dB reflection loss with an effective absorption bandwidth of 5.36 GHz                                                                                                                                                                                                                   | 0.0015–0.02576 S/cm at a loading of 15–25 wt%           | —                     | Suitable for FDM | <a href="#">Wang et al. (2022a)</a> |
|              | Two-layer composite laminate (carbon black impregnated rubber sheet (carbon black loading of 10–40 vol%) attached to the carbon fiber–epoxy composite panel) | –2 dB at 4 GHz to –3.5 dB at 12 GHz reflection loss                                                                                                                                                                                                                                           | —                                                       | —                     | —                | <a href="#">Kim and Kim (2018)</a>  |

(Continued)

TABLE 2 Continued

| Filler       | Composite                                                                                      | EMI shielding                                                                                                                                                             | Electrical conductivity                                                                                                                                       | Mechanical properties                                   | FDM printability                                                                                                                                                                                       | References              |
|--------------|------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------|
| Carbon fiber | Reinforced continuous carbon fiber with epoxy (curing agent 26.4 wt.%) containing 2 vol% MWCNT | The reflection coefficient is better than -10 dB from 4.9 to 10 GHz                                                                                                       | —                                                                                                                                                             | —                                                       | —                                                                                                                                                                                                      | Mehdipour et al. (2012) |
|              | A carbon fibre epoxy composite laminate                                                        | The minimum reflection occurs in the orthogonal case, with approximately six plies (typical ply thickness of 0.125 mm), where a maximum power absorption of 84% is found. | Parallel fiber orientation: 37.2 S/m<br>Orthogonal orientation: 17 S/m                                                                                        | —                                                       | —                                                                                                                                                                                                      | Li et al. (2019)        |
|              | Layered structure of carbon-fiber-reinforced polymer and copper mesh                           | Overall shielding effectiveness between 60% and 80% within the 50 MHz-10 GHz frequency range.                                                                             | 4 × 104 S/m in y-direction and 8 S/m along x and z-directions                                                                                                 | —                                                       | —                                                                                                                                                                                                      | Morales et al. (2023)   |
|              | Continuous carbon fibre reinforced epoxy prepared via hot pressing                             | Overall shielding effectiveness of 124 dB 0.3 MHz to 1.5 GHz                                                                                                              | —                                                                                                                                                             | —                                                       | —                                                                                                                                                                                                      | Luo and Chung (1999)    |
|              | Continuous carbon fibre reinforced polyamide 6 prepared via hot pressing                       | Overall shielding effectiveness of 66.9 dB 0.1 MHz to 1 GHz                                                                                                               | Approximately 145 ( $\Omega$ cm) <sup>-1</sup> in the longitudinal (fiber) and 0.156 ( $\Omega$ cm) <sup>-1</sup> in transverse (perpendicular to the fibers) | —                                                       | —                                                                                                                                                                                                      | Chung and Eddib (2019)  |
|              | 10 vol.% of carbon fiber reinforced polypropylene foam                                         | Shielding effectiveness of 24.9 dB 8–12 GHz.                                                                                                                              | 10–3 S/cm                                                                                                                                                     | —                                                       | —                                                                                                                                                                                                      | Ameli et al. (2013)     |
|              | 3D printed 6.41 vol.% of carbon fiber reinforced PLA                                           | Shielding effectiveness of 78.9 dB 8–12 GHz.                                                                                                                              | —                                                                                                                                                             | Tensile strength: 111 MPa, Flexural strength: 152.9 MPa | Shielding effectiveness due to the number of layers (2–12), hatch spacing (1.6–0.8 mm), and infill orientation of carbon fibers (90°–0°) are 25.1–69.9 dB, 51.1–75.6 dB, and 6.8–78.9 dB, respectively | Yin et al. (2019)       |

(Continued)

TABLE 2 Continued

| Filler                 | Composite                                                                                                           | EMI shielding                                                                                                                                                                                                     | Electrical conductivity                                                              | Mechanical properties | FDM printability | References                                     |
|------------------------|---------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|-----------------------|------------------|------------------------------------------------|
|                        | 3D printed low-melt polyaryletherketone containing 66 wt.% of continuous carbon fibers                              | Shielding effectiveness of 60.2 dB 8–12 GHz.                                                                                                                                                                      | 2.37 S/m                                                                             | —                     | —                | <a href="#">Abedi et al. (2022)</a>            |
| Carbon nanotubes (CNT) | 30 wt.% CNT in PLA-DCM ink for solvent-casted 3D printing used to make scaffold structures and compression molding. | Shielding effectiveness of 55 dB at 8.2–12.4 GHz. The PLA-CNT composite was prepared <i>via</i> ball milling and subsequently compression-molded to prepare specimens for EMI network analysis using a waveguide. | $\sim 1.4\text{E}-14$ to $\sim 1.7\text{E}+4$ S/m for CNT loading from 0 to 40 wt.%. | —                     | —                | <a href="#">Chizari et al. (2017)</a>          |
|                        | Alternating assemblies of CNTs and hexagonal boron nitride flakes on natural rubber (NR) latex                      | EMI shielding of 32.5 dB                                                                                                                                                                                          | A maximum of 0.98 S/cm for 8 wt.% CNT and 8 wt.% boron nitride combination           | —                     | —                | <a href="#">Zhan et al. (2020)</a>             |
|                        | Polyetherimide/0.06 vol.% CNT composites foam                                                                       | 32.4 dB EMI shielding                                                                                                                                                                                             | 7.98 S/m                                                                             | —                     | —                | <a href="#">Feng et al. (2019)</a>             |
|                        | Natural rubber latex foam comprised of 2.04 vol.% CNT                                                               | 44.2 dB EMI shielding                                                                                                                                                                                             | 36.6 S/m                                                                             | —                     | —                | <a href="#">Xie et al. (2022)</a>              |
|                        | PU containing 6.7 wt% MWCNT                                                                                         | 60 dB at a thickness of 3 mm                                                                                                                                                                                      | —                                                                                    | —                     | —                | <a href="#">Zhang et al. (2007)</a>            |
|                        | Ultrahigh molecular weight PE comprised of 10 wt.% MWCNT                                                            | 50 dB at a thickness of 1 mm                                                                                                                                                                                      | —                                                                                    | —                     | —                | <a href="#">Al-Saleh (2015)</a>                |
|                        | PE comprised of 10 wt.% MWCNT<br>PE comprised of 18 wt.% MWCNT                                                      | 35 dB at a thickness of 3 mm<br>58 dB EMI shielding                                                                                                                                                               | Approximately 2, 6, and 10 S/cm at the CNT loading of 10, 12, and 18 wt.%            | —                     | —                | <a href="#">Yim and Park (2015)</a>            |
|                        | ABS comprised of 10 wt% MWCNT                                                                                       | 40 dB at a thickness of 1 mm                                                                                                                                                                                      | —                                                                                    | —                     | —                | <a href="#">Al-Saleh et al. (2013)</a>         |
|                        | PP comprised of 16 wt.% MWCNT                                                                                       | 34.8 dB at a thickness of 1 mm                                                                                                                                                                                    | —                                                                                    | —                     | —                | <a href="#">Al-Saleh and Sundararaj (2009)</a> |

(Continued)

TABLE 2 Continued

| Filler   | Composite                                                      | EMI shielding                                                                            | Electrical conductivity                                                                                          | Mechanical properties                                                                                  | FDM printability | References               |
|----------|----------------------------------------------------------------|------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|------------------|--------------------------|
| Graphene | graphene/CEF-NF/PVDF                                           | 48.5 dB shielding with electrical conductivity ~31.3 S/cm at a filler loading of 40 wt.% | —                                                                                                                | —                                                                                                      | —                | Mei et al. (2019)        |
|          | PANI/Ag@ graphene                                              | 29.3 dB shielding with electrical conductivity ~20.3 S/cm at a filler loading of 5 wt.%  | PANI: $3.18 \times 10^{-4}$ S/cm<br>PANI-5 wt.%<br>Graphene: 2.53 S/cm<br>PANI-5 wt.%<br>Ag@Graphene: 20.32 S/cm | —                                                                                                      | —                | Chen et al. (2013)       |
|          | PANI/Ni@ graphene                                              | 24.9 dB shielding with electrical conductivity ~6.28 S/cm at a filler loading of 5 wt.%  | PANI-5 wt.%<br>Ni@Graphen6.28 S/cm                                                                               | —                                                                                                      | —                | Chen et al. (2013)       |
|          | PVDF/10 wt.% graphene nanoplatelets                            | 27 dB shielding effectiveness                                                            | 0.05 S/cm at a filler loading of 10 wt.%                                                                         | —                                                                                                      | —                | Zhao et al. (2018a)      |
|          | CuNW@ graphene aerogel                                         | 52.2 dB shielding at a filler loading of 8.7 wt.%                                        | 20.8 S/cm at a filler loading of 8.7 wt.%                                                                        | Compressive stress increases gradually with increasing strain and more rapidly at larger strain levels | —                | Wu et al. (2018)         |
|          | PANI/graphene                                                  | 69 dB at a filler loading of 25 wt%                                                      | —                                                                                                                | —                                                                                                      | —                | Basavaraja et al. (2011) |
|          | PANI/graphene/GO                                               | 120 dB at a filler loading of 25 wt%                                                     | —                                                                                                                | —                                                                                                      | —                | Basavaraja et al. (2011) |
| rGO      | TPU/graphite oxide                                             | ~20 dB at a filler loading of 20 wt.% and at a thickness of ~50 $\mu\text{m}$            | TPU/G-8: ~9.3 S/m<br>TPU/G-12: 25.9 S/m                                                                          | Tensile strength ~60 MPa                                                                               | —                | Shen et al. (2017)       |
|          | TPU/ $\text{Fe}_3\text{O}_4$ @rGO                              | 17.2 dB at a filler loading of 20 wt.% randomly and 13.93 when fillers are aligned       | —                                                                                                                | —                                                                                                      | —                | Hong et al. (2020)       |
| MXene    | 90 wt% $\text{Ti}_3\text{C}_2\text{T}_x$ cold pressed with wax | Electrical conductivity of $9 \times 10^{-3}$ and EMI shielding of 76.1 dB               | —                                                                                                                | —                                                                                                      | —                | Han et al. (2016)        |
|          | 60 wt% $\text{Ti}_3\text{C}_2\text{T}_x$ hot pressed with wax  | EMI shielding of 39.1 dB                                                                 | —                                                                                                                | —                                                                                                      | —                | Liu et al. (2017)        |
|          | Wax/ $\text{Ti}_3\text{C}_2\text{T}_x$ -CNT cold pressed       | EMI shielding of 52.9 dB at a filler loading of 35 wt.%                                  | —                                                                                                                | —                                                                                                      | —                | Li et al. (2017)         |

