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Exploring the Potential of Carbon-based Radar Absorbing Material Innovations

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Abstract—This review explored the potential of carbon-based radar absorbing materials (RAM), which had gained significant attention due to their superior properties and performance. In response to the growing demand for stealth technology in the military and civilian sectors, traditional radar absorbing materials encountered limitations: weight, cost, and effectiveness. Carbon-based materials, such as carbon nanotubes, graphene, and various composites, offered lightweight, flexible, and tunable solutions that enhanced electromagnetic wave absorption across a wide frequency range. This paper examined the underlying mechanisms of radar wave absorption in carbon-based materials, highlighting their advantages over conventional options. In addition, recent advancements in fabrication techniques, including 3D printing and hybrid composite development, were also discussed, emphasizing their role in optimizing performance and sustainability. By synthesizing current research findings, this review aimed to provide a comprehensive understanding of the carbon-based RAM potential in advancing the future of stealth technology. Ultimately, this study presented insights that contribute to the continuing investigation in advanced materials science, suggesting a potential way to develop materials that can enhance radar absorption capabilities and extend their applications in modern technology.

Keywords— *Carbon Materials; Electromagnetic absorption; Material efficiency; Nanocomposites; Radar absorption.*

1. INTRODUCTION

Radar absorbing materials (RAM) are essential in modern technological applications, particularly in the defense and aerospace sectors, where minimizing radar signatures is critical. The demand for effective radar absorbing materials has significantly surged as military and civilian applications prioritize stealth and covert operations. Among several candidates, carbon-based materials have emerged as promising options due to their exceptional properties, including lightweight characteristics, high mechanical strength, flexibility, and tunable electrical conductivity. Materials such as carbon nanotubes (CNTs), graphene, and carbon composites exhibit superior radar absorption performance and offer the advantage of multifunctionality, making them suitable for a diverse array of applications [1].

The fundamental principle behind radar absorption is based on the material's ability to attenuate electromagnetic waves, thereby reducing the reflection of radar signals back to the source. Common materials used for this purpose include ferrites and polymers. However, these materials often have limitations in weight, cost, and performance across different frequencies [2]. Carbon-based innovations help address many of the previously mentioned challenges by providing enhanced electromagnetic interference (EMI) shielding, mechanical resilience, and thermal stability. These characteristics are essential for effective radar absorption across different operational environments [3]. Moreover, the versatility of carbon nanomaterials enables their integration into various composite structures, offering opportunities for tailored solutions that meet specific radar absorption requirements. Recent advancements in nanotechnology and material science have led to significant breakthroughs in the synthesis and application of carbon-based RAM [4]. For instance, the development of 3D-printed structures and hybrid composites has opened new avenues for optimizing radar absorption properties while maintaining structural integrity. Additionally, the incorporation of dopants and functionalization techniques enables the fine-tuning of electrical and

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dielectric properties, further enhancing the efficiency of these materials [5],[6]. Ongoing research in this field aims to improve the performance metrics of carbon-based RAM and explores sustainable manufacturing processes, making them more environmentally friendly and cost-effective [7].

This review explores the efficiency of carbon-based radar absorbing materials by analyzing their absorption mechanisms, comparing their advantages over conventional materials, and examining the latest advancements in fabrication techniques. We delve into the mechanisms of radar wave absorption, including impedance matching, dielectric loss, and magnetic loss to provide a comprehensive understanding of how these materials function in various frequency ranges. Furthermore, we discuss the implications of these innovations for stealth technology and their potential applications in different industries, such as automotive, telecommunications, and electronics. Through a thorough examination of current research, this paper seeks to highlight the transformative potential of carbon-based radar absorbing materials in shaping the future of stealth technology.

2. MECHANISMS OF RADAR ABSORPTION

The effectiveness of radar absorbing materials (RAM) hinges on several mechanisms that dictate how these materials interact with electromagnetic waves. Understanding these mechanisms is crucial for optimizing radar absorption performance, particularly in carbon-based innovations.

