

Mechanisms and Practical Applications of Advanced Microwave Absorbing Nanomaterials: A Comprehensive Review

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ABSTRACT

Microwave absorbing nanomaterials (MAMs) have emerged as a critical class of functional materials designed to mitigate electromagnetic interference (EMI), enhance stealth technologies, and enable advanced biomedical and communication applications. 2008 onwards, there is a drastic change in nanomaterials which are linked with wide range of tailored dielectric and magnetic properties, optimized impedance matching, and multifunctional integration design of absorbers. This review provides a comprehensive overview of the fundamental mechanisms governing microwave absorption, including dielectric loss, magnetic resonance, interfacial polarization, and multiple scatter effects. Particular emphasis is placed on the role of nanostructuring, hybridization, and core shell architectures in enhancing absorption efficiency across broad frequency ranges. Nanomaterials such as graphene, carbon nanotubes, and carbon foams have demonstrated exceptional dielectric loss and tunable conductivity, while magnetic nanoparticles (Fe₃O₄, Co, Ni, ferrites) contribute to magnetic resonance and synergistic effects. Polymer and hybrid nanocomposites further expand the design space, offering lightweight, flexible, and scalable solutions. Fabrication techniques including sol-gel, hydrothermal synthesis, chemical vapor deposition, and melt blending have been refined to achieve reproducibility and industrial relevance. Diverse applications in consumer electronics, stealth coatings in defense, wireless communication devices, and biomedical platforms such as hyperthermia therapy and biosensing. With significant advances, the challenges remain in balancing absorption efficiency with material cost, scalability, and environmental sustainability. By systematically analyzing mechanisms, materials, fabrication strategies, and applications, this review aims to provide a roadmap for the next generation of microwave absorbing nanomaterials.

Keywords: Microwave absorbing nanomaterials, Carbon-based nanomaterials, Polymer nanocomposites, Wireless communication devices, Biomedical applications.

1. Introduction

The fast growing electronic and communication industry in the present scenario without any quality control resulted in a dramatic rise in electromagnetic pollution. These Electromagnetic interference (EMI) not only compromises the performance of electronic devices but also causes potential threats to human health and national security. To overcome these challenges, microwave absorbing materials (MAMs) have been engineered to attenuate incident electromagnetic waves, thereby reducing interference and enhancing system reliability. With the emergence of nanotechnology abrupt transforming changes this field, enabling precise control over morphology, composition, and interfacial properties to achieve superior absorption efficiency to the present traditional absorbers, such as ferrites and conductive polymers, provided limited bandwidth and heavy weight, restricting their practical use; transformed [1][2][3]. Over the past two decades, research has shifted from conventional bulk absorbers to nanostructured composites, with graphene discovered

in 2004 quickly becoming a cornerstone material due to its high electrical conductivity and tunable dielectric properties. By 2008, researchers began integrating graphene and carbon nanotubes (CNTs) into polymer matrices, achieving lightweight and flexible absorbers with broad bandwidth performance [1][4] [5], while advances in magnetic nanoparticles such as Fe_3O_4 and Co ferrites enabled synergistic dielectric magnetic coupling, enhancing absorption efficiency [2][6]. Hybrid systems combining carbon and magnetic nanomaterials have since emerged as a dominant strategy for broadband absorption [7][8][9]. Fundamentally, microwave absorption is governed by dielectric loss, arising from dipolar polarization, interfacial polarization, and conduction loss; magnetic loss, including natural resonance, exchange resonance, and eddy current effects; impedance matching, which is critical for minimizing reflection and maximizing absorption; and multiple scattering, enhanced by porous and hierarchical nanostructures. Nanostructuring allows fine tuning of these parameters, enabling absorbers with tailored performance across X-band (8–12 GHz) and Ku-band (12–18 GHz) frequencies [10][11][12]). Four major classes dominate current research: carbon-based nanomaterials such as graphene, CNTs, and foams, which are lightweight, flexible, and exhibit excellent dielectric loss; magnetic nanoparticles including Fe_3O_4 , Co, Ni, and ferrites, which provide strong magnetic resonance and synergistic effects; polymer nanocomposites, which are scalable, processable, and multifunctional; and hybrid structures, which balance dielectric magnetic responses for broadband absorption. Each class offers unique advantages and challenges, and their comparative performance is central to designing next-generation absorbers.