(Continued)

TABLE 2 Continued

| Filler         | Composite                                                 | EMI shielding                                                                                                                   | Electrical conductivity                       | Mechanical properties                                                                                                                                                                                                                   | FDM printability | References                                 |
|----------------|-----------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|--------------------------------------------|
| MXene          | 22.5 vol.% bulk $\text{Ti}_3\text{C}_2\text{T}_x$ in PVDF | 48.47 dB at a thickness of 2 mm                                                                                                 | —                                             | —                                                                                                                                                                                                                                       | —                | Zhao et al. (2018b), Rajavel et al. (2020) |
|                | 4 wt.% CNT/1 wt.% $\text{Ti}_2\text{CT}_x$ in PVDF        | 60.5 dB at a thickness of 0.2 mm                                                                                                | 17.02 S/m in-plane and 0.42 S/m through-plane | —                                                                                                                                                                                                                                       | —                | Li et al. (2021b)                          |
|                | 4 wt.% CNT/12 wt.% $\text{Ti}_2\text{CT}_x$ in PVDF       | 63 dB at a thickness of 0.2 mm                                                                                                  | —                                             | —                                                                                                                                                                                                                                       | —                | Li et al. (2021b)                          |
|                | 0.74 vol% few-layered $\text{Ti}_2\text{CT}_x$ in Epoxy   | 56.4 dB at a thickness of 2 mm                                                                                                  | 695.9 S/m                                     | —                                                                                                                                                                                                                                       | —                | Zhao et al. (2018b)                        |
|                | 2.5 vol% few-layered $\text{Ti}_2\text{CT}_x$ in PVA      | 21 dB at a thickness of 0.3 mm                                                                                                  | —                                             | —                                                                                                                                                                                                                                       | —                | Xu et al. (2019)                           |
| Boron nitrides | 35 wt.% h-BN in PP                                        | The highest thermal conductivity of composites with 27 $\mu\text{m}$ is above $2 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ | —                                             | Elastic modulus increases significantly without much compromise with the tensile strength                                                                                                                                               | FDM printable    | Li et al. (2021a)                          |
|                | 30 vol% h-BN in PA                                        | The highest thermal conductivity of composites is $2.03 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$                          | —                                             | —                                                                                                                                                                                                                                       | FDM printable    | Geng et al. (2019)                         |
|                | 30 wt.% h-BN in polydimethyl Isiloxane                    | The highest thermal conductivity of composites is $0.895 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$                         | —                                             | —                                                                                                                                                                                                                                       | DIW printing     | An et al. (2023)                           |
|                | 3D printed ABS containing 35 wt.% BN                      | The highest thermal conductivity of composites is $0.93 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$                          | —                                             | Lower flexural modulus in 3D-printed specimens than in injection-molded ones, irrespective of the conversion process chosen; it reduces with increasing filler loading, and infill orientation does not have a pronounced effect on it. | FDM printable    | Quill et al. (2018)                        |

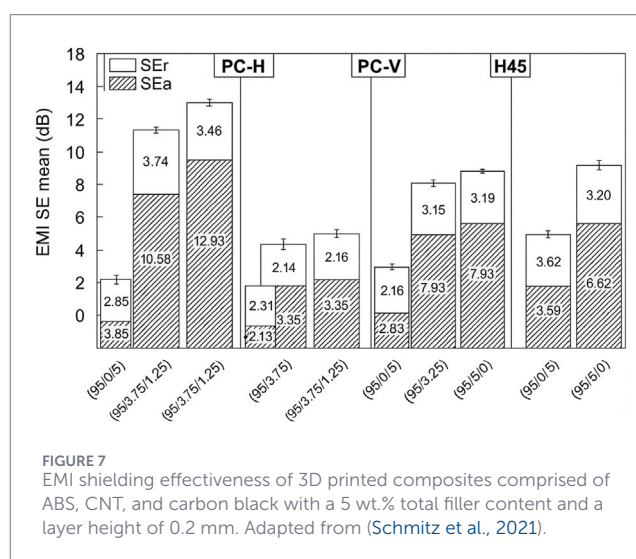
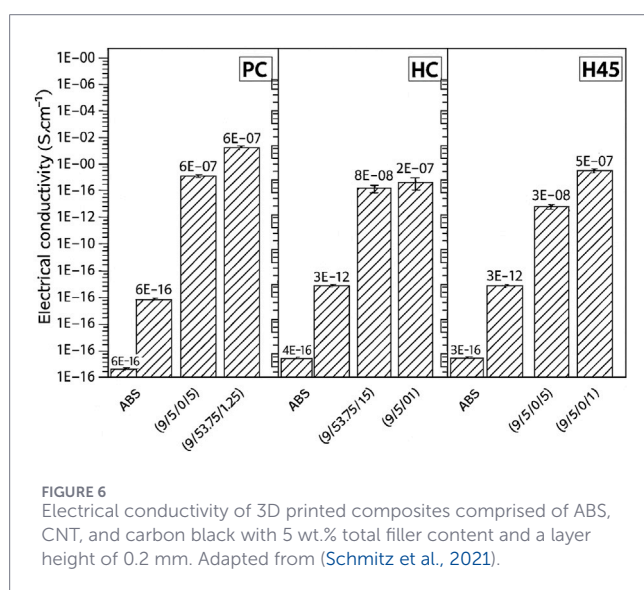
may cause nozzle clogging, abrasion, and poor layer adhesion, thereby limiting large-scale 3D printing. The high cost of nanofillers like CNTs should also be considered in product design.

The effects of filler types on shielding extent, limitations such as why carbon black or carbon fiber might not be the best option for stealth, whereas nanoparticles from the carbon family do, as well as the viability of composites for 3D printing, are discussed. Based on the above discussion, it is evident that CNT-based composites improve the electrical conductivity of

the matrix and are well-suited for the fabrication of lightweight EMI shielding materials. Interconnected CNT networks are key to improving electrical conductivity and, consequently, EMI shielding effectiveness. To achieve a similar extent of shielding effectiveness, the CNT loading required in a matrix can be drastically lower than that of conventional micron-sized filler-based polymer composites. Free volume, processing methods, and conditions play a critical role in controlling viscosity and shear, which in turn affect CNT distribution while maintaining aspect

TABLE 3 Typical properties of MY716, and MY717.

| Key performance parameter              | Measured performance MY716 | Measured performance MY717 | Control             | Typical filament available commercially with certain electrical conductivity |
|----------------------------------------|----------------------------|----------------------------|---------------------|------------------------------------------------------------------------------|
| Electrical conductivity ( $S.m^{-1}$ ) | $2.2e^{-05}$               | $2.3e^{-04}$               | $2.0e^{-09}$        | $2.1e^{-05}$                                                                 |
| EMI shielding (dB)                     | 17                         | 20                         | 2.4                 |                                                                              |
| Flexural modulus at 40 °C (Pa)         | $3.8e^{09}$                | $5.5e^{09}$                | $4.5e^{09}$         | $3.2e^{09}$                                                                  |
| Tensile modulus (MPa)                  | $1,359.6 \pm 50.9$         | $1,359.6 \pm 50.9$         | $1,598.6 \pm 132.7$ | $2,396.0 \pm 125.1$                                                          |
| Ultimate tensile strength (MPa)        | $47.1 \pm 2.5$             | $47.1 \pm 2.5$             | $63.0 \pm 5.2$      | $55.4 \pm 3.7$                                                               |
| Elongation at break (%)                | $16.6 \pm 2.8$             | $16.6 \pm 2.8$             | $21.7 \pm 4.2$      | $3.9 \pm 0.3$                                                                |
| Density ( $g/cm^3$ )                   | 1.2                        | 0.98                       | 1.2                 | 1.1                                                                          |
| Melt flow rate (g/10 min)              | 6.3                        | 6.3                        | 9.7                 | N/A                                                                          |
| Melting temperature (°C)               | 240.5                      | 241.2                      | 240.0               | 240.0                                                                        |
| Crystallization temperature (°C)       | 196.1                      | 196.6                      | N/A                 | N/A                                                                          |



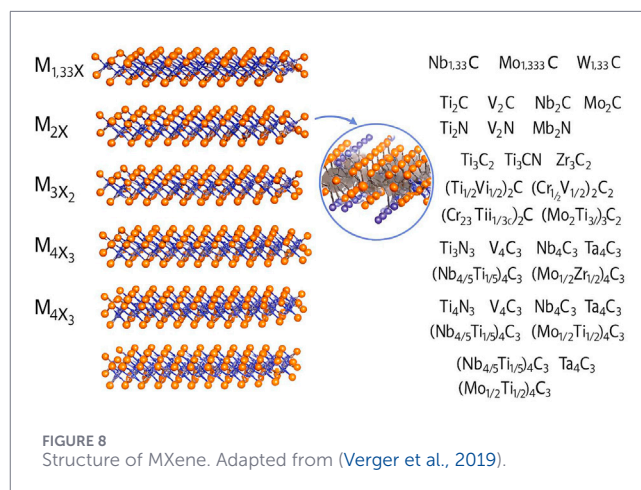
ratio. As a result, the percolation threshold can differ between polymers. In addition to multiple reflections and absorption, quantum tunneling between nearby CNT nanoparticles enables electron hopping before the percolation threshold is reached. The recent trend is shifting toward hybrid filler systems that offer added benefits, such as reduced absorption loss and improved impedance matching, which are important for lowering the RCS and facilitating stealth in other ways. When direct evidence of the dispersion and distribution characteristics of the nanofillers is not readily available, the composite's electrical conductivity can serve as a proxy to estimate the percolation threshold. Application of such composites for 3D printing requires attention to layer thickness, infill pattern, and density, since shielding decreases with thinner layers. This occurs mainly due to void formation when flow rate,

nozzle pressure, or interlayer adhesion are not optimized. Lower CNT loading in a polymer composite might reduce abrasiveness, processability challenges, and nozzle clogging compared to carbon fiber-based polymer composites, thereby reducing maintenance costs.