2.1. Dielectric Loss

Dielectric loss is a key mechanism in radar absorption, where electromagnetic energy is converted into heat within the material [8]. This process occurs due to the polarization of the material in response to the applied electric field. In carbon-based materials, such as graphene and carbon nanotubes, the unique electronic structure and high surface area contribute significantly to dielectric loss (**Table 1**) [9]. The dielectric constant of a material determines how well it can store and dissipate electrical energy. For effective radar absorption, materials with high dielectric constants are preferred, as they can enhance the interaction with radar waves [5]. The polarization mechanism can be divided into several types, including electronic, ionic, and dipolar polarization [10]. Electronic polarization occurs when the electron cloud of an atom distorts in response to an electric field, while ionic polarization involves the displacement of ions within a lattice [8]. Dipolar polarization, common in polar materials, occurs when molecular dipoles align with the electric field [11]. Carbon-based materials can exhibit complex polarization behavior due to their unique structures and hybridization states. For example, in graphene, the delocalized π-electrons can significantly enhance electronic polarization, leading to improved dielectric loss [12].

The loss tangent, a measure of the efficiency of energy dissipation, is crucial in evaluating radar absorption. A low-loss tangent indicates that the material stores energy effectively, while a high-loss tangent suggests that energy is dissipated as heat. Researchers have discovered that optimizing the ratio of the real and imaginary parts of the dielectric constant can enhance radar absorption efficiency [13]. By adjusting the composition and structural parameters of carbon-based materials, such as the ratio of carbon to polymer in composites, the loss tangent can be tailored for optimal performance [14].

Table 1. Dielectric Constant (Dielectric Loss) Comparison for Any Type of RAM

RAM Type	Dielectric Constant	Reference
$BaTiO_3/NiFe_2O_4$-rGO	0.25	[15]
Ni/Graphene/Epoxy	3.60	[16]
rGO/Fe	4.00	[17]
Fe_3O_4-rGO	4.20-5.50	[18]
Co-CeO_2/rGO	1.74-2.45	[19]
Carbon fiber-Epoxy	25.00	[20]
Fe/rGO	17.40-17.80	[3]
rGO/CeO_2	10.40-19.10	[21]
rGO/Epoxy	3.94	[22]

2.2. Magnetic Loss

Magnetic loss mechanisms play a significant role in radar absorption [23]. Magnetic materials absorb radar waves through hysteresis loss, eddy current loss, and magnetic resonance [5]. In carbon-based RAM, magnetic loss is often introduced by incorporating ferromagnetic or ferrimagnetic materials into a carbon matrix (**Table 2**) [24]. For instance, carbon-based composites that include materials like iron or nickel can leverage magnetic loss mechanisms alongside dielectric loss. Hysteresis loss occurs due to the lag between the magnetization of a material and the applied magnetic field [24]. As the frequency of the radar wave increases, the material may not respond quickly enough to the changing field, resulting in energy loss [15]. This effect is particularly pronounced in materials with high magnetic permeability, which can enhance energy absorption at specific frequency ranges [25].

Table 2. Magnetic Constant (Magnetic Loss) Comparison for Any Type of RAM

RAM Type	Magnetic Constant	Reference
$BaTiO_3/NiFe_2O_4$-rGO	0.90-1.24	[15]
Ni/Graphene/Epoxy	1.36-1.06	[16]
rGO/Fe	0.10	[17]
Fe_3O_4-rGO	0.97-1.02	[18]
Co-CeO_2/rGO	0.99-1.29	[19]
Fe/rGO	0.04-1.00	[3]

Eddy current loss is another magnetic loss mechanism that arises from the induction of currents within conductive materials when exposed to a changing magnetic field. In composite structures, the conductive nature of carbon materials can lead to significant eddy current losses, enhancing the overall radar absorption capability [26]. Researchers have explored the combination of carbon nanomaterials with magnetic nanoparticles to create hybrid composites that optimize dielectric and magnetic loss mechanisms, resulting in improved radar absorption performance [25].

