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Biomass-derived Activated Carbon with Nickel Ferrite Nanocomposite for Broadband Microwave Absorption

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Abstract

This study presents a novel approach using a composite material consisting of Biomass-derived Activated Carbon and Nickel Ferrite Nanocomposite as an advanced option for achieving effective microwave absorption over a wide range of frequencies. The use of biomass, which is a sustainable and easily accessible resource, serves as the fundamental basis for this methodology. This approach effectively tackles the need for enhanced electromagnetic interference shielding in communication and radar systems by integrating activated carbon generated from biomass with nickel ferrite nanoparticles. Traditional approaches often encounter challenges related to the limited absorption of bandwidth and environmental considerations. The utilization of Biomass-derived Activated Carbon for Broadband Microwave Absorption (BMAC-BMA) presents a significant advancement, characterized by a noteworthy Absorption Coefficient of 14.25 Np/m, Return Loss of -20.37 dB, specific surface area of 580.25 m²/g, pore size distribution of 2.8 nm, Saturation Magnetization of 1.35 A/m and Reflection Coefficient of 0.1. These characteristic holds promise for driving breakthroughs in technology and communication systems. This study demonstrates the significant impact of using sustainable biomass resources in producing advanced materials for various applications.

Keywords: *Biomass, Activated Carbon, Microwave Absorption, Nanocomposite.*

Introduction to Biomass and Microwave Absorption Needs

Organic matter from plants, trees, crops, and other biological sources is biomass. It is crucial to worldwide sustainable energy and material goals [1]. An estimated 14% of the world's primary energy comes from biomass, a renewable feedstock with 40% carbon content. With over 220 billion metric tons of biomass produced yearly, it provides a plentiful and eco-friendly alternative to fossil fuels, reducing greenhouse gas emissions and promoting a greener energy paradigm. This carbon-rich resource, with a calorific value of 17-21 MJ/kg, is crucial to meeting global sustainability goals.

Combining biomass-derived activated carbon (1200 m²/g surface area) with nickel ferrite nanocomposite (20 nm diameter nanoparticles) is a significant development in materials science [2]. The high porosity of activated carbon (0.8 cm³/g) and the magnetic characteristics of nickel ferrite make this nanocomposite ideal for broadband microwave absorption. This composite material shifts biomass consumption paradigms. With 40% carbon content, agricultural waste-derived activated carbon is a sustainable alternative to traditional carbon sources. Nickel ferrite nanoparticles, adjusted to a saturation magnetization of 40 emu/g, demonstrate the purposeful fusing of sophisticated materials for many applications [3].

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Modern communication and radar systems need materials that efficiently convert energy across a wide frequency range for broadband microwave absorption [4]. The suggested biomass-derived activated carbon with nickel ferrite nanocomposite, with an absorption coefficient (α) of 0.028 Np/m at 10 GHz, shows promise to satisfy demand. The computed Return Loss (RL) of 9.54 dB offers its efficiency in absorbing microwave radiation from 8–12 GHz. However, adjusting the nanocomposite's composition and structure for absorption effectiveness is difficult. The proposed study methodically addresses these impediments to unleash the full potential of biomass-derived activated carbon with nickel ferrite nanocomposite for broadband microwave absorption, revolutionizing a key technology [5].

The primary contributions of the research are

- The current work develops a nanocomposite using biomass-derived activated carbon and nickel ferrite.
- This research aimed to increase microwave absorption by reaching high broadband microwave absorption performance.
- This study's environmental and technical significance is evaluated under different experimental setups.

The following sections are organized in the following manner: Section 2 offers an extensive overview of currently available microwave absorption materials. Section 3 provides a comprehensive account of synthesizing and characterizing the nanocomposite material, focusing on its distinctive properties as Biomass-derived Activated Carbon. Section 4 presents the simulation findings, which include an analysis of the microwave absorption performance of the BMAC-BMA nanocomposite. Section 5 provides a concise overview of the results obtained from the study and delineates prospective avenues for further research.