Graphene, another carbon-based filler, universally improves electrical conductivity and EMI shielding in polymers, particularly at higher loadings (see Table 2) (Mei et al., 2019; Chen et al., 2013; Zhao et al., 2018a; Wu et al., 2008; Basavaraja et al., 2011). The highest shielding effectiveness was observed in PANI with a mixed filler system of graphene and GO (Basavaraja et al., 2011). This mixture increased shielding from 69 to 120 dB compared with PANI containing a single graphene filler, both containing 25 wt.% nanoparticles. This behavior is similar to that of CNTs, as previously discussed. Combining graphene with paramagnetic fillers, such as

manganese oxide and iron oxide nanoparticles, on the surface of graphene nanoplatelets induces magnetic losses during EM wave interaction, thereby boosting shielding efficiency. Dipole loss occurs when the magnetic component of an EM wave interacts with magnetic nanoparticles; the alignment of dipoles with the magnetic field is delayed by internal friction, converting EM energy into heat and attenuating the wave. Shen et al. found that TPU is highly filled with 20 wt.% graphite oxide can achieve about 20 dB of EMI shielding (Shen et al., 2017). Research has shown that adding iron oxide-decorated rGO results in slightly poorer performance than pure rGO at the same concentration (Hong et al., 2020). Beyond EMI shielding, research has demonstrated that CuNW@G core-shell aerogel acts like foam, with compressive stress increasing gradually with strain and accelerating at higher strain levels. The presence of a hysteresis loop indicates energy dissipation within the porous material during loading and unloading. Electrical conductivity and tunability of metal nanoparticle-decorated carbon nanomaterials, such as CuNW@G, can potentially be applied in RAM due to their electrical properties and EMI shielding capabilities. However, limiting factors include challenges in bulk production of decorated nanoparticles, processing issues, and cost, especially because a high filler concentration is required to achieve the desired performance.

Following the widespread interest in graphene, the materials research community has explored other two-dimensional materials, such as MXenes, hexagonal boron nitride, black phosphorus, transition metal dichalcogenides, and layered double hydroxides, to further enhance EMI shielding (Kumari et al., 2023). MXenes are a family of layered ternary carbides and nitrides derived from MAX phases, which have a general formula  $M_{[n+1]}AX_n$  (where  $n = 1, 2$ , or  $3$ ;  $A$  is a group 13 or 14 element of the periodic table;  $X$  is carbon and/or nitrogen; and  $M$  represents the transition element). MXenes are produced by selectively etching the  $A$ -layer from the MAX phase, thereby removing the intermediate element and yielding 2D MXene structures (Naguib et al., 2014). The typical structure is shown in Figure 8 (Verger et al., 2019). The general formula of MXenes is  $M_{[n+1]}AX_nT_x$ , where  $T_x$  represents a vanishing surficial functional group (OH, O/F). Reports have shown widespread EMI shielding in a highly filled wax composite with MXenes (e.g.,  $Ti_3C_2T_x$ ), which depends on the processing method; either cold or hot pressing is employed (Liu et al., 2020; Han et al., 2016). Wax/ $Ti_3C_2T_x$ /CNT showed a shielding effectiveness of 52.9 dB (Li et al., 2017). A similar trend is observed in PVDF-based composites (Zhao et al., 2018b; Li et al., 2021b; Rajavel et al., 2020). PVDF containing 4 wt.% CNT and 1 wt.%  $Ti_3C_2T_x$  can provide EMI shielding of 60.5 dB at a thickness of only 0.2 mm. When an incoming EM wave interacts with the MXene surface, some of it reflects due to carrier interactions (see Figure 9) (Vijayananth et al., 2025). The remaining waves propagate farther, undergo multiple internal reflections and absorption within the layered structure, and are significantly attenuated. This layered architecture facilitates efficient dispersion and attenuates EM wave energy, thereby enhancing overall shielding performance. Figure 10 illustrates the EMI shielding effectiveness of composites comprised of cellulose nanofibers (CNF), MXene, and mesoporous carbon hollow spheres (MCHS) (Tao et al., 2023). The porous structure of MCHS, in addition to MXene, increases reflections and interfacial losses of EM waves in its pores and between the interfaces



of MXene and MCHS, thereby attenuating the EM waves. In Epoxy/ $Ti_3C_2T_x$  composites, Wang et al. reported a significant improvement in EMI shielding effectiveness (transmission and absorption) with increasing  $Ti_3C_2T_x$  concentration and upon annealing, as shown in Figure 11 (Wang et al., 2019). Further improvement in EMI shielding is observed in an epoxy composite containing honeycomb-structured rGO-MXene at a much lower concentration across the examined frequency range, as depicted in Figure 12 (Song et al., 2020). MXene concentrations used were 10, 30, 50, 70, and 90 g/L, and the corresponding rGMHs were named rGMH-1, rGMH-2, rGMH-3, rGMH-4, and rGMH-5, respectively. Recent studies have shown that EMI shielding can be achieved even at lower MXene concentrations (Zhao et al., 2018b; Xu et al., 2019). Absorption of EM waves, loss of EM waves *via* interfacial polarization, and heat dissipation in MXene all contribute to its shielding effectiveness (Rajavel et al., 2020). At very high MXene loadings, an increase in thermal conductivity is expected. For example, a PVDF-MXene composite with 22.55 vol.% MXene has a thermal conductivity of  $0.767 \pm 0.034$  W/(m·K), which improves heat dissipation and may make MXene suitable for IR stealth. However, producing such composites on a large scale can be difficult using conventional polymer processing techniques, and the high cost could limit their commercial applications.

While boron nitride (BN) is widely recognized for boosting the thermal conductivity of insulating resins, as shown in Table 2, it also enhances mechanical properties and EMI shielding (Li et al., 2021a; Geng et al., 2019; An et al., 2023; Quill et al., 2018). BN has a high dielectric constant and can be polarized by an electric field, leading to dielectric loss in which part of the electromagnetic wave energy is absorbed and converted into heat. Its layered structure further attenuates EM waves through multiple internal reflections. A recent study on wax composites with rGO/h-BN hybrids featuring a microscale sandwich-like structure found that, during microwave transmission, electrons from graphene layers can hop at interlayer boundaries and move through the composite (Kumari et al., 2023). Parts a, b, and c of Figure 13 show, respectively, the real part ( $\epsilon'$ ), imaginary part ( $\epsilon''$ ) of the permittivity of wax composites with the rGO/h-BN hybrid sandwich structure, and a schematic depicting electronic transport and microwave dissipation. Several BN-containing polymer composites have been developed and are

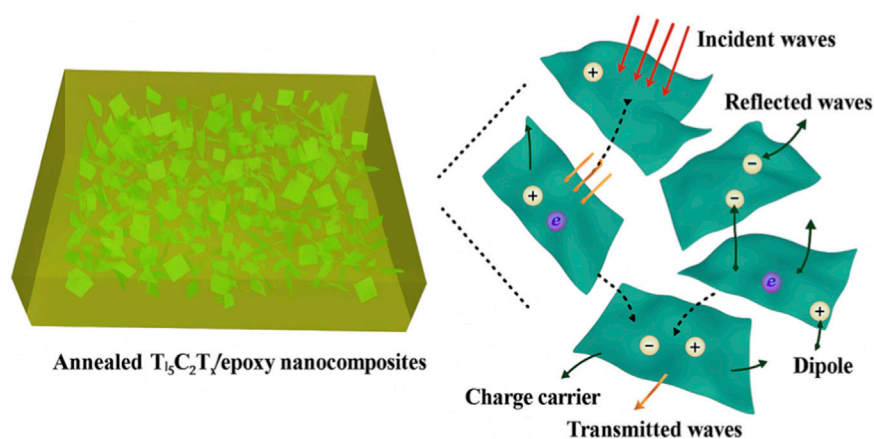


FIGURE 9  
Mechanism of EM wave attenuation by MXene Adapted from (Vijayananth et al., 2025).

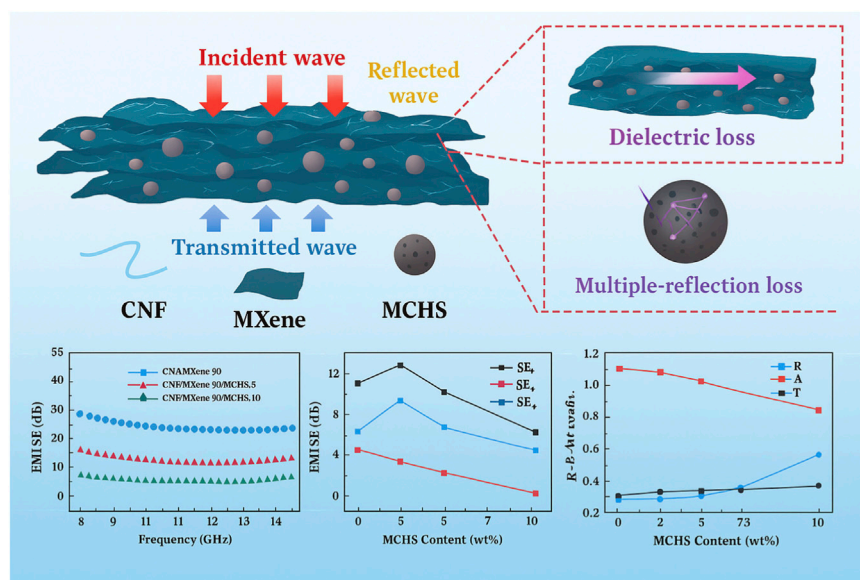


FIGURE 10  
EMI shielding effectiveness of composites comprised of cellulose nanofibers (CNF), MXene, and mesoporous carbon hollow spheres (MCHS). Adapted from (Tao et al., 2023).

suitable for FDM or DIW-type 3D printing (Table 2). However, research shows that their mechanical properties, such as flexural modulus, can be lower than those of injection-molded materials, especially when BN loading exceeds 5 wt.% (Quill et al., 2018). The flexural modulus generally decreases as BN loading increases, regardless of the processing method used. The authors found no significant difference in this property when varying the infill orientation angle during FDM printing. BN's low infrared emissivity, high thermal stability, thermal conductivity, chemical inertness, and low density make it attractive for designing lightweight IR stealth materials. The main challenges with these materials include equipment component abrasion and clogging, layer delamination, warping, and brittleness at high BN concentrations. This issue

is not unique to BN but applies to any inorganic filler with minimal interfacial interaction with the matrix. An optimal filler concentration is necessary to balance electrical conductivity and EMI shielding effectiveness across a wide frequency range while maintaining mechanical properties and ease of processing, including 3D printing. There is a lack of comprehensive reports on many EMI shielding materials, including their 3D printability, which requires further investigation. Additionally, the high cost of BN could limit its commercial adoption.