2.3. Impedance Matching

Impedance matching is a critical factor influencing radar absorption efficiency. The impedance of a material determines how much of the incoming radar energy is reflected versus absorbed [27]. Mismatched impedance can lead to significant reflections [19]. Carbon-based materials offer a unique advantage in this aspect, as their electrical properties can be finely tuned. By adjusting the composition, thickness, and structure of carbon-based RAM, researchers can manipulate the impedance to achieve a closer match with the desired radar frequencies [24], [28], [29]. For instance, composites that incorporate varying concentrations of carbon nanotubes or graphene can achieve specific impedance values, optimizing energy absorption across a broad frequency range [22].

One effective approach to impedance matching involves creating multilayer structures, where each layer has a different dielectric constant and thickness. This gradation allows for gradual changes in impedance, facilitating superior matching with free space. In carbon-based RAM, multilayer configurations can be designed using different carbon materials or blends with polymers, enabling tailored performance for specific radar applications [30]. For instance, graphene exhibits an exceptional dielectric constant, enabling effective energy dissipation across various frequencies. Similarly, carbon nanotubes, known for their high surface area and unique conductivity, provide pathways for enhanced electromagnetic wave interaction, resulting in superior absorption. Impedance matching is another vital mechanism that affects the efficiency of radar absorption. Carbon-based materials can be engineered to achieve optimal impedance levels, minimizing reflections, and maximizing absorption [31]. This can be accomplished through composite structures that combine carbon materials with polymers or ceramics, effectively tuning the dielectric properties to achieve desired performance outcomes. The versatility of carbon-based materials enables for innovative designs tailored to specific radar frequency ranges, thereby enhancing their overall effectiveness.

3. COMPARATIVE ADVANTAGES

The pursuit of advanced radar absorbing materials (RAM) has led to significant interest in carbon-based innovations. These materials exhibit unique properties and functionalities that provide several advantages over traditional radar absorbing materials, such as ferrites, polymers, and metals. Understanding these advantages is crucial for recognizing the potential impact of carbon-based RAM in modern technology.

3.1. Lightweight and High Strength

One of the most compelling advantages of carbon-based materials is their lightweight nature combined with high mechanical strength [6]. Traditional RAM, often composed of metals or thick polymeric layers, can significantly increase the weight of platforms, such as aircraft and naval vessels, adversely affecting their performance and fuel efficiency.

In contrast, materials like carbon fibre composites and graphene are known for their exceptional strength-to-weight ratios. For instance, carbon fiber composites are typically one-fifth the weight of aluminium while offering comparable or superior strength [32]. This property is especially critical in aerospace applications, where weight reduction translates directly to improved fuel efficiency, increase payload capacity, and enhanced manoeuverability. Moreover, the lightweight characteristics of carbon-based RAM enable new design paradigms in stealth technology. Engineers can incorporate radar absorbing materials without compromising structural integrity or aerodynamic performance, resulting in sleeker, more efficient platforms [1]. This advantage is particularly relevant in military applications, where stealth and agility are paramount for evading detection and improving mission success rates.

3.2. Tunable Electrical Properties

The electrical properties of carbon-based materials can be finely tuned through various fabrication techniques and compositional adjustments. This tunability allows for the optimization of radar absorption across a wide range of frequencies, a feat that is often challenging with traditional materials [33]. For instance, graphene can be functionalized or combined with other materials to achieve specific dielectric properties that enhance electromagnetic wave absorption. Carbon nanotubes (CNTs), with their unique electrical conductivity and large surface area, can also be tailored to target specific radar frequencies [14]. By adjusting the density, alignment, and orientation of CNTs within a composite matrix, researchers can create materials that exhibit peak absorption at desired frequencies. This high level of customization offers significant advantages in applications requiring precise radar absorption characteristics, such as in military aircraft or stealth drones.