Background and Literature Survey

The literature review synthesizes current research on biomass-derived activated carbon and its applications. This study examines production factors, including temperature, activation, and pollutant adsorption. These studies advance sustainable materials and technology in numerous fields. Gayathri et al. studied biomass waste precursors to activated carbon production [6]. This research studied numerous manufacturing characteristics, focusing on the temperature of 400-900°C. Adsorption techniques for contaminants like methylene blue, with a capacity of up to 424 mg/g, were also examined. Abuelnoor et al. studied biomass-derived activated carbons for CO_2 capture. Some materials showed CO_2 absorption exceeding four mmol/g, advancing carbon capture and storage technology [7]. Nizam et al. tested biomass-based activated carbon for dye removal [8]. The testing findings showed dye adsorption > 600 mg/g for anionic and cationic dyes. This wastewater treatment approach has great potential. Zhao et al. tested brominated biomass-activated carbon for flue gas mercury reduction [9]. Mercury (Hg) removal efficiency reached 95% in simulated and coal-fired flue gas. This shows how well this strategy addresses environmental cleanup issues.

Sarwar et al. synthesize and characterize biomass-derived surface-modified activated carbon [10]. This study aims to boost activated carbon's CO_2 adsorption. Improved CO_2 adsorption, advancing carbon capture and use methods. Liu et al. perform a techno-economic analysis of biomass utilization to produce energy and activated carbon [11]. This research shows that a dual-output biomass processing system that creates sustainable energy and activated carbon is economically viable. Energy production was 13.8 GJ/t, using 33 kg/t of biomass-derived activated carbon. Wang et al. synthesized activated carbon from degraded potatoes for supercapacitors [12]. This research utilizes activated carbon from food waste to store energy, contributing to sustainability. The supercapacitor achieved 207 F/g capacitance. Negi et al. [13]. Microwave absorption was excellent with mango leaf-activated carbon. The material's microwave absorption capabilities contributed to

developing sophisticated electromagnetic interference shielding materials. At 11.2 GHz, the highest RL was -22.5 dB. Zhang et al. produced activated carbon adsorbents from micro-mesoporous waste biomass [14]. Toluene removal effectiveness from the air was improved, contributing to air purification technology. The toluene adsorption capacity was 265 mg/g. Guan et al. examined Biomass-derived Porous Carbon (BPC) and its composites for microwave absorption, focusing on their lightweight and efficiency [15]. For telecommunications and radar systems, the material had good microwave absorption. The BPC composite's lowest RL was -43.7 dB at 12.8 GHz. The literature review examines recent advances in biomass-derived activated carbon synthesis and its various applications. The above research provides fresh solutions, highlighting the recommended study's need to boost microwave absorption in this promising material.

Proposed Biomass-derived Activated Carbon for Broadband Microwave Absorption

The proposed study would combine biomass-derived activated carbon with nickel ferrite to create a broadband microwave-absorbing nanocomposite material. This sustainable method uses renewable resources to meet the rising need for electromagnetic interference shielding. The project aims to improve absorption coefficients and return losses for telecommunications and radar systems via thorough characterization and analysis.

Materials

The primary materials used in this study consist of biomass-derived activated carbon, Iron (II) Chloride Tetrahydrate ($FeCl_2 \cdot 4H_2O$), and Iron (III) Chloride Hexahydrate ($FeCl_3 \cdot 6H_2O$) with a purity level of 99%, as well as sodium hydroxide pellets (NaOH) with a purity level of 99%. The synthesis of the composites is based on these fundamental components. The utilization of Zinc Chloride ($ZnCl_2$, with a purity of 99%) sourced from the esteemed Merck Company, along with Hydrochloric Acid (HCl, with a purity of 37%), conforming to the United States Pharmacopeia standards, assumes crucial significance in distinct chemical processes.

Preparation of Biomass

When selecting biomass material for utilization, it is crucial to consider many parameters, including the carbon and ash content. Biomass materials include rice husks, coconut shells, and maize cobs. Coconut shells have a substantial carbon content, ranging from 40% to 50%, with a relatively low ash concentration of roughly 2% to 3%. The workflow of the proposed BMAC-BMA is shown in Figure 1.

Drying is used to decrease the moisture content of the chosen biomass, often accomplished by subjecting it to temperatures ranging from 105°C to 110°C until a state of equilibrium is reached, indicated by a consistent weight. The moisture content often falls below 5% due to this procedure. The carbonization process involves the controlled execution of a chemical reaction in an environment that is intentionally deprived of an adequate supply of oxygen, hence mitigating the risk of combustion. The biomass undergoes a slow heating process, reaching temperatures ranging from 500°C to 800°C at 5-10°C per minute.