Image 1: Research progress in Microwave absorbing Nanomaterials.

Advances in fabrication techniques have enabled reproducible and scalable production of nanomaterials, with sol–gel and hydrothermal synthesis providing precise control over particle size and morphology, chemical vapor deposition (CVD) yielding high-quality graphene and CNTs, melt blending and in situ polymerization producing scalable polymer nanocomposites, and foaming and templating methods creating porous structures for multiple scattering [7][13]. These advances are critical for translating laboratory innovation into industrial applications. Microwave absorbing nanomaterials now have diverse applications, including EMI shielding in consumer electronics and communication devices, stealth technology in aerospace and defense coatings, wireless communication through integration into antennas and circuit boards, and biomedical platforms such as hyperthermia therapy and biosensing [10][14]. The multifunctionality of nanomaterials allows integration into lightweight, flexible, and environmentally sustainable systems. Despite significant advances, challenges remain in scalability and cost, particularly in large-scale production of high-quality nanomaterials; environmental sustainability, requiring eco-friendly synthesis routes; and multifunctional integration, combining absorption with mechanical, thermal, and optical properties. Drastic generational change the future research will focus on multifunctional absorbers that integrate EMI shielding with thermal management, mechanical robustness, and optical transparency. This review therefore systematically addresses advances in carbon-based nanomaterials, progress in magnetic nanoparticles and ferrites, development of polymer nanocomposites and hybrid systems, emerging fabrication techniques for scalable production, and applications in EMI shielding, stealth, communication, and biomedicine. This review bridges fundamental science and engineering practice, offering a roadmap for next-generation microwave absorbing nanomaterials.

2. The Mechanism of Shielding and EM Absorption

Microwave absorption in nanomaterials is governed by a combination of dielectric loss, magnetic loss, impedance matching, and multiple scattering, each of which contributes to the attenuation of electromagnetic waves in distinct ways. **Dielectric loss** arises from dipolar polarization, interfacial polarization, and conduction loss, mechanisms that are particularly pronounced in carbon-based nanomaterials such as graphene and carbon nanotubes (CNTs), where high conductivity and large surface area promote electron hopping and charge accumulation at heterogeneous interfaces [1][3][4].

Table 1: Mechanisms vs. Material types

Mechanism	Key Materials	Dominant Effect	Frequency Range (GHz)	Ref.
Dielectric Loss	Graphene, CNTs, carbon foams	Dipolar & interfacial polarization, conduction	2–18 (broadband)	Liu et al., 2008; Sun et al., 2010
Magnetic Loss	Fe ₃ O ₄ , Co, Ni, ferrites	Natural resonance, eddy current loss	2–12 (X-band)	Wang et al., 2012; Zhang et al., 2015
Impedance Matching	Graphene–ferrite hybrids	Balanced dielectric & magnetic response	8–18 (X/Ku-band)	Chen et al., 2018
Multiple Scattering	Carbon foams, hollow spheres	Extended path length, multi-reflection	8–18 (X/Ku-band)	Li et al., 2021

Magnetic loss is dominated by natural resonance, exchange resonance, and eddy current effects, with ferrites (Fe₃O₄, CoFe₂O₄, NiFe₂O₄) and metallic nanoparticles (Ni, Co, Fe) exhibiting strong magnetic responses in the GHz range [2][6][11]. **Impedance matching** is critical for minimizing reflection and maximizing absorption, and hybrid systems that combine dielectric and magnetic components—such as graphene–ferrite composites—achieve balanced electromagnetic responses across wide bandwidths [7][9]. Finally, **multiple scattering** is enhanced in porous and hierarchical nanostructures, such as carbon foams and aerogels, which extend the path length of microwaves and increase the probability of attenuation [10][12]. Nanostructuring thus enables fine-tuning of these mechanisms, allowing absorbers to achieve tailored performance across X-band (8–12 GHz) and Ku-band (12–18 GHz) frequencies.