In this context, we have developed conductive polymer materials, MY716, and MY717, for use in FDM 3D printing. Table 3 compares the performance of MY716, and MY717 to the control and to a commercial material. Both MY716, and MY717 show significant

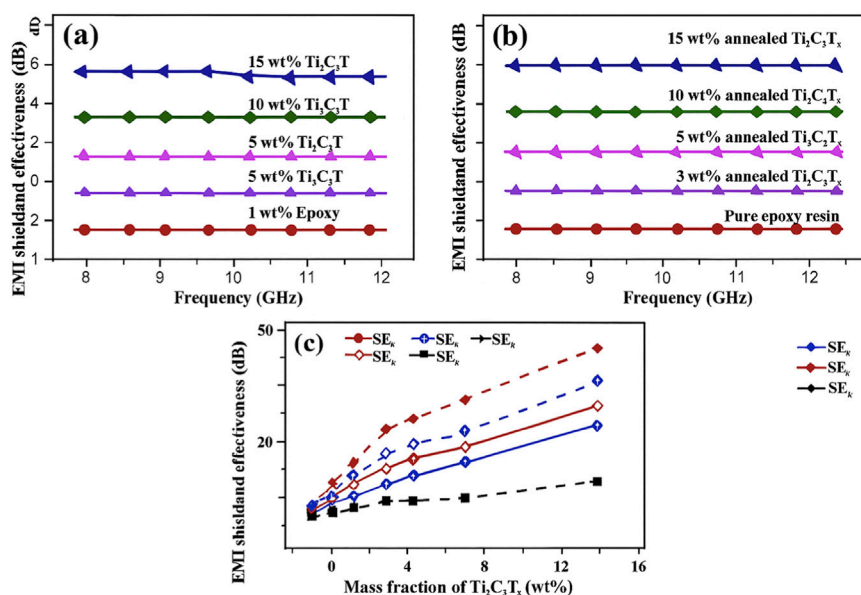


FIGURE 11 EMI shielding performances of (a)  $\text{Ti}_3\text{C}_2\text{T}_x$ /epoxy within the frequency range examined, (b) the same for the annealed  $\text{Ti}_3\text{C}_2\text{T}_x$ /epoxy EMI shielding nanocomposites; and (c)  $\text{SE}_t$ ,  $\text{SE}_a$ , and  $\text{SE}_r$  of the  $\text{Ti}_3\text{C}_2\text{T}_x$ /epoxy (Open symbol) and annealed  $\text{Ti}_3\text{C}_2\text{T}_x$ /epoxy EMI shielding nanocomposites (Solid symbol). Adapted from (Wang et al., 2019).

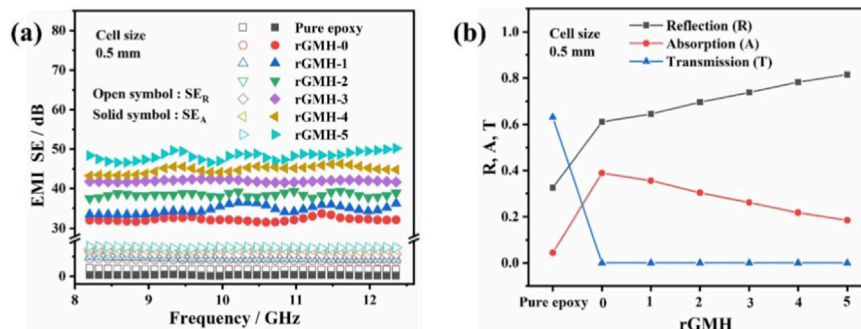


FIGURE 12 (a)  $\text{SE}_t$  and  $\text{SE}_a$  and (b) reflection, absorption, and transmission coefficients of the rGMH/epoxy nanocomposites. Adapted from (Song et al., 2020).

improvements in electrical conductivity compared to the control, with levels comparable to a typical commercial material available in the market. This enhanced conductivity leads to considerably better EMI shielding. The tensile properties of the control, MY716, and MY717 are similar, although a typical commercial material has a slightly higher modulus but much lower elongation at break. Additionally, their densities, melt flow rates, and melting temperatures are similar.

To further investigate the material's suitability for RAM, an RF shielding experiment was conducted with a Rohde and Schwarz vector analyzer (model ZVA40) and a waveguide over the 6–18 GHz frequency range. Experiments involving waveguides and a vector network analyzer are widely used to determine the S-parameters related to the electromagnetic properties of composites and to analyze materials for antenna applications (Vovchenko et al., 2024). Figure 14 presents the transmission

coefficient and return loss for the waveguide. Control specimens, MY716, and MY717 are 3D-printed in a dog-bone shape that matches the waveguide window's contour dimensions and are shown in Figure 15 with different thicknesses. Figure 16 displays data for one of the 3D printable and one of the commercial material used in gasket but not 3D printable. The spike in the 9–10 GHz range is due to the waveguide. Figure 15 indicates that the control specimens transmit nearly 100% of RF energy regardless of thickness. MY716, and MY717 effectively shield RF transmission from 4 to 18 GHz, with shielding effectiveness increasing with thickness. For example, at a thickness of 3 mm, MY716 shields RF transmission from –6 dB at 6 GHz to –8 dB around 14 GHz. An RF shielding loss of –8 dB means about 84% of the signal is blocked. MY717 shields from –6 dB at 6 GHz to –10 dB at approximately 10 GHz, blocking about 90%. In comparison, the typical example of a commercial material shows a maximum transmission

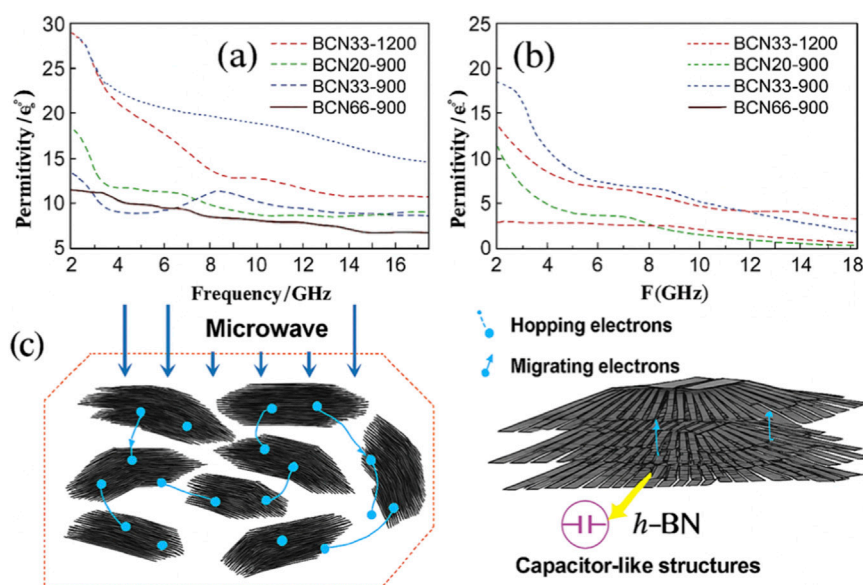


FIGURE 13

(a) Real part ( $\epsilon'$ ) of permittivity, (b) imaginary part ( $\epsilon''$ ) of wax composites comprised of rGO/h-BN hybrids' microscale sandwich-like structure, and (c) illustration showing electronic transit and microwave dissipation. Adapted from ((Kumari et al., 2023).

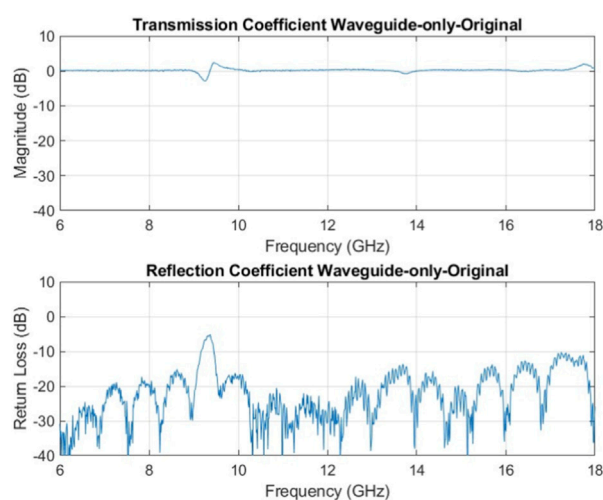


FIGURE 14

The transmission coefficient and the return loss for the wave guide.

coefficient of  $-8$  dB (around 84% shielding) at a thickness of 1 mm.

The RF shielding performance of the MY716, and MY717 is quite similar. Additionally, MY716, and MY717 offer advantages such as low density, high heat deflection temperature, and greater elongation at break than one available commercially. Commercial EMI gaskets, sheets, absorbers, and shields which are not 3D printable—have a transmission coefficient of about  $-18$  dB to  $-26$  dB across the tested frequency range. These materials are typically thick and heavy. The ability to 3D print materials offers

benefits in customizable component design and fabricating complex enclosures for effective EMI and RF shielding.

Return loss can be determined from the reflection coefficient as (Bird, 2009):

$$\text{Return loss (dB)} = -20 \log_{10} |r| \quad (14)$$

The reflection coefficient in dB can be expressed by

$$r(\text{dB}) = 10^{(-\text{Return loss}/20)} \quad (15)$$

The reflected power is proportional to the square of the reflection coefficient (Fong et al., 2002), i.e.,

$$P_{\text{reflected}} = |r|^2 * P_{\text{incident}} \quad (16)$$

Figure 15 indicates that the reflection coefficient for a 0.5 mm-thick control is around  $-20$  dB, while for a 3 mm-thick specimen, it is about  $-6$  dB. Based on (Equations 14 and 15), the reflected power at  $-20$  dB drops to 0.01, meaning roughly 1% of the power is reflected, and 99% is transmitted. Transmission decreases somewhat as thickness increases. EMI shielding effectiveness can be calculated from the S-parameter as (Schmitz et al., 2021):

$$\text{EMI shielding effectiveness} = 10 \log \frac{1}{|S_{21}|^2} \quad (17)$$

This means that a  $-10$  dB transmission loss, as seen in MY717, indicates an EMI shielding effectiveness of 20 dB. The EMI SE of MY717 is 20 dB. For an EMI shield to be effective, it should have an EMI SE of at least 10–20 dB, which corresponds to about 90%–99% attenuation of the incoming signal (Zhang et al., 2007; Li et al., 2008). Besides carbon nanofillers, two-dimensional MXenes—layered transition metal carbides, nitrides, or carbonitrides—are promising options. Their intricate

