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Materials Synthesis and Characterization of Nano-Titanium Carbide-Filled Acrylonitrile Butadiene-Styrene Polymer Composites for Electromagnetic Interference Shielding

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ABSTRACT

The demand for electronic devices and miniaturization has led to the need for sustainable and cost-effective EMI shielding materials. The advent of new-age technologies in the aerospace, energy, healthcare, telecommunications, and automobile industries demands alternative material candidates that are more cost-effective and environmentally sustainable than the currently used metallic alloys. Conducting polymers is a suitable material choice for EMI shielding in this regard. This study presents a low-cost, environmentally friendly EMI shielding nanocomposites made from regrind ABS and nano-TiC at 5 wt%, 10 wt%, and 15 wt% filler loadings. The composites show a homogenous distribution of nano-TiC particles, increased crystallinity with nano-TiC loading, and improved EMI shielding effectiveness by 16.8% when the nano-TiC filler content is increased from 0 wt% to 15 wt%. These findings could contribute to the development of advanced EMI shielding materials made from recycled ABS/nano-TiC composites for various industrial applications.

1. INTRODUCTION

Electromagnetic interference (EMI) in an electrical path refers to the electromagnetic noise caused by disturbances originating from natural sources like lightning or solar flares, or when an electrical circuit or an electronic device comes into contact with an electromagnetic field [1]. EMI often occurs over a range of frequencies that can lead to diminished performance of electronic devices and circuits, causing malfunctions and occasionally resulting in the loss of stored data, thereby impairing the proper operation of electronics or causing them to malfunction or cease functioning altogether [2, 3]. EMI thus poses a significant influence on the performance and reliability of electronic devices like wireless communication devices, automotive electronics, consumer electronics, or industrial control systems [4, 5]. The effectiveness of a shielding material to prevent or protect electronic devices is expressed through its shielding effectiveness (SE) values. SE is the ratio of incident power to transmitted power, also represented as a ratio between incident electric/magnetic field intensities to transmitted electric/magnetic field intensities [6].

Permeable and electrically conducting materials like ferrous metals and alloys having high SE have been the preferable choice for shielding materials. However, EMI signals tend to get reflected on the metal surface, and moreover, metals are less flexible and more prone to corrosion and environmental degradation. With the increasing demand for electronic gadgets and miniaturization of electronic components, there is an increasing demand for the development of EMI shielding materials that are both more effective and sustainable [6, 7]. Besides consumer electronics, the utility of EMI shielding comprises a vast array of applications in the aerospace, healthcare, energy, and automobile industries including airplanes, electric vehicles, telecommunication equipment, medical devices drones, and wind turbines. These industries typically opt for EMI shielding racks, fabrics, and enclosures that are made from metals including copper, aluminum, and stainless steel [8, 9].

The advent of new-age technologies in such industries demands alternative material candidates like conducting polymers that are lightweight, cost-effective, and environmentally sustainable which can be a suitable material of choice for EMI shielding applications [10]. Polymers filled with conductive titanium carbide (TiC) nanoparticles that are lightweight, flexible, and cost-effective have been investigated for their effectiveness in shielding EMI [11]. For example, the inclusion of Ti_3C_2, which is a novel type of 2D TiC, in paraffin increases the SE value to 39.1dB, for a maximum loading of 60 wt% Ti_3C_2. The main contributory factor behind the SE of this composite is absorption. However, the material also reflects electromagnetic radiations along with absorption [12].

However, synthetic polymers pose a major environmental concern particularly in terms of their carbon footprint and disposal issues [13-16]. The reuse of disposed or recycled polymers for EMI shielding applications therefore should help promote sustainability. About 12% of the global plastic demand primarily consists of acrylonitrile-butadiene-styrene (ABS). ABS is a widely used thermoplastic polymer known for its excellent mechanical properties, good thermal stability, and low cost [17-19]. There are established methods of recycling ABS into new forms and shapes [20-22]. The low melting point of ABS facilitates its utilization as a convenient material for 3D printing and injection molding. However, the poor EMI shielding properties of ABS limit its applicability [20, 23].