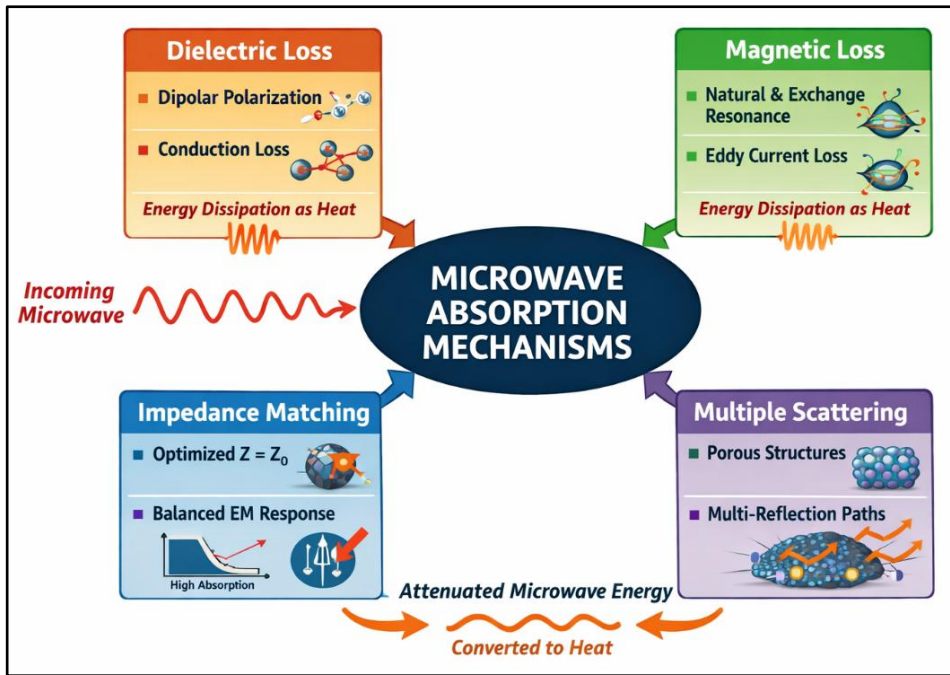


Image 2: microwave absorption mechanisms

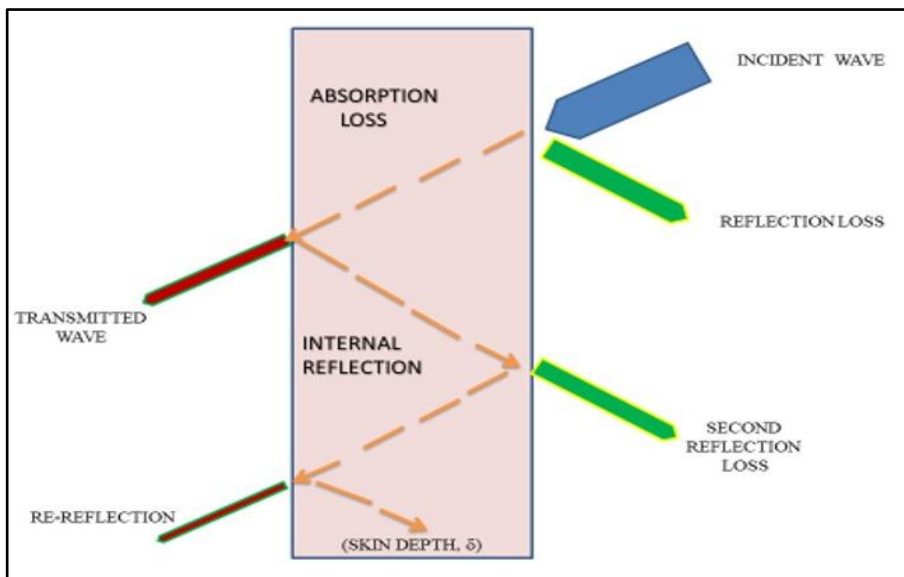


Image 3: Propagation of an electromagnetic wave through a material sheet.

The process of minimizing the insertion of electromagnetic (EM) waves into a required space is called EM shielding. Reflection, absorption, and transmission are experienced by an incident wave when an EM wave scintillates an EM interference (EMI) shielding substance, as depicted in **image 3**.