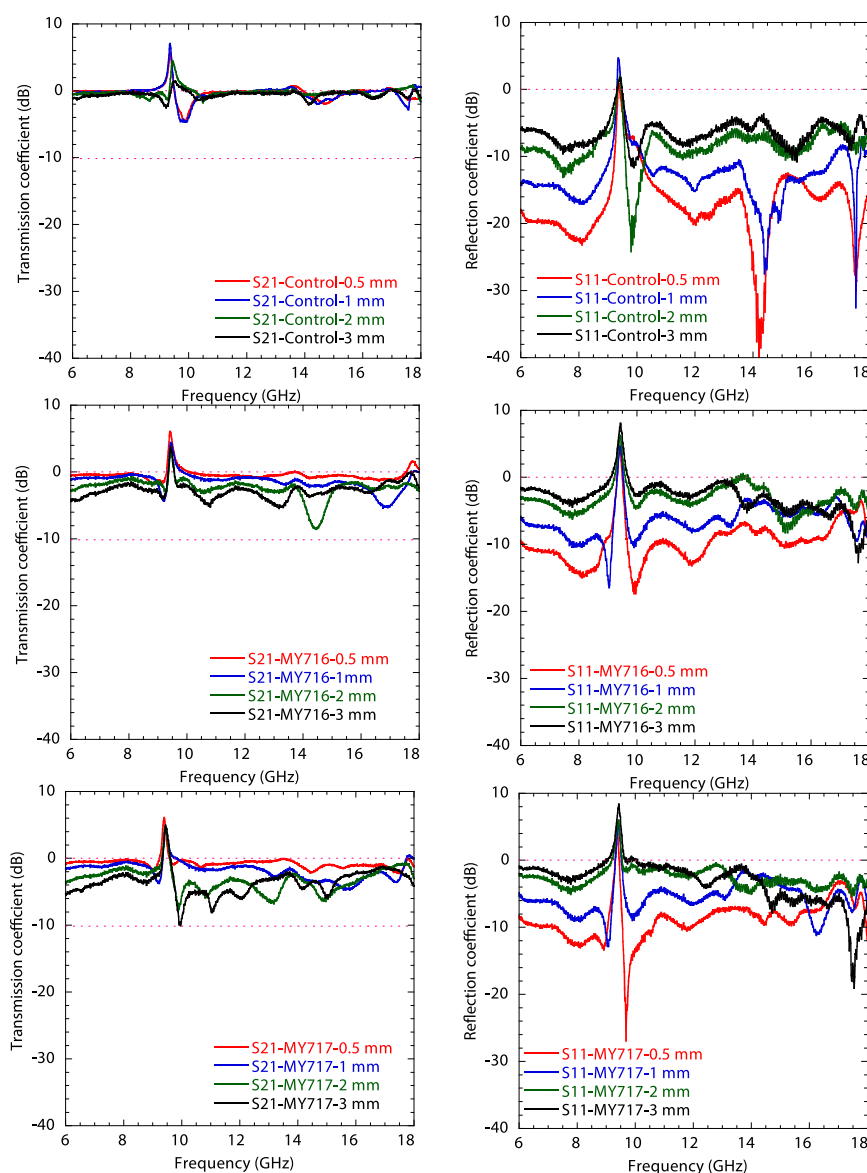


FIGURE 15 The transmission coefficient and the return loss for the 3D printed (dog-bone shaped) specimens made of control, MY716 and MY717.

3D interfaces enhance internal reflections and scattering, thereby extending conductive pathways and improving EMI shielding performance (Lee et al., 2021). However, the high cost of the complex synthesis process can limit its use. The standard MXene synthesis involves several steps: precursor selection, etching, exfoliation, and intercalation or delamination.

The key point is that not all fillers have inherent wave-absorbing capabilities that require both high microwave attenuation and effective impedance matching. Therefore, not all electrically conductive materials, even those with high EMI shielding, are suitable for RAM design. In some cases, they can be engineered for this purpose. For example, Liang et al. recently developed a fiber-reinforced periodic gradient absorber (ASM) consisting of an FR4 transmission layer for impedance matching, a dielectric meta-structure to promote multiple reflections

and resonances, and a magnetic skin layer (Carbonyl iron powder/MWCNTs/polyurethane) for electromagnetic energy dissipation (Liang et al., 2025). This structure permits dual-gradient electromagnetic parameter modulation, achieving 94% absorption across the X, Ku, and K bands (8.6–26.4 GHz) with a total thickness of 3.5 mm and a density one-third that of conventional magnetic metamaterials. Although some research has been done on developing 3D-printable metamaterial absorbers (Peng et al., 2024), a similar concept, such as ASM, could be considered a future direction. This could expand applications in stealth and communication.

Wireless communication technology is rapidly advancing toward the next-generation (e.g., 5G), enabling the Internet of Things (IoT) to become a reality. This increases the likelihood of EMI interference as the number of electronic devices grows. To ensure

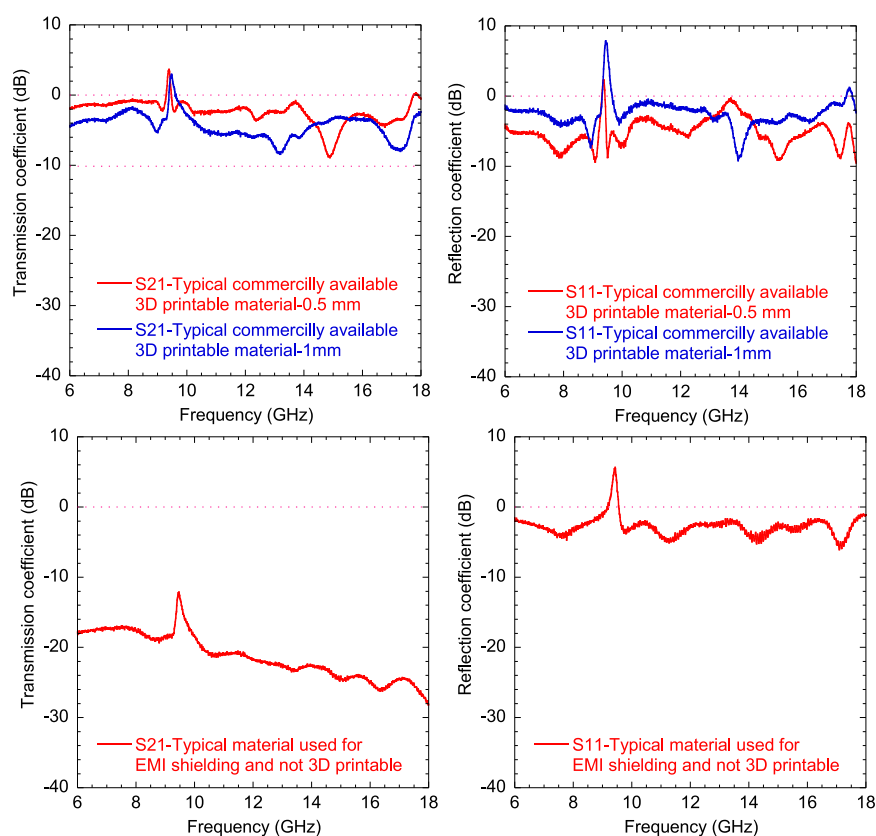


FIGURE 16

The transmission coefficient and the return loss for the 3D printed (dog-bone shaped and of the exact contour dimensions as the wave guide window) a typical example of commercially available 3D printable material and a typical material used for EMI shielding and not 3D printable.

efficient 5G networks while maintaining secure communication and protecting components, EMI shielding effectiveness in the K<sub>a</sub> band (26–40 GHz) and the millimeter-wave regime becomes crucial (Wang and Li, 2024). To meet this need, researchers worldwide are focusing on new materials that provide EMI shielding across a broad frequency range, including the K<sub>a</sub> and millimeter-wave bands. Recently, Wang et al. used polydimethylsiloxane (PDMS) as the polymer substrate and incorporated it with carbonyl iron powder and a freestanding carbon fabric to develop composites for EMI shielding in the 5G K<sub>a</sub>-Band (26–40 GHz) (Wang and Li, 2024). The carbon fabric greatly enhances the absorption of EM waves. The absorption capacity can be further improved by adding more carbonyl iron powder. The study showed that increasing SEA from 33 dB to 60 dB is possible by raising the carbonyl iron powder loading from 75 wt.% to 87 wt.%. Although the material meets performance requirements and can be fabricated from readily available materials, concerns remain about the cost of carbonyl iron powder and carbon fabric, and especially the composite's weight. Therefore, there is significant potential for developing lightweight new materials that meet EMI shielding criteria within these frequency bands. As a result, there is room for creating 3D printable polymer composites to design lightweight, complex structures.

Although predicting properties of composites with two-dimensional (2D) nanofillers is complex, it is valuable to

consider during early product development. It is also advisable to evaluate cost factors, the niche application, and potential challenges in scaling up production. Certain properties, such as tensile strength, elastic modulus, and electrical conductivity, can be estimated using the rule of mixtures as follows (FitzPatrick and Gogotsi, 2025):

$$P_c = fP_f + (1 - f)P_m \quad (18)$$

Where,  $P_c$ ,  $P_f$ ,  $P_m$ , and  $f$  represent the properties of the composite, filler, matrix, and filler concentration (in wt.%), respectively. This relationship can vary depending on the fillers' geometry and anisotropy. Therefore, the modified equation to estimate properties in the transverse directions, rather than those in the parallel alignment, simplifies to,

$$P_c = \left( \frac{f}{P_f} - \frac{(1-f)}{P_m} \right)^{-1} \quad (19)$$

Data-driven modeling approaches, such as the L9 orthogonal array technique, can be useful for identifying optimal 3D printing parameters, including nozzle temperature, layer height, printing speed, and infill density (Palaniyappan et al., 2022).

Based on the above discussion, layered architectures of nanofillers facilitate efficient dispersion and attenuate EM wave

energy, thereby enhancing overall shielding performance. However, overall performance depends on filler concentration, and when high concentrations of such fillers (approximately five to six wt.%) are needed, the composite's commercial application can be limited by cost-performance ratios and processability challenges. For design flexibility and on-demand manufacturing, FDM printability remains the more viable option for these thermoplastic-based composites. Changes in viscosity, as indicated by MFR, do not affect the filament's processability or subsequent FDM printing. Moreover, the technology is scalable using an existing commercial asset. The opportunity for further development encompasses shielding effectiveness over a broad band of frequencies and materials that provide low RCS and high IR stealth. The stealth requirements are not limited to defense and warfare but also apply to civilian applications. High-performance, electrically conductive, and 3D-printable materials are also highly desired in the medical field and are briefly discussed in the following section.