Several studies have reported the use of carbon-based fillers, and metallic and metal oxide particles in ABS to improve their properties. The presence of metallic filler forms like fibers, flakes, or nanoparticles in polymer matrices will also increase the absorption of incident electromagnetic radiation. Unfortunately, these fillers have limitations such as high cost, low dispersion, and poor compatibility with the polymer matrix. Polymers like nylon, ABS, polycarbonate, and polyphenylene oxide when reinforced with stainless steel fibres exhibited an increase in SE through absorption [6, 7, 24]. However, an increase in weight due to the addition of metallic fibers and non-uniform distribution in the matrix deemed it commercially unfit for EMI shielding applications [22, 25].

Due to their distinctive physical, chemical, and mechanical properties, Graphene-reinforced polymer nanocomposite materials have been reported to have higher EMI shielding capabilities even at low concentrations. The common polymer matrices that use graphene as a filler are polyvinylidene fluoride (PVDF), thermoplastic polyurethane (PU), and Polydimethylsiloxane (PDMS). Polymer nanocomposites based on reduced graphene oxide (rGO) have better reinforcement and contribute to improvements in the electrical and thermal characteristics of the polymer. Polystyrene infused with sulfur-doped rGO demonstrated notably higher shielding effectiveness (SE) values compared to polystyrene with undoped rGO [26].

Carbon fillers also can impart high electrical conductivity to a polymer matrix, and therefore, the possibility of using carbon-based nanocomposites as EMI shielding materials has been investigated but no breakthrough has been reported thus far [27-29]. Various studies have utilized carbon nanotubes (CNTs) coated with different polymer matrices such as polyaniline (PANI), PU, PVDF, ABS, polymethyl methacrylate, polypyrrole, epoxy, and polypropylene (PP) to enhance their shielding effectiveness.

CNTs were preferred over other carbon fillers due to their cost-effectiveness, reasonable electrical conductivity, and substantial mechanical strength. Composites of high-density polyethylene (HDPE), PP, PANI, and ABS filled with carbon black/multi-walled carbon nanotubes are also found to be suitable for EMI shielding. The overall SE tends to increase with a higher concentration of carbon black. Composites based on continuous carbon fibers exhibit higher SE compared to those with discontinuous carbon fibers [27, 28].

The incorporation of carbonaceous fillers in polymer composites has increased their thermal conductivity all the while having a positive influence on the effectiveness of EMI shielding. The EMI shielding characteristics of high-thermal-conductivity polymer-based composites with hybrid fillers have been widely investigated along with their heat management abilities [7]. The thermal conductivity and shielding effectiveness values for some of the common polymer matrices are listed in Table 1.

Table 1. Thermal conductivity and SE of some polymer matrices [4, 7, 29]

Polymer Matrix	Thermal Conductivity at 25°C (W/mK)	SE in Decibels (dB)
Acrylonitrile butadiene styrene (ABS)	0.33	25
High-density polyethylene (HDPE)	0.44	27.1
Polymethyl methacrylate (PMMA)	0.21	36
Polylactic acid (PLA)	0.13	55
Epoxy (Ep)	0.19	25
Polypropylene (PP)	0.11	50-74.3
Polyvinyl acetate (PVA)	0.34	30.74
Polyvinylidene fluoride/acrylonitrile	0.19	26
Polytrimethylene terephthalate (PTT)	0.15	38
Poly 3,4-ethylene dioxythiophene (PEDOT)	0.20	58
Poly vinylidene fluoride (PVDF)	0.19	11.6
Polydimethylsiloxane (PDMS)	0.25	52-55
Polycarbonate/ethylene methyl acrylate (PC/EMA)	0.33	34
Ultrahigh-molecular-weight polyethylene (UHMWPE)	0.41	50

This work addresses a critical gap in the current literature by exploring the use of nano-titanium carbide (nano-TiC) as a filler in polymer composites for electromagnetic interference (EMI) shielding, a material combination that has not been extensively studied before. Traditional EMI shielding materials, such as metal-based shields and conventional polymer composites filled with carbon black, graphene, or carbon nanotubes, often present challenges related to weight, flexibility, and processing complexity. While these materials provide effective EMI shielding, they can be limited by their mechanical properties, cost, or ease of integration into existing manufacturing processes. TiC nanoparticles (nano-TiC) have good conductivity and are chemically inert as compared to steel and iron. It also has a high melting point, resistance to abrasion, and fire resistance. The inclusion of nano-TiC in ABS is therefore expected to improve their EMI SE.