Heat is produced due to energy dissipation when EM radiations interact with material. As a result, the energy of incident EM waves is converted into heat or other modes of energy [15]. Therefore, Total EM shielding effectiveness (SE_T) is the addition of three distinct procedures mechanisms such as absorption (SE_A), reflection (SE_R), and multiple internal reflection (SE_M) [16] as illustrated in equation (2.1).

$$SE_T = SE_R + SE_A + SE_M \quad (2.1)$$

The penetration depth of EM waves can be approximated by the skin depth when they travel through an absorptive material. It is the depth inward the absorptive substance where the amplitude of the EM wave is reduced to $1/e$ (37%) of its propagating value. This depth can be represented in this way (equation 2.2):

$$\delta = \frac{1}{\sqrt{\pi f \mu_o \mu_r \sigma}} \quad (2.2)$$

Where,

δ denotes skin depth,

μ_o stands for permeability of vacuum (4×10^{-7} H/m),

σ represents the conductivity of the absorber,

μ_r denotes the relative complex permeability and,

f is the frequency of electromagnetic waves.

To gain maximum absorption of EM waves, the following two conditions must be fulfilled;

The material absorbing the EM waves must have specialty impedance, approximately or exactly equal to that of a vacuum (377Ω), and

There needs to be a rapid reduction in EM wave amplitude within the material [17][18].

The basic requirement to fulfil these conditions is that the material must have strong dielectric and magnetic loss capability because EM waves are composed of time-changing magnetic and electric field components [19]. The excellent compatibility between magnetic loss ($\tan \delta\mu$) and dielectric loss ($\tan \delta\varepsilon$), and fulfillment of impedance (Z) value approximately or exactly equal to one [20] is indicated by the improved MA (completed by exquisite impedance matching). On the other hand, impedance mismatches lead to greater reflection of the EM wave or large transmission with small or zero disappearance; consequently, the obtained value of absorption will be low. MAP of a porous material can be influenced mainly by the characteristics like relative complex permittivity (ε_r) and permeability (μ_r) (Equation 2.3- 2.5) [18].

$$\varepsilon = \varepsilon' - \varepsilon'' \quad (2.3)$$

$$\varepsilon = \varepsilon' - \varepsilon'' \quad (2.4)$$

$$\mu_r = \mu' - j\mu'' \quad (2.5)$$

Imaginary components (ε'' and μ'') belong to dielectric and magnetic energy dissipation, whereas real components of the complex permittivity and permeability (ε_r and μ_r) indicate the electric and magnetic storage capability, respectively. The reduction in the value of energy can be approximated by the magnetic and dielectric loss tangents ($\tan \delta\mu$ and $\tan \delta\varepsilon$) given by equations 2.6 and 2.7 [21].

$$\tan \delta_{\epsilon} = \frac{\epsilon''}{\epsilon'} \quad (2.6)$$

$$\tan \delta_{\mu} = \frac{\mu''}{\mu'} \quad (2.7)$$

When an EM wave propagates through a material and brings about the polarization of bound/free charges, it leads to dielectric loss. These motions are opposed by intrinsic forces inward of the material, like inertia, frictional forces, and elasticity, which result in the disappearance of energy [22]. Therefore, conductivity and polarization loss [23] are the main factors that result in dielectric loss. In the free electron theory, conduction loss is generally the main dielectric loss mechanism [24] because a rise in conductivity (σ) promotes the imaginary components of the complex permittivity. While ionic, interfacial, electronic, and dipole polarization are the factors that result in polarization loss [21].

When dipoles cannot act in respond rapidly to a large frequency alternating electric field, then dipoles' orientation polarization takes place, and it results in diminishing the values of ϵ' and ϵ'' , generating typical frequency spreading behaviours [25]. Despite the magnetic loss generally arising from relaxation methods in the course of magnetization, namely hysteresis, natural resonance, exchange resonance, and eddy current. The coefficient of EM absorption, which is denoted by reflection loss (RL) for a sole layer absorptive material, is determined by the following equations established on the transmission line theory (equations 2.8- 2.10) [26].

$$RL(dB) = 20 \log_{10}[\Gamma_{\neq}] \quad (2.8)$$

$$\Gamma_{\neq} = \frac{Z_{in} - Z_o}{Z_{in} + Z_o} \quad (2.9)$$

$$Z_{in} = Z_o \sqrt{\frac{\epsilon_r}{\mu_r}} \tan h \left[j \frac{2\pi f d}{c} \sqrt{\epsilon_r \mu_r} \right] \quad (2.10)$$

In the above equation (2.8-2.10): -

Z_{in} is the input impedance value for the absorber.