### 3 Conductive polymers for biomedical applications

Applications of functional 3D-printable polymers with electrical conductivity in the antistatic, ESD, or conductive range span the biomedical field, including device manufacturing, customized prosthetics, tissue engineering, and even anatomical modeling. The growing use of miniaturized diagnostics and neuroimaging devices opens new opportunities to develop lightweight, durable, non-toxic shielding materials that provide effective radiation protection in space- and weight-limited environments (Mirabedini et al., 2025). In this regard, the protective cover for any device must include EMI/RFI shielding to ensure reliable signal quality, and hence the need for conductive polymeric materials. Given the benefits of 3D printing, particularly FDM printing, there is an additional advantage in design flexibility. In modern times, there is a shift toward smart prosthetics with embedded electronics. Therefore, ESD-grade materials can minimize static charge accumulation, reduce EMI, and thereby improve the signal-to-noise ratio. Moreover, they can reduce particulate attraction, protect electronics from contamination, and thereby increase the product's lifespan. Optimistically, a highly electrically conductive, FDM-printable polymer can enable the printing of electrical pathways directly onto printed prosthetics. This can, in turn, enable avoiding, e.g., post-process assembly. Similarly, in tissue engineering, an antistatic or ESD-safe polymer cannot only ensure electrostatic stability during 3D printing but also enhance precision. Moreover, it can influence biological processes, such as uniform protein absorption and reduced cell clustering due to electrostatic attraction. It should be noted that biocompatible, approved materials are required for this purpose. Similar benefits are also anticipated in the analytical modeling application. The following section summarizes recent research on the relevant topics and provides a perspective on future developments.

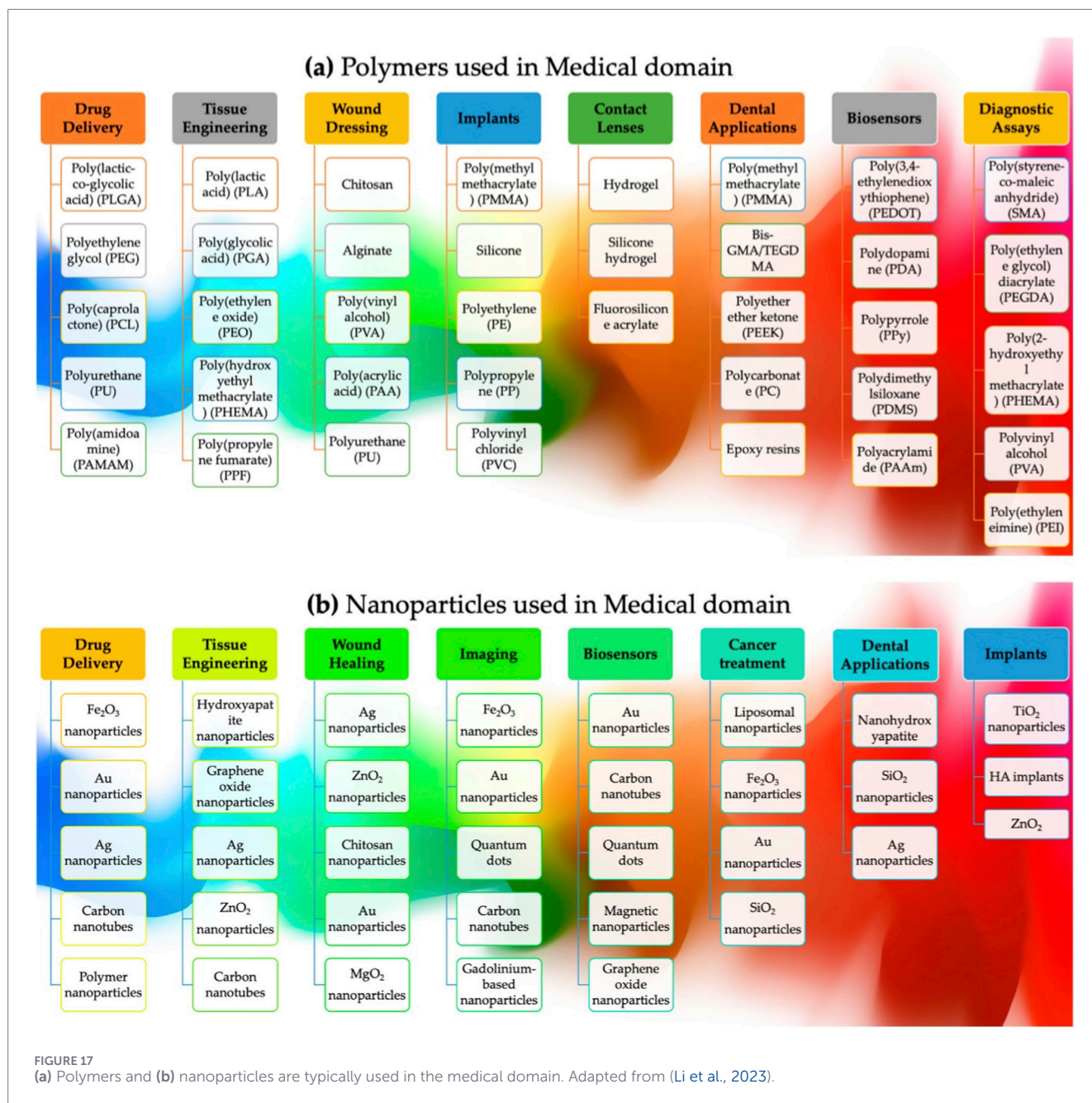
#### 3.1 Medical devices

Shielding against EMI/RFI and X-ray is very important in medical devices. Traditionally, metals such as copper, aluminium,

and lead are used for shielding because they can block EMI and X-rays. However, these materials present issues such as rigidity, toxicity, and heaviness, which hinder their suitability for portable devices. Copper, aluminium, and lead have densities around 8.96, 2.70, and 11.34 g/cm<sup>3</sup>, respectively, making them less practical for portable applications. This has driven research toward alternative conductive thermoplastics, with densities generally between 0.9 and 1.4 g/cm<sup>3</sup>, depending on the polymers and fillers used. Medical implants, including pacemakers, neurostimulators, and insulin pumps, are susceptible to EMI from devices like mobile phones and MRI machines. As evinced from the preceding section, shielding in conventional FDM printable thermoplastics relies on the type and concentration of conductive fillers incorporated into it to form conductive networks. Figure 17 provides a glimpse of polymers and nanoparticles commonly used across various medical applications via 3D printing (Li et al., 2023). The choice of polymers and nanofillers is quite broad and includes CNT and graphene oxide, among others. Therefore, to satisfy EMI/RFI shielding requirements, similar materials listed in Tables 2 and 3 can be used. In a recent study, Mirabedini et al. explored two polymers to create lightweight, non-toxic shielding materials suitable for ultraportable neuroimaging devices (Mirabedini et al., 2025). They found that Koltron (probably a graphene-containing polymer filament suited for FDM printing) provides approximately 65.5% of the lead's X-ray shielding efficiency when normalized by density, suggesting the potential to design lightweight, effective X-ray shielding materials tailored for miniaturized diagnostic devices rather than traditional metal-based options. This is an emerging area, and continued investigation and advancement in this domain are expected to yield further remarkable advances in the coming years.

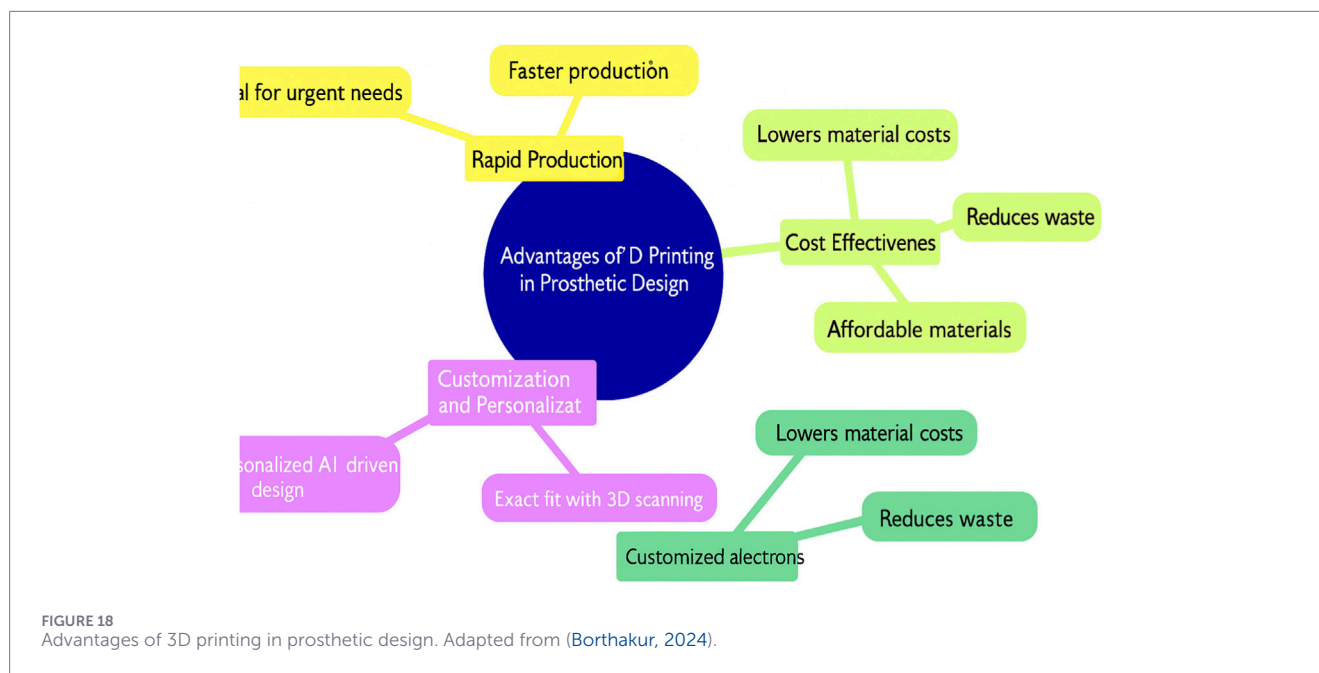
#### 3.2 Medical prosthetics

Traditional prosthetic manufacturing is often labor-intensive and time-consuming, significantly increasing production costs, extending wait times, and reducing accessibility for amputees. In contrast, 3D-printed prosthetic parts are customizable, easy to modify, cost-effective, and quick to produce. Mechanical analysis of the prosthetic fingers using Euler-Bernoulli beam theory shows a minimum finger height of 6.3 mm. The stress analysis indicates a minimum hook thickness of 0.0032 mm and a minimum pin diameter of 0.68 mm (Pisano, 2024). Figure 18 illustrates the advantages of 3D printing in prosthetics (Borthakur, 2024; Patel and Piyush, 2022). Research indicates that 3D printing can save up to 75% of time compared to traditional methods. In certain cases, it allows for same-day prosthetic delivery. In humanitarian settings, this revolutionary technology facilitates the quick provision of functional prostheses to those in need, greatly enhancing their quality of life (Pathak et al., 2023). 3D printing is expected to eliminate the need for molds and manual machining, reducing production overheads. This can increase access to prosthetics in rural healthcare facilities and low-income regions (Al-Masafah et al., 2024). Figure 19 illustrates the design and production process for creating custom 3D-printed braces for broken limbs (Patel and Piyush, 2022). The process starts with an X-ray of the injured area to evaluate the injury in detail. Next, a 3D scan captures the exact geometry of the region, followed by refining the digital model to ensure a perfect fit and