Nano-TiC stands out due to its unique combination of electrical conductivity, thermal stability, and mechanical strength. These properties make it an excellent candidate for enhancing the EMI shielding effectiveness of polymer composites. Unlike more commonly used fillers such as carbon black, graphene, or carbon nanotubes, nano-TiC offers a distinctive balance of properties that can lead to superior performance [30, 31]. Additionally, the incorporation of nano-TiC into an Acrylonitrile Butadiene-Styrene (ABS) matrix is innovative, as it leverages the favorable processing characteristics and mechanical properties of ABS while significantly boosting its EMI shielding capabilities. This combination of materials not only enhances the shielding effectiveness but also provides a durable and lightweight solution suitable for various industrial applications, including electronics and telecommunications. The exploration of nano-TiC in this context opens up new avenues for the development of advanced materials tailored for high-performance EMI shielding [32]. The nano-TiC/ABS composites is expected to maintain or improve the mechanical properties of the ABS polymer, benefiting from the mechanical strength and thermal stability of nano-TiC. Proper dispersion of nano-TiC within the ABS matrix can create an efficient conductive network, which is critical for achieving high EMI shielding performance without compromising the material's processability and mechanical integrity.

This study presents the development of a cost-effective, environmentally-friendly nanocomposite material from recycled ABS and nano-TiC for EMI shielding applications. The synthesis, microstructural characterization, thermal stability, and EMI shielding performance of the recycled ABS/nano-TiC composites are reported. This study also evaluates the electromagnetic interference (EMI) shielding effectiveness of the developed nano-TiC/ABS composites, aiming to understand the relationship between filler content and shielding efficiency. The results of this study will have practical implications in developing advanced EMI shielding materials from recycled ABS/nano-TiC for various applications. This work not only demonstrates the feasibility of using nano-TiC in polymer composites but also opens up new possibilities for designing advanced materials with tailored properties for specific applications. By addressing the limitations of existing materials and presenting a novel approach, this study significantly contributes to the advancement of EMI shielding technologies, providing a pathway for the development of next-generation materials that combine superior performance with practical manufacturing and application potential.

2. MATERIALS AND METHODS

2.1 Preparation of ABS/nano-Tic specimens

This study uses Commercial-grade TiC nanoparticles with 99% purity and an average particle size (APS) of 100 nm at a density of 4930 kg/m^3. Regrind ABS granules are used as the base matrix, which is sourced from the Central Institute of Plastics Engineering and Technology (CIPET): Institute of Petrochemicals Technology (IPT)—Kochi. Figure 1 shows the various stages in the preparation of the ABS/nano-TiC composites.

The regrind ABS matrix is filled with 5%, 10%, and 15% of nano-TiC (by weight) to prepare three ABS/nano-TiC composite specimens that weigh 200 g each. The ABS/nano-TiC mixture is rolled at a temperature of 200ºC using a two-roll mill before being compressed at a pressure of 1,420 psi and a temperature of 180ºC in a compression moulding machine to form thin planar sheets of 3-mm thickness. These sheets are then cut to the required dimensions using water jet cutting with a nozzle pressure of 60,000 psi using a CNC Water jet cutter at Metal Craft Waterjet Cutting, Kochi, India.

The challenges in scaling up the production of these composites include maintaining the homogeneity of the nano-filler dispersion and ensuring cost-effective manufacturing processes. The compatibility of nano-titanium carbide with existing large-scale polymer processing techniques also poses a challenge that needs to be addressed.

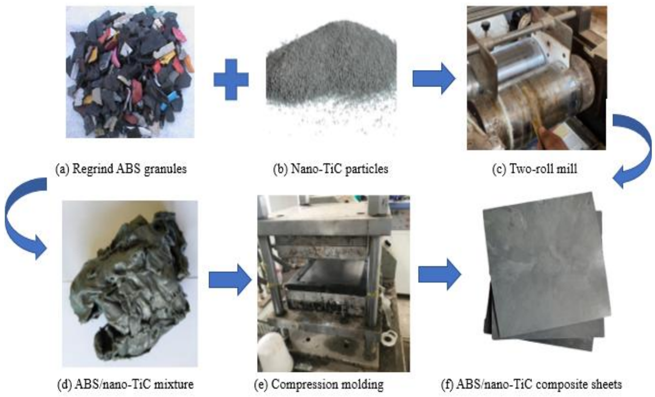


Figure 1. Preparation process flow of the ABS/nano-TiC composites

2.2 Microstructural characterization

The nano-TiC filler dispersion and surface morphology, and the crystalline phases of the ABS/nano-TiC composites are studied via scanning electron microscopy (SEM) and X-ray diffraction (XRD), respectively. The filler dispersion and surface morphologies of the composites are observed using a Scanning Electron Microscope with an energy-dispersive X-ray spectroscope (JEOL, JSW-6390 LV) at the Sophisticated test and instrumentation center, Kochi.