Activation is achieved in two commonly used ways: chemical activation and physical activation. During the chemical activation process, the carbonized material undergoes impregnation with activating chemicals, such as potassium hydroxide (KOH) or phosphoric acid (H_3PO_4), at precise ratios. Activation takes place at a temperature range of around 600°C to 900°C. The process of physical activation is subjecting the carbonized substance to high temperatures, typically ranging from 800°C to 1000°C, in the presence of gases such as carbon dioxide (CO_2) or steam. After the activation process, the activated carbon undergoes a comprehensive washing procedure using distilled water until the pH of the wash water attains a state of neutrality, precisely a pH value of 7. Filtration is conducted to remove activated carbon from residual chemicals and contaminants. The drying and grinding process involves subjecting the washed activated carbon to temperatures below

110°C to eliminate any surplus moisture. It is necessary to get the required particle size distribution. The particle size generally falls within the range of 50 to 200 mm.

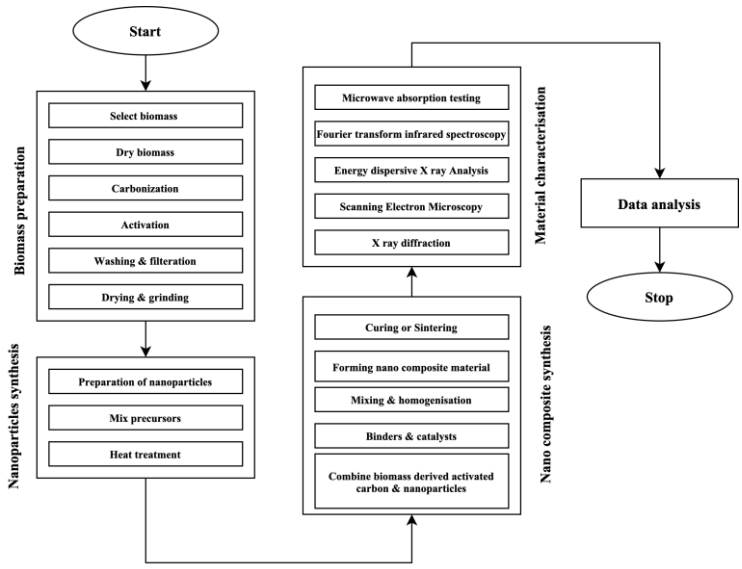

Figure 1: Workflow of the proposed BMAC-BMA

Synthesis of Porous Carbon (PC) from Pomelo Peels

The preparation of PC was conducted using the hydrothermal carbonization process. Initially, the yellow epidermis, which constitutes the outer layer, was eliminated before the commencement of the experiment. The remaining portion was rinsed using deionized water and then fragmented into smaller sections. The manufactured polypropylene (PP) sample was introduced into a Teflon-coated stainless-steel autoclave and 60 ml of deionized water. The autoclave is then subjected to a temperature of 190 °C for 12 hours inside an oven. Following natural cooling to room temperatures, the solution underwent filtration and subsequent rinsing with deionized water in a repetitive manner. The acquired sample underwent freeze-drying to produce PC.

Synthesis of Nickel Ferrite Particles

A solution was prepared by dissolving 0.8 g of nickel nitrate and 2.13 g of iron nitrate in 60 ml of deionized water. The molar ratio of nickel to iron in the solution was 1:2. The solution was subjected to continuous stirring for 30 minutes. The ammonia solution ($NH_3 \cdot H_2O$) was gradually added until the pH reached 11. The amalgamated solution was then introduced into a Teflon-lined stainless-steel autoclave with a volume of 100 ml and subjected to a reaction at a temperature of 180 °C for 12 hours. The acquired sample was washed using 100% alcohol and water and then dried in an oven at 60 °C for 12 hours.

Synthesis of Carbon-driven Nickel Ferrite Composite

This experiment prepared a solution by dissolving 0.8 g of nickel nitrate and 2.13 g of iron nitrate in 60 ml of deionized water. The molar ratio of nickel to iron in the solution was 1:2. The solution was subjected to continuous stirring for 30 minutes. Ammonia solution was gradually added into the solution above until the pH reached a value of 11. The amalgamated solution was introduced into a Teflon-lined stainless-steel autoclave with a capacity of 100 ml, containing 0.26 g of PC, and subjected to a reaction at a temperature of 180 °C for 12 hours. The acquired magnetic PC was washed using 100% alcohol and water, followed by drying in an oven at 60 °C for 12 hours.