Z_o is the impedance value for free space,

ϵ_r denotes complex permittivity,

μ_r represents complex permeability,

c denotes the velocity of EM wave propagation in vacuum,

f represents the frequency of the microwave,

d denotes the width of the absorber,

and Γ stands for the coefficient of reflection, serially.

The extent of reflection of EM waves by impedance interruption at the absorber interface is expressed by the reflection coefficient (Γ). ϵ_r and μ_r have nearby values, and they are compatible with decreasing reflectivity and promoting the absorption of the EM wave [27]. Accordingly, productive compatibility between dielectric/magnetic loss and the impedance characteristic should be achieved [16]. Therefore, the coefficient of reduction in the amplitude EM wave, which depicts the ability of the absorbent material to readily attenuate and dissipate EM wave through its implicit magnetic and dielectric loss power, which can be determined with the help of the attenuation constant [15].

$$\alpha = \frac{\sqrt{2\pi f}}{c} \times \sqrt{(\mu''\varepsilon'' - \mu'\varepsilon') + \sqrt{(\mu''\varepsilon'' - \mu'\varepsilon')^2 + (\mu'\varepsilon' - \mu''\varepsilon'')^2}} \quad (2.11)$$

In the above equation (equation 2.11): -

f denotes the frequency and

c denotes the velocity of EM (in vacuum) serially.

From this equation, it can be inferred that the magnetic and dielectric losses are the main dominating attenuation mechanisms for MA.

Usually, there are two means to improve the coefficient of absorption of materials:

By modifying their nanostructures to increase the absorptive materials' attenuation ability.

Via optimizing the material's EM parameters (permittivity and permeability) to achieve impedance matching and enhance EM absorption [16].

A good microwave absorber needs to meet two requirements: well impedance matching and strong electromagnetic attenuation [28]. Moreover, it can produce magnetic loss for a microwave absorber. Generally, the excellent microwave absorption performance is primarily due to the efficient complementarity of complex permittivity and permeability. So single magnetic loss or dielectric loss in absorbers could only produce a weak impedance matching. Yan et al. fabricated two kinds of ZnFe₂O₄ nanomaterials and found that the ZnFe₂O₄ hollow nanospheres exhibited much better microwave absorption performance than that of ZnFe₂O₄ nanosheets [29]. Li et al. fabricated the ZnFe₂O₄/poly-pyrrole core-shell NPs, which exhibited enhanced microwave absorption compared to pure ZnFe₂O₄ NPs, and the RL_{min} reached -28.9 dB [30]. The EM-wave absorption capability of ultrathin Fe₃O₄/CNT sandwich bucky paper was studied by Lu et al. [31]. Their results indicated that the reflection loss (RL) of ultrathin Fe₃O₄/CNT reached -12.62 dB at 17.72 GHz with an absorption thickness of 0.1 mm. Lan et al. prepared Fe₃O₄/MWCNTs hybrids; the strongest reflection loss values reached -60.7 dB at 11 GHz by optimizing the absorber thickness [32].

3. Applications of Microwave Absorbing Nanomaterials

Microwave absorbing nanomaterials have found diverse applications across multiple domains owing to their tunable dielectric and magnetic properties, lightweight nature, and multifunctionality. Their integration into modern technologies reflects both fundamental advances in material science and pressing societal needs for electromagnetic compatibility, stealth, and biomedical innovation.

3.1 Electromagnetic Interference (EMI) Shielding

Electromagnetic interference poses a critical challenge in consumer electronics, communication systems, and industrial devices. Nanocomposites incorporating graphene, carbon nanotubes (CNTs), and ferrites have emerged as leading candidates for EMI shielding due to their high electrical conductivity, strong interfacial polarization, and ability to dissipate electromagnetic energy. Graphene polymer composites, for instance, achieve shielding effectiveness values exceeding 30–40 dB, sufficient to block most interference in portable electronics [5][7]. CNT-based foams and aerogels further enhance shielding by combining conductive networks with lightweight, porous structures that promote multiple scattering. Ferrite-based polymer composites add magnetic loss pathways, enabling balanced dielectric–magnetic absorption and improved impedance matching.