Furthermore, the ability to engineer the electrical properties of carbon-based RAM means they can be adapted for specific operational environments. For example, materials can be designed to function effectively in low-frequency and high-frequency radar applications. This versatility enhances their utility across various defence and civilian sectors.

3.3. Multifunctionality

Carbon-based RAM is not limited to radar absorption; these materials offer multiple functionalities, making them highly versatile for various applications. For example, carbon nanomaterials can simultaneously serve as radar absorbers, electromagnetic interference (EMI) shields, and structural components [34]. This multifunctionality reduces the need for additional layers or materials, which can simplify design and manufacturing processes. In addition to radar absorption, carbon-based materials can enhance thermal management by providing efficient heat dissipation on electronic devices [35]. This characteristic is particularly beneficial for applications where radar and electronic systems must operate within strict thermal limits. By integrating radar absorbing materials that also act as heat sinks, the overall performance and reliability of systems can be improved.

Moreover, incorporating carbon-based RAM into existing infrastructure and materials can lead to innovations in other domains [36]. For instance, integrating carbon-based radar absorbers into building materials can contribute to the development of stealthy civilian structures, enhancing privacy and security. The multifunctionality of carbon-based materials renders them a compelling option for a range of modern applications [12]. Additionally, carbon-based materials are more environmentally friendly than some conventional options [37]. Producing them using sustainable methods, such as chemical vapour deposition and environmentally conscious sourcing of raw materials, presents an opportunity to reduce the ecological footprint associated with RAM production [38]. This aspect is increasingly crucial in an era where sustainability has become a paramount concern.

4. RECENT ADVANCEMENTS IN FABRICATION TECHNIQUES

4.1. Chemical Vapor Deposition (CVD)

Chemical vapor deposition (CVD) is a widely employed technique for synthesizing high-quality carbon-based materials, such as graphene and carbon nanotubes (CNTs) [31]. In the CVD, gaseous precursors react on a substrate to form solid carbon structures. This method is highly regarded for its ability to produce large-area films with uniform thickness and exceptional purity. Recent advancements in CVD techniques have focused on optimizing parameters like temperature, pressure, and precursor composition to enhance the yield and quality of carbon materials [39]. For example, researchers have developed low-temperature CVD processes that allow for the growth of graphene at temperatures compatible with various substrates, including polymers and metals [40]–[42]. This adaptability is crucial for integrating RAM into diverse applications, from military aircraft to consumer electronics.

Additionally, innovations in catalyst design have enabled the growth of CNTs with tailored properties. By manipulating the metal catalysts used in the CVD process, scientists can precisely control the diameter, length, and orientation of the nanotubes. This ability is crucial for developing materials with specific electromagnetic properties [41]. Such control is essential for optimizing radar absorption across various frequencies

4.2. Solution Processing

Solution-processing techniques have gained popularity due to their simplicity and scalability. Methods such as sol-gel synthesis, liquid-phase exfoliation, and spin-coating allow for the production of carbon-based materials in various forms, including nanoparticles, films, and coatings [43]. These techniques are particularly advantageous for developing composite materials that integrate carbon nanomaterials with polymers or ceramics. Recent advancements in solution processing have focused on enhancing the dispersion and stability of carbon nanomaterials in solvents. For instance, researchers have developed functionalization strategies that modify the surface chemistry of CNTs and graphene, improving their compatibility with different polymer matrices [20]. This improvement facilitates the creation of homogeneous composites with enhanced radar absorption properties.

Moreover, recent advancements in spin-coating techniques have allowed precise control of film thickness and uniformity. By optimizing the spinning speed and solution concentration, researchers can produce thin films of carbon-based materials that maximize radar wave interaction while minimizing weight [1]. This characteristic is particularly advantageous for applications in stealth technology, where maintaining a low profile is crucial.