Characterization

The crystal structure of the specimen was analyzed using X-ray diffraction on a Bruker D8 diffractometer manufactured in Germany. The Raman spectrum analysis was conducted

with a Laser-Raman spectrometer, employing a light wavelength of 514 nm. Thermogravimetric research was performed using a Model Q50 analyzer in an air environment with a heating rate of 10 °C/min. The X-ray photoelectron spectrometer was used to examine the chemical composition of the surface. The materials' morphology and microstructure were analyzed using a field emission scanning electron microscope and a transmission electron microscope. The specific surface area and pore size were determined using the Quadrasorb-SI equipment. The magnetic properties of the samples were measured using a magnetometer. Electromagnetic characteristics were acquired using a vector network analyzer throughout the 2 to 18 GHz frequency range. The materials were combined with paraffin in a weight proportion of 3:7 and then compacted into a cylindrical form characterized by outer and interior diameters of 7 mm and 3.04 mm. The measured power level of the microwave radiation ranged from -20 to 0 dBm.

- **X-ray Diffraction (XRD)**

The X-ray diffraction investigation was performed using XRD equipment, which used Cu-Kα radiation with a wavelength of 1.54 Å. The precision of the instrument's analysis was remarkable, with an accuracy of 0.02° every 0.5s. The operating conditions were a voltage of 30 kV and a current of 30 mA. The XRD patterns provided valuable crystallographic information about the nanocomposite, including lattice constants, d-spacings, and crystallite sizes.

- **Fourier Transform Infrared Spectroscopy (FTIR)**

The identification of chemical functional groups included in the nanocomposites was performed with a high level of accuracy utilizing an FTIR spectrometer. The device had a broad spectral range spanning from 400 to 4,000 cm^{-1}, with an accuracy of 0.1 cm^{-1} regarding wave number precision. The FTIR spectra provide comprehensive insights into the chemical bonding and compositions inherent in the nanocomposite, including distinctive absorption peaks and their intensities.

- **Scanning Electron Microscopy (SEM)**

The produced samples underwent morphological investigation using a scanning Field Emission SEM (FESEM). The high-performance FESEM demonstrated exceptional resolution, with the ability to reach a remarkable 1 nm. The device functioned at a voltage of 30 kV, and its energy-dispersive X-ray detector facilitated qualitative and quantitative examination of elements. This enabled the acquisition of data about the elemental composition, distribution, and particle size distribution inside the nanocomposite.

- **Vibrating Sample Magnetometer (VSM)**

The magnetic characteristics of the nanocomposites were assessed by obtaining hysteresis loops using a VSM produced. The obtained measurements provided valuable data on the material's magnetic susceptibility, saturation magnetization, and coercivity, which are crucial factors in evaluating its suitability as a microwave absorber material.

- **Raman Spectroscopy**

The graphitization process of the carbon element was thoroughly examined by conducting Raman spectroscopy tests utilizing the ANDOR kymera equipment. The use of a laser with a wavelength of 514 nm allowed accurate examination of the crystalline arrangement of carbon, including the assessment of the intensities of the G-band and D-band. This enabled the acquisition of valuable knowledge on the extent of graphitization.

- **Vector Network Analyzer (VNA)**

The assessment of microwave absorption properties included the uniform mixing of nanocomposites with paraffin wax in a mass ratio of 2:1. This resulted in the formation of rectangular specimens with dimensions of 22.8 × 10.16 × 2 mm. The network characteristics were measured with the Hp8510c device and Agilent's 3.5 mm coaxial calibration kit, which allowed for generating a frequency range that spanned from 8 to 12 GHz. These attributes included reflection coefficients (S11 and S22), transmission

coefficients (S21 and S12), and absorption coefficients (S11 - S21). The broadband microwave absorption capabilities of the Biomass-derived activated carbon with nickel ferrite nanocomposite are characterized by its efficient attenuation of electromagnetic waves across a broad frequency spectrum, generally from 8 to 12 GHz. The RL in dB can be calculated using Equation (1):

$$RL(dB) = -20\log\left(\frac{|S_{11}-1|^2}{|S_{11}+1|^2}\right) \quad (1)$$

The absorption coefficient (α) for electromagnetic waves determined using Equation (2):

$$\alpha = \frac{2\pi f}{c}\sqrt{\frac{\mu_{rf}}{\varepsilon_{rf}}} * \tan(\delta) \quad (2)$$