3.2 Stealth Technology

Defense and aerospace applications demand materials capable of reducing radar cross-section signatures across wide frequency ranges. Ferrite nanoparticles and hybrid carbon magnetic systems are widely employed in stealth coatings, where their broadband absorption across X-band (8–12 GHz) and Ku-band (12–18 GHz) frequencies is particularly valuable. Fe_3O_4 and $CoFe_2O_4$ nanoparticles exhibit strong natural resonance and eddy current losses, while graphene ferrite hybrids combine dielectric and magnetic mechanisms to achieve reflection loss values below -40 dB (Wang et al., 2012; Zhang et al., 2015). Such coatings are lightweight, conformal, and adaptable to complex aerospace geometries, making them indispensable in modern stealth technology.

3.3 Wireless Communication Devices

The proliferation of wireless communication devices requires materials that minimize interference while maintaining flexibility and durability. Polymer nanocomposites embedded with conductive fillers such as CNTs, graphene, or metallic nanoparticles are increasingly integrated into antennas, circuit boards, and casings. These composites provide broadband absorption, reduce signal distortion, and enhance device reliability. Flexible CNT/polyurethane foams, for example, achieve broadband absorption across 8–18 GHz, making them suitable for foldable and wearable electronics [8][9]. Their lightweight and scalable fabrication further support widespread adoption in consumer and industrial communication systems.

3.4 Biomedical Applications

Beyond electronics and defense, microwave absorbing nanomaterials are being explored in biomedical platforms. Ferrite nanoparticles, due to their magnetic and dielectric properties, can generate localized heating under microwave irradiation, offering potential in hyperthermia therapy for cancer treatment. By carefully tuning particle size and surface chemistry, researchers achieve controlled heating profiles that selectively target tumor tissues while minimizing damage to surrounding healthy cells [10]. Additionally, carbon-based nanomaterials are being investigated for biosensing and diagnostic imaging, where their high surface area and conductivity enable sensitive detection of biomolecules. Hybrid systems combining ferrites and graphene further expand biomedical applications by integrating therapeutic and diagnostic functionalities [14].