4.3. 3D Printing

The 3D printing has emerged as a transformative fabrication technique in materials science, offering unprecedented design flexibility and customization capabilities. In the context of carbon-based RAM, 3D printing allows for the creation of complex geometries that optimize radar absorption performance [44].

Recent developments in 3D printing technologies, such as fused deposition modelling (FDM) and stereolithography, have facilitated the integration of carbon-based materials into multi-material structures

[22], [45]. By incorporating carbon nanomaterials into printable filaments or resins, researchers can design and fabricate RAM with tailored properties that meet specific application requirements.

Furthermore, 3D printing enables the fabrication of porous structures that enhance radar absorption through increased surface area and multiple scattering pathways [12]. By designing hierarchical architectures, researchers can exploit the unique properties of carbon-based materials to achieve superior absorption across a broad frequency spectrum. The scalability of 3D printing also presents a significant advantage. This capability reduces production time and enables the exploration of innovative designs that would have been impractical with traditional manufacturing methods.

4.4. Electrospinning

Electrospinning is a promising technique for fabricating carbon-based nanofibers, which exhibit unique properties conducive to radar absorption. This method involves applying a high-voltage electric field to a polymer solution containing carbon nanomaterials, resulting in the formation of continuous nanofibers [46].

Recent advancements in electrospinning have focused on optimizing parameters such as solution viscosity, electric field strength, and collector design to enhance fiber uniformity and alignment. Aligned carbon nanofibers can create anisotropic materials with tailored electromagnetic properties, which improve radar absorption performance [47].

Moreover, the ability to incorporate various additives during the electrospinning process allows for the development of multifunctional materials. For instance, integrating magnetic nanoparticles or dielectric fillers can enhance the absorption mechanisms and broaden the operational frequency range of the resulting materials. This versatility makes electrospinning a powerful tool for creating advanced radar absorbing composites [26].

Additionally, electrospin fibers can be easily processed into flexible, lightweight mats, making them suitable for integration into various substrates, including textiles and flexible electronics. The flexibility of these materials opens up new possibilities for applications in wearable technology and smart textiles, where radar absorption capabilities can enhance privacy and security.

4.5. Hybrid Approaches

The combination of different fabrication techniques has led to the development of hybrid approaches that leverage the strengths of various methods [15]. For example, integrating CVD with electrospinning can yield nanofibers with enhanced structural integrity and superior electromagnetic properties [40], [48]. By using CVD to grow carbon nanotubes on electrospun fibers, researchers can create composites that exhibit excellent radar absorption while maintaining mechanical strength [38]. Hybrid approaches also extend to the combination of carbon-based materials

Table 3. Comparison of fabrication technique

Fabrication Technique	Excellence	Weakness
CVD	This technique excels in forming coatings on complex geometries, ensuring consistent electromagnetic properties crucial for effective radar wave absorption.	CVD processes can be time-consuming, as they often require lengthy deposition times to achieve the desired thickness and uniformity of the films.
Solution Processing	This method allows for the easy formulation of complex materials, including composites and nanostructured films, by dissolving precursors in a solvent to create homogeneous solutions.	The evaporation of solvents can also lead to cracks or delamination in the final product, compromising structural integrity.
3D Printing	This technique allows for precise control over material distribution and the integration of different materials within a single component, enabling the design of multi-functional RAM that can be tailored for specific frequencies and absorption characteristics.	The mechanical properties of 3D-printed materials may vary due to the layer-by-layer fabrication process, potentially resulting in weaker interfaces and lower overall durability than traditionally fabricated materials.
Electrospinning	This method involves applying a high voltage to a polymer solution, which results in the formation of fibers that can be collected as non-woven mats or aligned structures.	The process is sensitive to a variety of factors, including solution viscosity and applied voltage, making it challenging to reproduce the desired results consistently.
Hybrid	This approach leverages the strengths of each individual technique, allowing for the creation of complex structures that can be tailored for specific electromagnetic absorption needs.	Achieving uniformity and reproducibility across hybrid methods can be difficult, especially when transitioning from laboratory-scale to larger-scale production.

with other substances, such as polymers or metals, to create composite structures that optimize radar absorption performance [44]. For instance, researchers have explored the use of polymeric binders in conjunction with carbon nanomaterials to create lightweight, flexible RAM that retains effective absorption characteristics [22], [49].