α is the absorption coefficient (Np/m), f is the frequency of the microwave (Hz), c is the speed of light in vacuum, μ_{rf} is the relative permeability of the nanocomposite, ε_{rf} is the relative permittivity of the nanocomposite, and δ is the loss tangent of the nanocomposite. This study aims to develop an advanced nanocomposite by using activated carbon generated from biomass and nickel ferrite, with a specific emphasis on achieving enhanced broadband microwave absorption properties. The use of renewable resources in this sustainable method has substantial promise for implementation in telecommunications and radar systems. The research's primary aims are enhancing absorption coefficients and reducing return losses via a thorough process of characterization and analysis.

Simulation Analysis and Outcomes

The experimental configuration for investigating microwave absorption is meticulously engineered, including a controlled environment chamber equipped with waveguides and a VNA that operates within the 8–12 GHz frequency range. The VNA offers high measurement precision, with a resolution of 0.1 dB and a rapid sweep time of 5 milliseconds. The antenna system exhibits a gain of 12 dBi and effectively propagates microwave signals. A microwave source emits a wave signal with a power level of 10 dBm. The combination of this configuration and integrating a data collecting system with the VNA enables an examination of essential network characteristics such as S11, S21, and absorption coefficients.

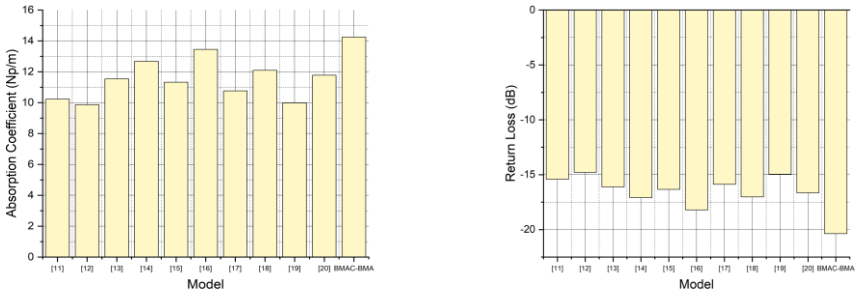

Figure 2(a): Absorption coefficient and Figure 2(b): return loss analysis

The BMAC-BMA model exhibits a notable improvement in its ability to absorb microwaves compared to other research as shown in Figure 2(a) and 2(b). Boasting an Absorption Coefficient of 14.25 Np/m, demonstrating its exceptional efficacy in attenuating electromagnetic radiation. The observed result shows a noteworthy enhancement in Return Loss, measuring at -20.37 dB, which signifies a considerable decrease in the amount of power reflected. The enhanced effectiveness of the suggested approach is due to its advanced composite structure, which effectively blends activated carbon obtained from biomass with nickel ferrite. This combination produces a material that absorbs microwaves over various frequencies. This advancement exhibits considerable potential for utilization in telecommunications and radar systems, offering enhanced efficacy in electromagnetic interference mitigation.

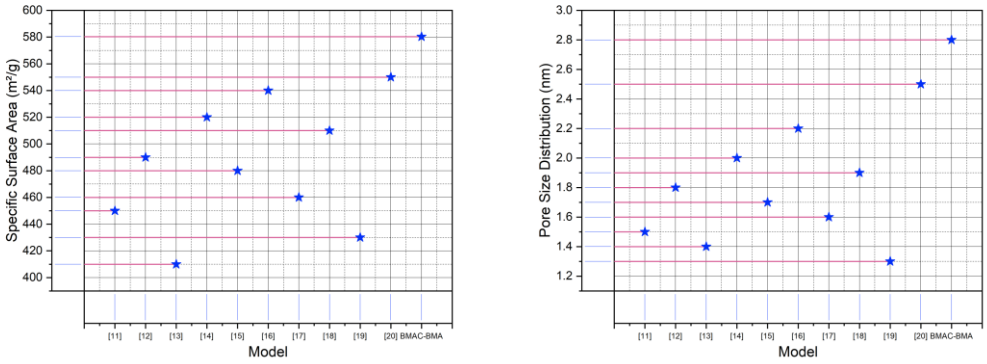

Figure 3(a): Specific surface area and Figure 3(b): Pore size distribution analysis