adequate support. The final design is exported as an STL file for 3D printing. Then, a brace line is generated on the digital model to identify areas needing reinforcement. This is followed by creating a brace pattern tailored to the patient's needs. After final adjustments for comfort and support, the model is sent to a 3D printer to produce a custom-fit brace. Materials such as thermoplastic elastomers, PLA, carbon fiber-reinforced polymers, and biocompatible metals, such as titanium, are commonly used in modern prosthetic manufacturing (Borthakur, 2024). Such technological advancements can revolutionize the medical field. Strength, flexibility to adapt to size changes with heat guns or warm water, and water- and sweat-resistance to reduce skin itching or irritation are important criteria for 3D-printed

prostheses. Moreover, they must allow for precise shaping and design specifications, including units, angles, and wall thickness. Recently, the focus has shifted to 3D-printed smart prosthetics, for which the material's electrical conductivity is important. In this context, Pentek et al. studied the effects of printing parameters on the electrical conductivity and mechanical properties of commercially available ESD-grade PLA and ABS containing carbon fillers for upper limb prosthetics (Pentek et al., 2020). The authors observed that ABS offers less resistance than PLA, and printing orientation can influence this. In the case of PLA, in the Z orientation, layer height did not significantly affect resistivity. In orientation X, increasing the layer height increased the resistance in the PLA composite. Much research in this



direction remains to be conducted, and there is immense scope to develop a functional, 3D-printable polymer for smart prosthetic applications.

### 3.3 Tissue engineering

Approximately 310 million major surgical procedures are performed worldwide each year (Meneses et al., 2022). Many of these procedures involve repairing or replacing damaged tissues and organs caused by disease, degeneration, or injury. Materials for tissue engineering—such as scaffolds, implants, screws, and plates—must possess electrical conductivity, biocompatibility, and mechanical properties that mimic soft tissue stiffness (for neural tissue) or are rigid (for bone). They should be processable and easy to fabricate, stable with an acceptable shelf life, surface modifiable, and capable of functionalization. Furthermore, they need to support the attachment of biomolecules or cells (Wang et al., 2017; Balint et al., 2014). To promote healing, electrically conductive polymer-based orthopedic implants can facilitate bone growth and deliver localized therapies, while ensuring biocompatibility and mechanical stability. They minimize the need for multiple surgeries compared to metallic implants. Furthermore, 3D printing enables patient-specific designs that conform to anatomical contours, resulting in a better fit and fewer complications, such as implant misalignment (Cong and Zhang, 2025). Studies have shown that polymer composite scaffolds with rGO improve neural regeneration. Examples include polycaprolactone (PCL)/rGO bioprinted scaffolds, graphene mesh tubes filled with alginate and gelatin methacrylate hydrogels, and poly(lactic-co-glycolic) acid/graphene scaffolds for neural repair (Qian et al., 2018; Banupriya et al., 2025). In another study, Sharma et al. investigated polydopamine-reduced GO-reinforced 3D-printed PLA scaffolds with distinct porosity (Sharma et al., 2022). These scaffolds showed promise for bone tissue regeneration and responded in

a multifunctional manner to stem cells. Stereolithography was used to produce GO-doped gelatin-based artificial scaffolds with specific architectures, which significantly increased collagen and glycosaminoglycan levels following GO-induced chondrogenic differentiation of human mesenchymal stem cells (Zhou et al., 2017). Graphene-majority, polylactide-co-glycolide-minority composites enhanced human mesenchymal stem cell attachment, proliferation, and neurogenic differentiation, also boosting glial and neuronal gene expression (Jakus et al., 2015). Additionally, magnetized graphene-decorated scaffolds improved biological activities and supported the *in vitro* development of bone mesenchymal stem cells (Li et al., 2022). Correia Pinto et al. studied PLA/graphene nanoplatelets (GNP) and PLA/functionalized carbon nanotubes (PLA/CNT-COOH) for anterior cruciate ligament reinforcement (Correia Pinto et al., 2017; Correia Pinto et al., 2017). Bussy et al. established guidelines for the safe use of carbon-based nanoparticles in biomedical applications, including reducing nanoparticle size (i.e., CNTs < 5–10  $\mu\text{m}$  length and 20 nm diameter, and graphene nanosheets) and ensuring good dispersion through surface hydrophilicity, such as surface functionalization for CNTs and oxidation for graphene (Bussy et al., 2013). Despite extensive research on graphene materials for tissue engineering scaffolds, their therapeutic use remains experimental and has not yet undergone human clinical trials for safety assessment (Ou et al., 2016; Jia et al., 2019). Graphene nanoparticles vary in size (1–100 nm in length and 1–10 nm in thickness) and chemical form (oxidized or reduced, with varying oxygen content), each displaying unique properties. This diversity poses occupational and environmental risks, necessitating precautions. Biodegradable polymers such as PCL and PLA are used in scaffold development. PCL is FDA-approved, biocompatible, and compatible with many polymers, making it popular in 3D printing due to its thermal stability, low melting point, and suitability for large-scale production, often combined with nanofillers. FDA-approved PLA and PLGA are

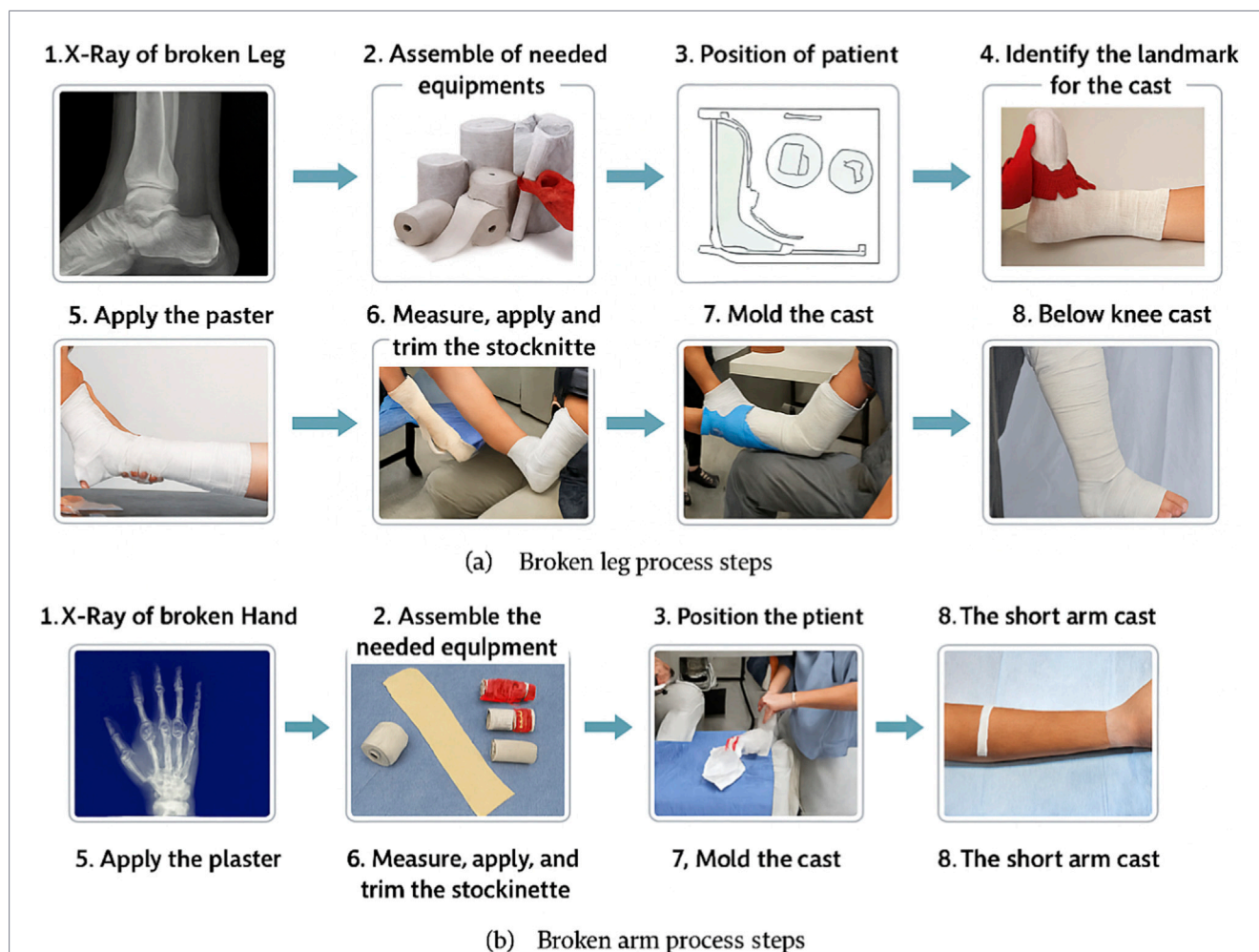


**FIGURE 19**  
The illustration shows the process of making 3D-printed prosthetics (a) for legs and (b) for arms. Adapted from (Patel and Piyush, 2022; Borthakur, 2024).

also widely used in biomedical applications. PLA degrades upon contact with biological media *via* hydrolysis, producing lactic acid, carbon dioxide, and water, which are naturally metabolized or excreted. PLA degradation can exacerbate bacterial infection and inflammation through enzymes that break down the polymer. The natural biodegradation pathways of PLA at implantation sites should inform device design (Figure 20; Da Silva et al., 2018). To avoid such infections, high-performance polymers may be preferable for many medical applications, and companies like Invivo and Evonik have developed PEEK-based materials for these applications. PEEK, PMMA, and their composites are well-suited for 3D-printed scaffolds due to their excellent biocompatibility, durability, and high strength, which resemble those of human bone (Surendran et al., 2023, Ultifit3DPRO). However, high-temperature processing in 3D printing of PEEK, along with the polymer's cost, can result in expensive products. Bi-layer 3D printing with conventional polymers and elastomers, such as TPU, enables the creation of 4D-printed structures that exhibit shape-memory effects (Rahmatabadi et al., 2022). The thermoplastic layer typically restricts the elastomeric layer. Stabilizing a temporary

shape and storing deformational stress for later recovery to the permanent shape can be achieved by reversing the phase change of the thermoplastic layer as it passes through its glass transition temperature. Rahmatabadi et al. reported fixity and recovery rates exceeding 90% for ABS-TPU, and 90% for PCL-TPU (Rahmatabadi et al., 2022).