Furthermore, the integration of machine learning and computational modelling into the design and fabrication processes represents a promising frontier in materials science. By predicting the properties of hybrid composites based on their composition and structure, researchers can streamline the development of advanced RAM tailored for specific applications. The advancement of fabrication techniques has played a crucial role in enhancing the performance of carbon-based RAM [50]. Innovative methods, such as 3D printing and electrospinning, enable the creation of complex geometries and hierarchical structures that optimize radar absorption capabilities. For example, 3D printing allows for the precise control of porosity and thickness, which are critical factors influencing absorption efficiency.

Additionally, hybrid composite materials, combining carbon-based substances with other polymers or metals, have also shown great promise [31]. These composites leverage the strengths of each material, resulting in enhanced mechanical properties and improved radar absorption performance. The ability to tailor the composition and structure of these materials allows researchers to achieve specific radar absorption characteristics, thereby broadening the potential applications.

Surface functionalization techniques have been developed to improve the interaction between radar waves and carbon-based materials. By modifying the surface properties, researchers can enhance dielectric and magnetic loss mechanisms, following increased absorption efficiency [28], [51]. This research area shows great promise as it opens new avenues for developing multifunctional materials capable of addressing diverse challenges in radar technology [52].

The development of effective radar absorbing materials (RAM) has been significantly influenced by advancements in fabrication techniques, particularly concerning carbon-based materials. As the demand for lightweight, efficient, and multifunctional RAM increases, innovative manufacturing methods have emerged that not only enhance the performance of these materials but also facilitate scalability and cost-effectiveness. Briefly, comparison of fabrication technique has been presented in **Table 3**.

5. CHALLENGES AND LIMITATIONS

Carbon-based radar absorbing materials (RAM) present numerous advantages over traditional radar absorbing technologies. However, several challenges and limitations hinder their widespread adoption and optimal performance. This discussion delves into the key obstacles encountered in the development and application of carbon-based RAM, focusing on material performance, scalability, manufacturing costs, integration with existing systems, and environmental considerations

5.1. Material Performance Variability

One of the primary challenges in the field of carbon-based RAM is the variability in material performance. The effectiveness of radar absorption depends on several factors, including the composition, morphology, and microstructure of the materials used [53]. For instance, while graphene and carbon nanotubes (CNTs) exhibit excellent electromagnetic properties, their performance can vary significantly based on how they are synthesized and processed [40], [54].

Inconsistent quality control during production can lead to defects, such as vacancies, impurities, or structural irregularities, adversely affecting radar absorption capabilities. For instance, defects in graphene can disrupt its electron mobility, thereby diminishing its effectiveness as a radar absorber [31]. Additionally, the dispersion of carbon nanomaterials within a matrix can affect the overall performance; agglomeration can lead to reduced surface area and compromised electromagnetic properties [22].

Furthermore, the performance of carbon-based RAM can be highly dependent on frequency. While certain materials may excel at absorbing specific radar frequencies, they may not perform as well across the entire spectrum [19]. This frequency dependence poses a challenge for applications requiring broad-spectrum absorption, as optimizing materials for a specific frequency range may sacrifice performance in others

5.2. Scalability of Production

Scalability remains a significant challenge in the commercialization of carbon-based RAM [41]. Although several advanced fabrication techniques, such as chemical vapor deposition (CVD) and electrospinning, have demonstrated the ability to produce high-quality carbon materials at small scales, translating these methods into large-scale production often encounters obstacles. For instance, CVD processes are generally time-consuming and require specialized equipment, making them less suitable for mass production [7]. The high costs associated with maintaining controlled environments, such as vacuum chambers and temperature regulation, can also limit scalability. While researchers have made strides in optimizing these processes, the need for continuous monitoring and quality assurance adds complexity to large-scale manufacturing [40].