The magnification factor used was 2000 at a scale of 10μm with a 10 kV electron beam. XRD analysis of the specimens in powder form is performed using an X-ray diffractometer (Bruker AXS D8 Advance X-Ray powder diffractometer) system at the Sophisticated Test and Instrumentation Centre, Kochi. The fine-grain powdered samples for this analysis are prepared by hand grinding method.

2.3 Thermal decomposition

The changes in the mass of the specimens with increasing temperature are measured via thermogravimetric analysis (TGA) using a Simultaneous Thermal Analyzer (Perkin Elmer STA 6000) system at the Sophisticated Test and instrumentation center, Kochi. The temperature ranges used were from 30℃ to 400℃ at a scan rate of 10℃/min. Sample weight not less than 10 mg in powder form was used. Forced air and chiller are used to maintain the cooling rate of the furnace.

2.4 Effectiveness of shielding against electromagnetic interference

The shielding effectiveness of the planar ABS/nano-TiC composite sheets is determined using an N9917A Field Fox Handheld Microwave Analyzer, 18 GHz as per the ASTM D4935-99 test standard for a sample size of 76 × 38 × 3 mm inside an anechoic chamber at a frequency band between 2 GHz and 4 GHz. The schematic diagram of the experimental setup for the Shielded Room SE Measurement is shown in Figure 2.

The method of the shielded room is a sophisticated method that involves comparing the measurement of the different shield materials. The signal generator, recorder, transmitting and receiving antennas are placed respectively in different rooms to avoid such interferences. Furthermore, the size of the test specimen can also be increased since the antennas are placed in an anechoic chamber of increase size [6].

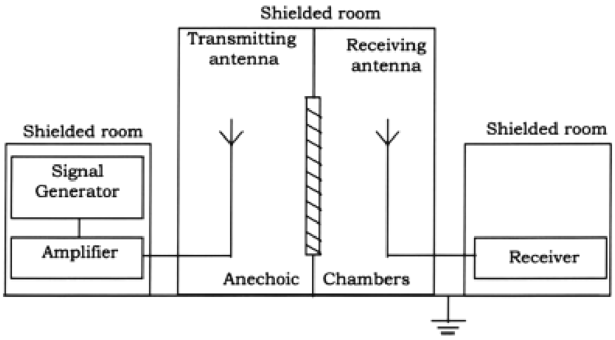


Figure 2. The schematic diagram for Shielded Room SE Measurement [6]

The electric field strength levels of the composites are measured with both reference (E_R) and load (E_L) specimens with and without the shielding material, respectively. A vector network analyzer is used to measure the reflection ($R=S_{112}$) and transmission ($T=S_{212}$) coefficients of the specimens, from which their absorption coefficients (A) are calculated as follows:

$$A=1–R–T \quad (1)$$

The total shielding effectiveness of the specimens is calculated from their reflection (SE_R) and absorption shielding effectiveness (SE_A) [27]:

$$SE_R=10 \log(1/(1-R)) \quad (2)$$

$$SE_A=10 \log((1-R)/T) \quad (3)$$

$$\text{Total shielding effectiveness}=SE_R+SE_A \quad (4)$$

3. RESULTS AND DISCUSSION

3.1 Characterization of microstructures

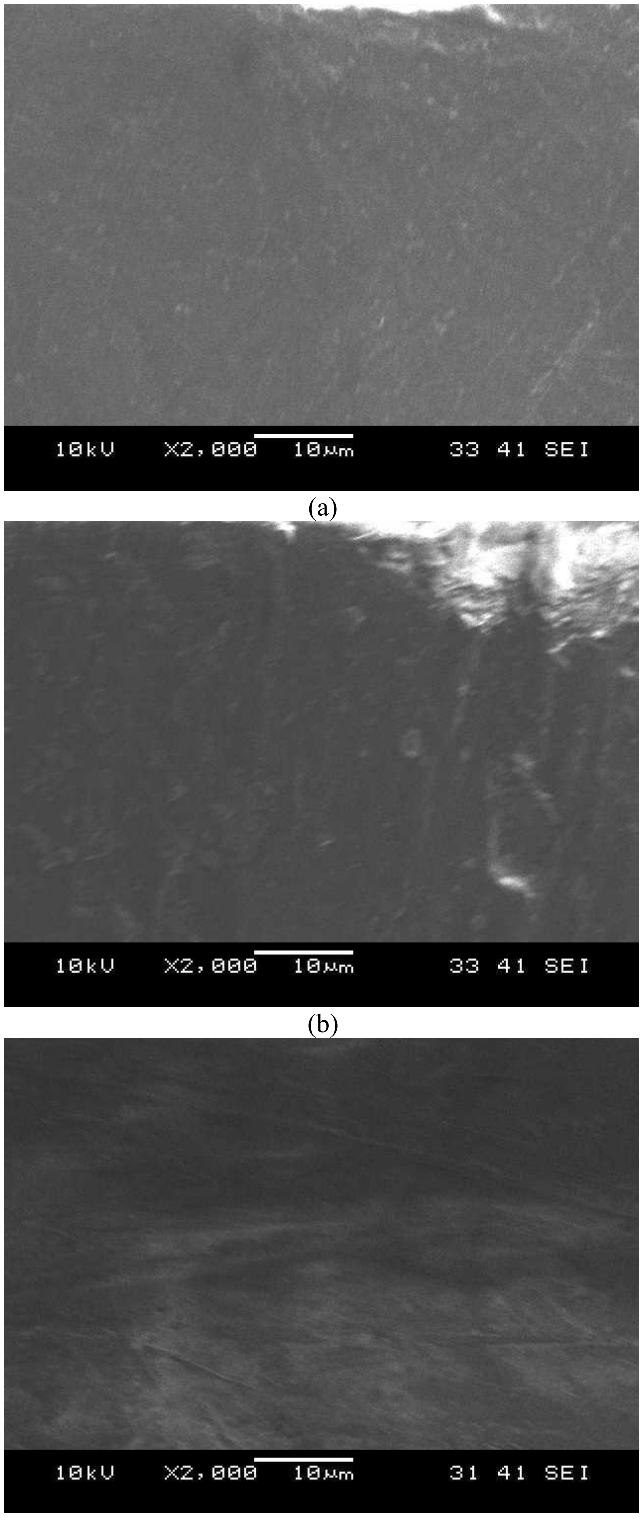
3.1.1 Surface morphology and filler dispersion

Analysis of the SEM images (shown in Figure 3) indicates that the distribution of the nano-TiC particles is mostly homogenous, and no visible agglomeration was present. The images also show that the composites are largely crystalline.

3.1.2 X-Ray diffraction

The crystalline phases of the composites are studied using their XRD patterns. The XRD results shown in Figure 4 indicate that there is an increase in crystallinity of the ABS/nano-TiC composites as the nano-TiC particles are increased from 5 wt% to 15 wt%. The initial broader peak at 20 implies either some minor defects in the crystal structure or a certain level of inhomogeneity in the mixture of ABS and nano-TiC.

Figure 4 shows the X-ray diffractogram for all the three samples. It is obvious that the samples are made of ABS polymer and trace amounts of nano Titanium carbide. The X-ray diffraction pattern reveals distinct patterns for each phase. Sticks in the pattern represent reference patterns, aligning well with the obtained input data. Though minor reference peaks appear in the background, they can be disregarded for the sake of consistency. The resulting diffraction pattern is a summation of the patterns generated by each phase in the mixture.



(c)

Figure 3. SEM images of the ABS/nano-TiC composites with (a) 5 wt%, (b) 10 wt%, and (c) 15 wt% of nano-TiC particles