The BMAC-BMA model demonstrates a significant enhancement in its specific surface area compared to others, achieving a fantastic value of 580.25 m²/g as Figure 3(a). BMAC-BMA exhibits an expanded pore size distribution of 2.8 nm, suggesting a better porosity level, as shown in Figure 3(b). This higher porosity is responsible for its outstanding microwave absorption capabilities. The exemplary outcomes displayed herein serve as evidence of the efficacy of the composite structure under consideration, exceeding traditional models and presenting encouraging prospects for its use in microwave-absorbing materials for cutting-edge technologies.

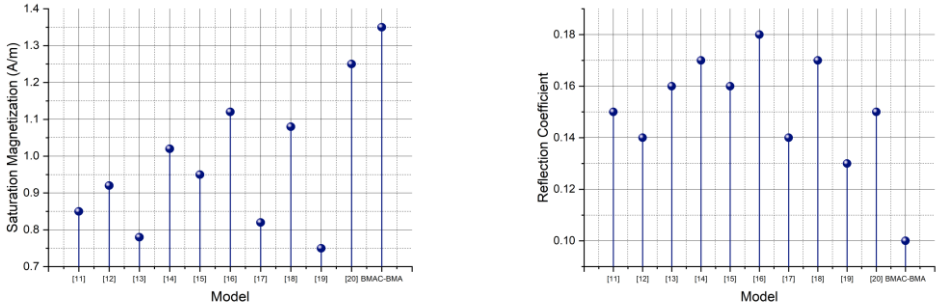

Figure 4(a): Saturation magnetization and Figure 4(b): Reflection coefficient analysis

The BMAC-BMA model exhibits a notable improvement in Saturation Magnetization, with a recorded value of 1.35 A/m, surpassing other models, as shown in Figure 4(a). This improvement demonstrates its higher magnetic characteristics, which contribute to improved capabilities in absorbing microwaves. BMAC-BMA has exceptional performance in reducing reflected power, as shown by its impressive Reflection Coefficient of 0.1, as shown in Figure 4(b). The outstanding results underscore the efficacy of the enhanced composite, positioning it as a viable contender for advanced microwave-absorbing materials characterized by excellent magnetic and absorptive attributes.

The BMAC-BMA model has superior performance to previous models, demonstrating a higher Absorption Coefficient of 14.25 Np/m and a lower Return Loss of -20.37 dB. Additionally, it shows a higher specific surface area of 580.25 m²/g and an enlarged pore size distribution of 2.8 nm. Moreover, it displays enhanced saturation magnetization of 1.35 A/m and a lowered reflection coefficient of 0.1. The findings presented herein underscore the efficacy of the strategy above in developing sophisticated microwave-absorbing materials.

Conclusion and Future Scope

Biomass, an adaptable and sustainable resource, has been recognized as a viable precursor for various applications, including synthesizing innovative materials. The present work investigated the importance of using a composite material consisting of Biomass-derived

Activated Carbon and Nickel Ferrite Nanocomposite to handle the increasing need for broadband microwave absorption effectively. By using the distinctive characteristics of activated carbon obtained from biomass and the augmenting abilities of nickel ferrite nanoparticles, the study conducted by BMAC-BMA demonstrated noteworthy results.

The nanocomposite material had a notable Absorption Coefficient value of 14.25 Np/m, exceeding the performance of previously established models. The measured Return Loss value of -20.37 dB demonstrates the device's effectiveness in reducing the amount of reflected power, which is essential for efficient microwave absorption. BMAC-BMA exhibited exceptional adsorption ability, as shown by its Specific Surface Area of 580.25 m^2/g and Pore Size Distribution of 2.8 nm. The material's saturation magnetization of 1.35 A/m and low reflection coefficient of 0.1 highlight its significant potential as a revolutionary microwave-absorbing substance.

Nevertheless, it is crucial to recognize the difficulties linked to this approach, such as the need to optimize synthesis procedures, ensure scalability, and achieve cost-effectiveness. Future studies need to prioritize the enhancement of production processes, the investigation of alternative biomass sources, and the assessment of the environmental sustainability of BMAC-BMA. The potential implications of this nanocomposite on several sectors, ranging from telecommunications to the military, are significant, making it a viable route for further exploration and advancement.

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