Moreover, the synthesis of carbon nanomaterials often involves the use of toxic or hazardous chemicals, raising concerns about workplace safety and environmental impact [55]. As the demand for carbon-based RAM increases, addressing these challenges will be crucial for establishing sustainable production methods that meet market needs [56], [57].

5.3. High Manufacturing Costs

The cost of manufacturing carbon-based RAM is another significant limitation that can hinder widespread adoption [38]. Although the prices of some carbon materials, such as graphene, have decreased in recent years due to advancements in production techniques, they can still be prohibitively expensive compared to traditional radar absorbing materials. The cost factor is particularly critical in defence applications, where budget constraints often dictate material selection. If carbon-based RAM cannot compete with the cost of established materials, their integration into military platforms may be limited [58]. For civilian applications, such as consumer electronics or automotive industries, the cost-sensitive nature of these markets may further impede the adoption of carbon-based solutions.

In addition to raw material costs, the expenses associated with the processing and integration of carbon-based RAM into existing systems can be substantial [24]. For instance, the need for specialized equipment and skilled personnel to handle advanced materials can escalate production costs, making it challenging for manufacturers to justify the investment

5.4. Integration Challenges

Integrating carbon-based RAM into existing systems presents several challenges [13]. Many current platforms, particularly in military applications, are designed for traditional radar absorbing materials, making the transition to carbon-based solutions complex. Ensuring compatibility with existing designs and performance requirements can necessitate extensive testing and modification. Moreover, the mechanical properties of carbon-based materials may differ significantly from those of conventional RAM. For example, while carbon fiber composites offer high strength and low weight, they may not possess the same impact resistance or thermal properties as traditional materials [14], [59]. This discrepancy can pose challenges in ensuring all systems maintain structural integrity and functionality.

The flexibility and processing techniques required for carbon-based RAM introduce complications in manufacturing. Many current applications rely on rigid materials, and adapting these systems to accommodate the unique properties of carbon-based solutions may require significant redesign efforts [41].

5.5. Environmental and Safety Concerns

The environmental impact of producing carbon-based RAM is another important consideration [60]. While advancements in fabrication techniques have made strides toward sustainability, many traditional production methods still involve toxic chemicals and energy-intensive processes. The use of hazardous materials in synthesis poses risks not only to workers but also to the environment [55]. Furthermore, the disposal of carbon-based materials raises questions about their long-term environmental impact. While some carbon-based materials can be designed for biodegradability, many are not, leading to concerns about waste and pollution. As the demand for radar absorbing technologies grows, addressing these environmental challenges will be essential to ensure sustainable practices within the industry [57], [61].

Additionally, the potential health risks associated with exposure to carbon nanomaterials are not fully comprehend. Ongoing research into the toxicity and biocompatibility of carbon-based materials may lead to evolving regulatory guidelines regarding their use and disposal [62]. This uncertainty can hinder investment and development in carbon-based RAM, as manufacturers may be cautious about adopting materials that could face future restrictions.

6. FUTURE ISSUE

6.1. Advanced Material Design

One of the most critical future directions for carbon-based RAM lies in the development of advanced material designs that can optimize radar absorption capabilities. Researchers are increasingly exploring composite materials that combine carbon-based substances with other functional materials, such as metals, ceramics, and polymers [63].