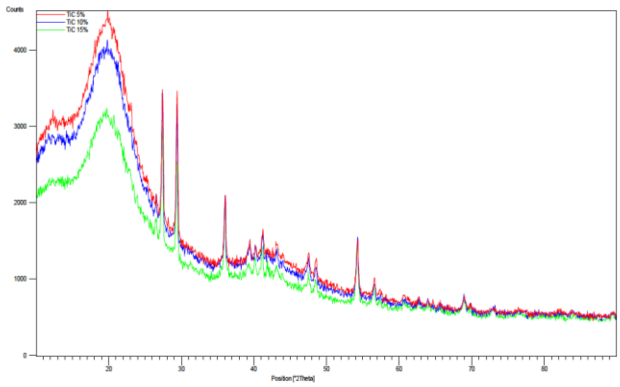


Figure 4. X-ray diffractogram for ABS/nano-TiC composites

3.2 Thermal decomposition

TGA results for all three ABS/nano-TiC composite samples are shown in Figure 5. The percentage of weight loss increases with a temperature rise. The first thermal decomposition occurred at around 50°C for all the specimens. This is followed by a second stage of decomposition from around 100°C, where any moisture content in the specimens is removed. The TGA results show that there is an increase in thermal stability as more nanoparticles are added to the ABS matrix. The addition of nano-TiC particles thus enhanced the thermal stability of resulting composites ABS. This enhancement is primarily due to the high thermal resistance of the TiC material.

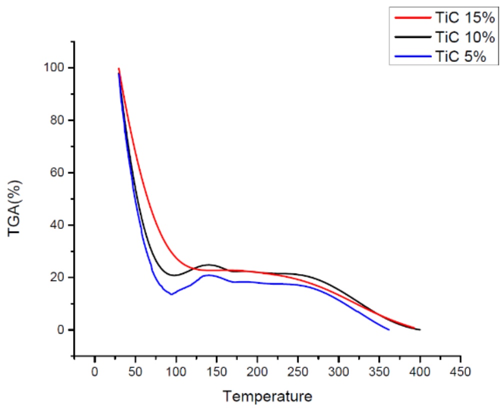


Figure 5. Thermal decomposition curves of the ABS/nano-TiC composites

3.3 EMI shielding effectiveness

The EMI SE of the composites is determined from Eqs. (1-4) stated in section 2.4 and listed in Table 2. The results indicate an improvement of 16.8% in the EMI attenuation by the composites when the filler loading is increased from 0 wt% to 15 wt%. This observation illustrates the enhancing effect of nano-TiC fillers on the shielding effect of ABS/nano-TiC composites.

Table 2. Shielding effectiveness of the ABS/nano-TiC reinforced composites

Samples	SE (dB)
Virgin ABS matrix (0 wt% of nano-TiC)	26.67 dB
Specimen 1 (5 wt% of nano-TiC)	27.85 dB
Specimen 2 (10 wt% of nano-TiC)	28.47 dB
Specimen 3 (15 wt% of nano-TiC)	31.15 dB

4. CONCLUSIONS

With the increasing demand for electronic gadgets and miniaturization of electronic components, there is a growing need to develop cost-effective and sustainable EMI shielding materials. The advent of new-age technologies in the aerospace, energy, telecommunications, healthcare, and automobile industries demands alternative material candidates that are more cost-effective and environmentally sustainable than the currently used metallic alloys. Conducting polymers is a suitable material choice for EMI shielding in this regard.

This study presents the synthesis and characterization of an environmentally friendly EMI shielding nanocomposite material made from regrind ABS and nano-TiC at various (5 wt%, 10 wt%, and 15 wt%) filler loadings. The synthesis, microstructural characterization, thermal stability, and EMI shielding performance of the recycled ABS/nano-TiC composites are reported. The distribution of the nano-TiC particles was homogenous and largely crystalline when the SEM images were analyzed. The XRD results indicate that there is an increase in crystallinity of the ABS/nano-TiC composites as the nano-TiC particles are increased from 5 wt% to 15 wt%. The TGA results also signify a moderate increase in the thermal stability of the composites as the nano-TiC filler loading is increased in ABS. The EMI shielding effectiveness improves by 16.8% when the nano-TiC loading is increased from 0 wt% (virgin) to 15 wt% (maximum filler loading). The results presented in this study shall lead to the development of advanced EMI shielding materials made from recycled ABS/nano-TiC composites for various industrial applications depending on the emission from and immunity against their respective electromagnetic energy source generation.

For future research, exploring different polymer matrices, such as polycarbonate or polypropylene, could offer insights into achieving better mechanical properties and enhanced EMI shielding effectiveness. Investigating alternative filler materials, including other nano-sized conductive fillers like graphene or carbon nanotubes, might provide further improvements in performance. Additionally, optimizing the manufacturing processes, such as using advanced techniques like 3D printing or in situ polymerization, could help in achieving better filler distribution and more efficient production. Overall, these directions could lead to the development of advanced composites with superior EMI shielding capabilities suitable for a wide range of commercial applications.

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