Based on the above discussion, it is clear that significant research has been conducted on conductive polymers, particularly those containing graphene-based nanoparticles. However, graphene nanoparticles vary in size (1–100 nm in length and 1–10 nm in thickness) and chemical form (oxidized or reduced, with varying oxygen content), each displaying unique properties. This diversity poses occupational and environmental risks, necessitating precautions. Despite extensive research on graphene materials for tissue engineering scaffolds, their therapeutic use remains experimental and has not yet undergone human clinical trials for safety assessment. Another challenge lies with PLA-based materials, which can cause infection and inflammation. This necessitates further development of high-performance, polymer-based, 3D-printable materials for such applications in the near future.

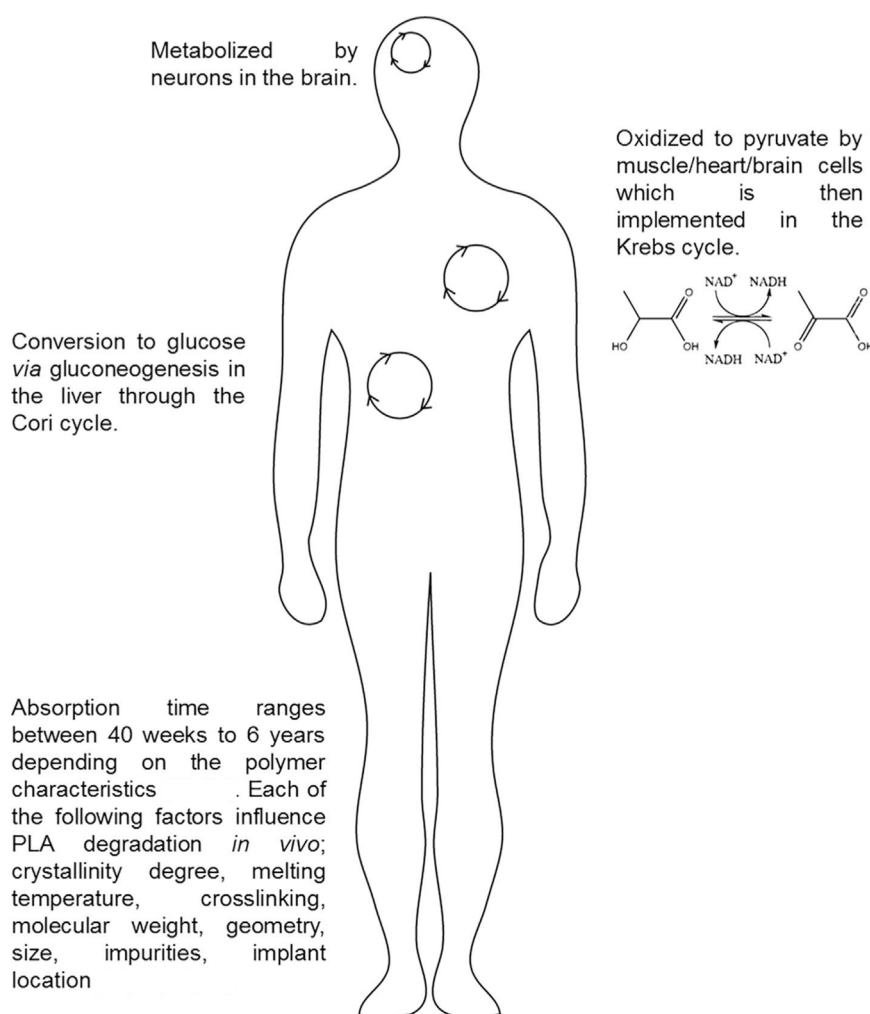


FIGURE 20  
Natural biodegrading pathways of PLA in primary sites of medical device implantation. Adapted from (Da Silva et al., 2018).

### 3.4 Anatomical models

Anatomical models, once primarily used for education, now offer unprecedented utility in medicine. An anatomical model must have anatomical accuracy, modularity, precise dimensions (including surface finish), sterility, biocompatibility, durability, and realistic tactile feedback. 3D-printed anatomical models are revolutionizing medicine by providing precise, patient-specific views of the human body. These models assist in pre-surgical planning, the design of personalized medical devices and surgical guides, enhanced patient communication by providing tangible visuals of their condition and treatment options, and support medical education and surgical training. They are also used in prototyping and various other applications (Solis et al., 2024). Integrating these models into current educational and clinical workflows poses several challenges, including the need for specialized training, the replication of complex details and biophysical features, ensuring affordability, and creating seamless software interfaces (Solis et al., 2024; He et al., 2018). Besides

tackling technical and material issues related to functionality and processability, supportive healthcare policies, regulations, and ethical standards are essential for effectively utilizing the new technology.

Figure 21 illustrates the process of creating these models, which includes image acquisition, image processing, file conversion, 3D model preparation, 3D printing, and post-processing. Similar to tissue engineering, PLA filament is ideal for fabricating anatomical models through FDM. By adjusting layer thickness and infill percentages, both rigid and flexible structures can be achieved for the models (Solis et al., 2024). Other potential polymers for such applications include thermoplastic urethane (TPU), polyglycolic acid (PGA), ABS, polypropylene (PP), polyether ether ketone (PEEK), and polyphenylene sulfide (PPS) (Kannan and Ramamoorthy, 2020; Yin and Wang, 2010; Li et al., 2023). While electrical conductivity, EMI, and RFI shielding may not be essential for non-electronic models, compliance with IEC 60601-1-2 for EMI and RF shielding is often necessary for medical devices and electronic equipment (Nick, 2025). IEC 60601-1-2 is

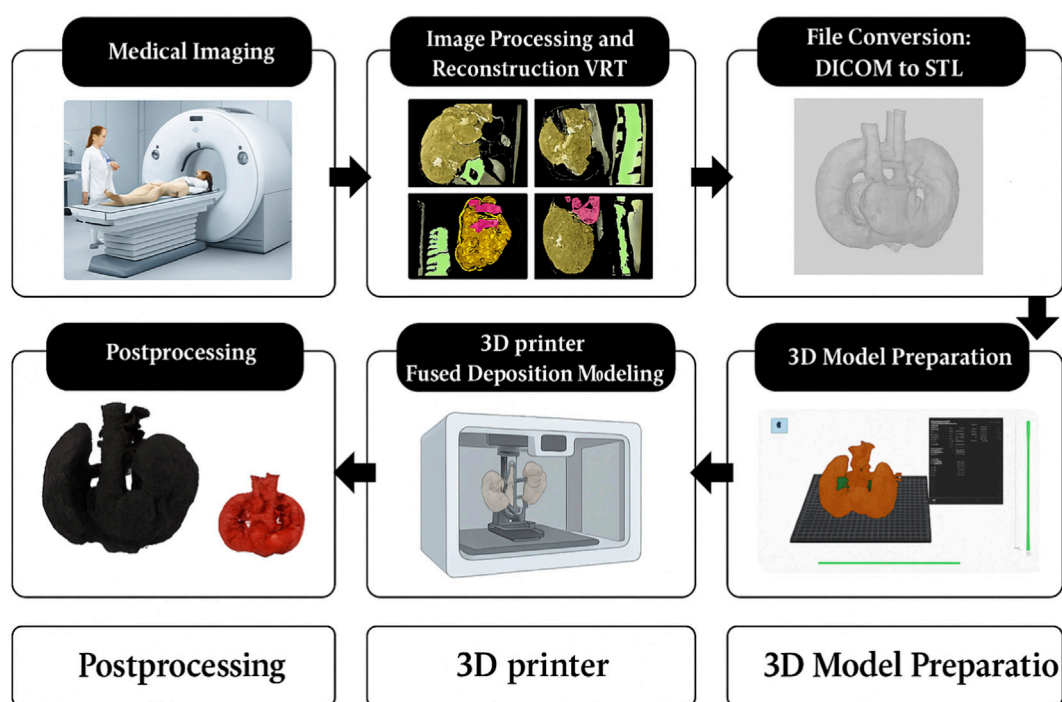


FIGURE 21

The illustration shows a process of making anatomical models. [adapted from (Solis et al., 2024)].

an International Electrotechnical Commission standard that sets requirements for electromagnetic compatibility in medical devices. It is part of the extensive 60,601 standards family. Meeting IEC 60601-1-2 compliance is essential to ensuring your device operates safely and adheres to FDA standards (CTComplianceTesting). This includes not only an anatomical model but also any necessary medical devices, which must undergo various tests to evaluate their EM wave emissions, immunity to external EM emissions, and overall electrical performance and reliability.

## 4 Conclusion

Combining 3D printing with functional materials—such as those that provide electrical conductivity, stealth, and mechanical properties—is transforming the design of advanced materials for aerospace, defense, and medical sectors. Researchers are extensively exploring polymer composites with various nanofillers, especially carbon-based ones, to achieve specific characteristics. The longevity of these materials and the balancing of performance, cost, and printability are crucial for integrating electrical conductivity and stealth into 3D printable polymers. It is very difficult to define precise limits for the electrical conductivity requirements of a polymer composite. The specific requirements for an application are usually determined by factors like desired performance, cost, and market affordability. Generally, a minimum of 10 dB shielding effectiveness—which offers about 90% EMI shielding—can be considered a baseline. Additionally, effective shielding across a broad frequency range, including the  $K_a$  and millimeter-wave regions, is desirable. The need for electrical conductivity is not limited to

defense and warfare but also applies to civilian applications. High-performance, electrically conductive, and 3D-printable materials are highly sought after across a range of applications, including medical devices, smart prosthetics, tissue engineering, and anatomical modeling. Many of these areas are emerging, and continued investigation and advancement in this domain are expected to yield further remarkable advances in the coming years. Further research is needed to ensure these products meet relevant standards before commercialization.

## 5 Future direction

The demand for functional 3D-printable polymers and their varied applications beyond current fields is fueling an active and promising research landscape. The development of new high-performance, eco-friendly polymers, along with advancements in integrated processes and innovative designs, is expected to shape the future of this sector. To meet environmental sustainability goals, durable, biodegradable materials tailored to specific applications and end-of-life considerations are needed. In tandem with progress in recycling techniques, establishing new manufacturing standards aligns with global sustainability efforts. Additionally, innovations such as IoT-enabled printing for automation and smart monitoring, independent dual extruder systems, multi-nozzle printing for increased speed and productivity, hybrid workflows combining FDM with CNC milling, laser engraving, and other post-processing methods, as well as micro- and precision FDM for producing small, detailed components with higher accuracy, are set to drive the adoption of 3D printing in large-scale manufacturing soon.

## Author contributions

JB: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft. SR: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review and editing.

## Funding

The author(s) declared that financial support was received for this work and/or its publication. Technology Innovation Agency (C6V0253) and Parliamentary funding from the Council for Scientific and Industrial Research (C1V223).

## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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