This hybrid approach can enhance the electromagnetic properties and mechanical performance of RAM [64]. For example, integrating magnetic materials with carbon-based composites can lead to improved radar absorption through magnetic loss mechanisms [24], [59]. This synergy between different material types may enable the creation of multifunctional RAM that not only absorbs radar waves but also provides additional benefits, such as thermal management and mechanical strength [65]. By leveraging the unique properties of each component, researchers can design materials that excel across a broader frequency spectrum, thus expanding their applicability in various scenarios

6.2. Tailored Electromagnetic Properties

Future research should focus on the tailored design of carbon-based RAM to achieve specific electromagnetic properties [8], [66]. Utilizing advanced computational modeling and simulation techniques can enable researchers to predict how variations in material composition, structure, and morphology will affect radar absorption performance. This approach allows for a more systematic exploration of design parameters, leading to optimized materials that meet precise performance criteria.

Additionally, machine learning and artificial intelligence (AI) can facilitate the rapid identification of material combinations that exhibit desired electromagnetic properties [47]. By analyzing vast datasets of material performance, AI algorithms can uncover correlations that may not be readily apparent, guiding researchers toward innovative material formulations and structures

6.3. 3D Printing and Additive Manufacturing

The future of carbon-based RAM is likely to be significantly influenced by advancements in 3D printing and additive manufacturing technologies [67], [68]. These techniques provide unprecedented flexibility in material design and enable the creation of complex geometries that are difficult to achieve through traditional manufacturing methods. As 3D printing technologies evolve, researchers can explore the production of RAM with tailored architectures that enhance radar absorption through increased surface area and improved scattering mechanisms. For example, researchers can design porous structures that trap electromagnetic waves, effectively enhancing absorption [6].

Moreover, integrating multiple materials within a single 3D printing process could lead to the development of multifunctional RAM that combines the benefits of various components. This capability can enable the creation of lightweight, efficient solutions that meet the stringent requirements of modern applications, particularly in the aerospace and military sectors

6.4. Sustainable Production Methods

Sustainability will play a crucial role in the future of carbon-based RAM development. As environmental concerns continue to rise, there is an increasing demand for materials that can be produced with minimal ecological impact [50]. Future research should focus on developing sustainable production methods that reduce reliance on hazardous chemicals and energy-intensive processes [34]. Green synthesis methods, which utilize renewable resources or less toxic chemicals, are a promising area of exploration. For example, researchers are investigating biomass-derived precursors to produce carbon nanomaterials, minimizing waste and energy consumption [57].

In addition, designing biodegradable or recyclable RAM could contribute to more sustainable practices [57]. By creating materials that can be easily repurposed or decomposed, the industry can mitigate the environmental impact associated with traditional radar absorbing technologies. Emphasizing sustainability in production will not only align with global ecological goals but also enhance the marketability of carbon-based RAM.

As the demand for advanced radar absorbing materials (RAM) grows across various sectors, including defense, aerospace, and consumer electronics, the future of carbon-based materials appears promising. Although significant advancements have been made in the field, there are still numerous opportunities for innovation and development

CONCLUSION

Carbon-based radar absorbing materials represented a significant advancement in effective stealth technology. Their distinctive attributes, coupled with recent advancements in fabrication methodologies, established them as superior substitutes to conventional RAM. Nevertheless, to fully realize the potential of these materials, researchers must continue to address the challenges related to scalability, integration, and cost. As the field progresses, interdisciplinary collaboration among scientists and engineers would be essential to unlock the full potential of carbon-based RAM. This could lead to transformative applications in military, aerospace, and other industries. The findings presented in this review were constrained to the prospective development of carbon-based radar absorbing materials and potential enhancements to the physical and chemical attributes of the materials. Further research is required to facilitate a more comprehensive examination of the development of these materials.

SUPPORTING INFORMATION

There is no supporting information for this paper. The data that support the findings of this research are available upon request from the corresponding author (P.I.W. Bolilanga).

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CONFLICT OF INTEREST

The authors have no conflict of interest in this publication.

AUTHOR CONTRIBUTIONS

MF and PIWB was conducted the research design, conceptualization, and validation of final revision. PIWB, Gunaryo, ES, and TK wrote and revised the manuscript.

All authors agreed to the final version of this manuscript.

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