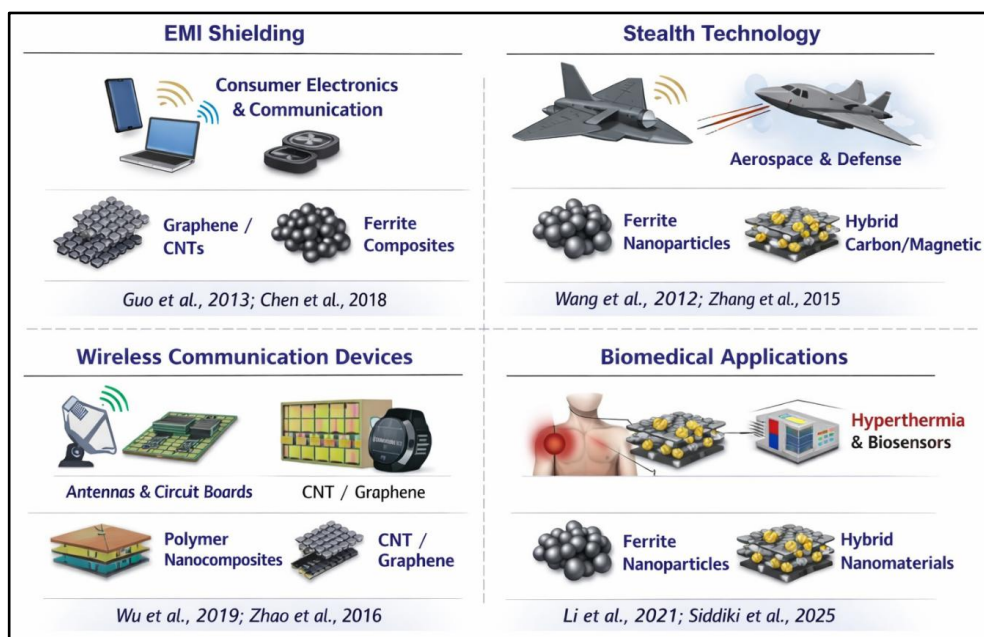


Image 4: Applications of microwave absorbing nanomaterials

4. Challenges and Future Perspectives

Despite the rapid advancement of microwave absorbing nanomaterials and their integration into diverse applications, several critical challenges remain that hinder their widespread industrial adoption and multifunctional deployment. These challenges span scalability, cost, environmental sustainability, and the need for multifunctional integration, each of which demands targeted research and innovation.

4.1 Scalability and Cost-Effectiveness

One of the foremost barriers to commercialization is the scalable production of high quality nanomaterials. Techniques such as chemical vapor deposition (CVD) for graphene and arc-discharge or laser ablation for CNTs yield excellent material properties but are often cost prohibitive and difficult to scale [13]. Similarly, the synthesis of magnetic nanoparticles with controlled morphology and crystallinity requires precise conditions and expensive precursors. To address this, researchers are exploring low cost alternatives such as biomass derived carbon materials, solution-based ferrite synthesis, and hybridization strategies that reduce the reliance on high-purity nanomaterials while maintaining performance [12].

4.2 Environmental Sustainability

Traditional fabrication methods often involve toxic solvents, high energy input, and non-renewable feedstocks. This raises concerns about the environmental footprint of microwave absorbing materials, especially when deployed at scale. Green synthesis approaches such as hydrothermal processing using water-based solvents, plant-derived carbon sources, and low-temperature annealing are gaining traction as sustainable alternatives [7]. Moreover, lifecycle assessments and recyclability studies are essential to ensure that these materials do not contribute to long-term environmental degradation.

4.3 Integration with Multifunctional Materials

Modern applications increasingly demand materials that serve multiple roles beyond microwave absorption. For instance, aerospace coatings must combine stealth with thermal insulation and mechanical durability, while biomedical platforms require biocompatibility, targeted delivery, and diagnostic functionality. Achieving such multifunctionality necessitates the design of hierarchical architectures and hybrid systems that integrate dielectric, magnetic, mechanical, and optical properties [10]. Recent studies have demonstrated graphene ferrite polymer hybrids that offer EMI shielding, thermal conductivity, and mechanical flexibility, pointing toward a new generation of multifunctional absorbers [14].

5. Conclusion

Growing challenges of electromagnetic pollution, device reliability, and stealth technology the microwave absorbing nanomaterials have emerged as one of the most promising classes of advanced functional materials. To overcome these challenges, past two decades, this field has evolved from conventional ferrite and polymer absorbers to highly engineered nanostructures that leverage dielectric and magnetic losses, impedance matching, and multiple scattering to achieve broadband absorption across critical frequency ranges. Carbon-based nanomaterials such as graphene and CNTs have provided lightweight, flexible, and highly conductive platforms, while magnetic nanoparticles and ferrites have introduced strong resonance effects. The composite systems, integrating both dielectric and magnetic components, now represent the state of the art, balancing performance with multifunctionality. The versatility and societal relevance of these materials span the applications consumer electronics, aerospace defense, wireless communication, and biomedicine, demonstrating their significance. After this development, challenges remains faced for production, reducing costs, and ensuring environmental sustainability. The future of microwave absorbing nanomaterials lies in multifunctional integration absorbers that not only shield against EMI but also provide mechanical robustness, thermal management, and biocompatibility. Smart emerging directions such as adaptive absorbers, additive manufacturing, and artificial machine

learning guided material design promise to accelerate innovation and bridge the gap between laboratory research and industrial deployment. In summary, microwave absorbing nanomaterials represent a rapidly advancing frontier that bridges fundamental science with practical engineering. Their continued development will not only mitigate electromagnetic pollution but also enable transformative technologies in defense, communication, and healthcare. By shaping a cleaner and safer environment next generation absorbers will play a pivotal role in addressing scalability, sustainability, and multifunctionality.

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