Sustainable Biochar-Derived Nanocomposites for Electromagnetic Interference Shielding: Design Strategies, Loss Mechanisms, and Emerging Applications

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Abstract

The rapid expansion of high-frequency electronic and communication systems has intensified the need for electromagnetic interference (EMI) shielding materials that combine high attenuation efficiency with low weight and environmental sustainability. Conventional metallic shields, while effective, are limited by high density, corrosion susceptibility, and restricted design flexibility. Biochar-derived nanocomposites have recently emerged as an alternative class of shielding materials due to their renewable origin, porous carbon architecture, and tunable electrical characteristics. This review synthesises recent advances in biochar-based hybrid nanocomposites for EMI shielding, focusing on the influence of biomass selection, thermal processing, and surface modification on electromagnetic performance. We evaluate material formulations, discuss the underlying shielding mechanisms, examine structure-property relationships, and highlight present issues and future research areas. This review provides design insights for developing next-generation green EMI shielding materials suitable for advanced electronic and communication technologies.

Keywords

Biochar carbon materials, Hybrid nanocomposites, Electromagnetic Interference (EMI) Shielding, Sustainable Materials, Shielding Effectiveness (SE).

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1. Introduction

Electromagnetic interference (EMI), caused by undesired electromagnetic radiation emitted by or interacting with electronic equipment, compromises device performance, data integrity, and personal safety. The shielding effectiveness (SE) required in various applications often spans tens of decibels (dB) over frequency bands from MHz to tens of GHz.(Zecchi et al., 2024). Traditional metallic shields (copper, aluminum) reflect strongly but are heavy, prone to corrosion, inflexible, and can occasionally produce unwanted secondary reflections. The materials research community is consequently looking for innovative composites with high absorption, low density, processability, and sustainability. One interesting option is to use biomass-derived carbon ("biochar") as a filler or substrate for conductive and magnetic nanofillers.

Biochar is produced by pyrolysis of biomass wastes (e.g., agricultural residues) under limited oxygen conditions, yielding a porous, carbon-rich structure with tunable pore size, surface area, conductivity and heteroatom content. Its sustainable origin, low cost, and adjustable microstructure make it attractive for EMI shielding composites. When hybridised with conductive fillers (graphene, carbon nanotubes, MXenes) or magnetic particles (Fe_3O_4, Ni, etc.), biochar-based nanocomposites can achieve high shielding effectiveness while retaining low density and environmental benefits.

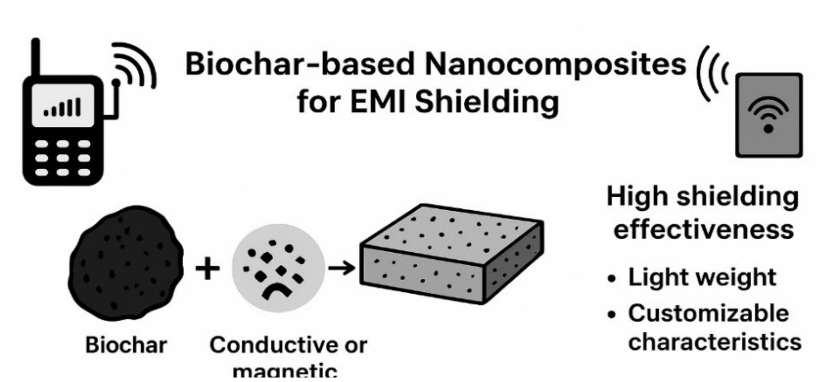

Figure 1: biochar-based nanocomposites for EMI shielding, which mix sustainable biomass-derived carbon (biochar) with conductive or magnetic nanofillers to produce high shielding effectiveness, light weight, and customizable characteristics.

2. Biochar: Preparation, Structure and Properties for EMI Shielding

2.1 Preparation and tuning of biochar

Biochar is typically produced through the pyrolysis of biomass (such as agricultural residues and woody waste) in an inert or low-oxygen environment. Key parameters include pyrolysis temperature, heating rate, residence time, and activation/functionalisation. Higher temperatures (e.g., > 700 °C) promote graphitisation, increased conductivity, and greater microporosity, which can enhance conductive pathways and the internal reflection of electromagnetic (EM) waves.

For instance, a study demonstrated that biochar produced at ~600 °C from olive tree prunings exhibited micropores (~4-8 µm) and low shielding (1.5–4 dB) until modified with carbon black, reaching ~39 dB in 1–3 GHz. But the performance increased significantly with the addition of a conductive filler (Nikolopoulos et al., 2023a).

Other studies have shown that biochar derived from biomass, when used in composites with gypsum, increases SE with increasing biochar content (Natalio et al., 2020a). Thus, adjusting the pore structure of biochar, surface functionality (including heteroatoms), and conductivity is crucial.

2.2 Structure and property of biochar for EMI shielding

Important biochar characteristics for EMI shielding include electrical conductivity, porosity, defect sites, Graphitised domains and Low density. A higher value of electrical conductivity (σ) provides conductive networks, improving reflection and absorption losses. The pore size and hierarchical porosity support multiple internal reflections and impedance matching. The surface heteroatoms or defect sites enhance dipolar polarisation loss. The graphitised domains facilitate conduction and charge-carrier mobility. Low density is desirable for lightweight shielding structures. In its composite form, biochar often provides modest SE (a few dB) on its own, unless modified or combined with other fillers (Ruscica et al., 2024). Hence, hybridisation strategies are needed.

3. Biochar-Based Nanocomposites for EMI Shielding

This section summarises important performance and design aspects of the main classes of biochar-based nanocomposites.

3.1 Polymer/Biochar Composites

Biochar alone, when mixed into polymer matrices (e.g., epoxy, polyurethane, HDPE), can yield improved shielding compared to virgin polymer but often falls short of optimal levels due to limited conductivity or poor filler dispersion. For instance, in an HDPE-biochar composite, the importance of conductivity, porosity, and filler dispersion for effective EMI shielding was emphasised (Fenta & Ali, 2024). Thus, pure polymer/biochar composites are a low-cost, sustainable baseline solution but typically require higher filler loadings (>20 wt%) and may compromise mechanical properties or processability.

3.2 Biochar + Conductive Carbon Nanofillers (Graphene, CNTs)

Combining biochar with conductive nanofillers, such as graphene or carbon nanotubes (CNTs), significantly enhances electrical conductivity, network formation, and shielding performance. Biochar-graphene nanocomposites demonstrated shielding effectiveness above −32.7 dB with a bandwidth of 4.4 GHz at 1.7 mm through synergistic conductive pathways and enhanced dipolar polarisation (Chen et al., 2021).

Similarly, CNT-decorated biochar composites provided absorption-dominant shielding in the X-band (8-12 GHz) due to good impedance matching and the formation of a conductive network. The incorporation of a Fe_3O_4 coating did not negatively affect the electrical conductivity of the composites obtained (∼21 S/m) but instead endowed the composites with good magnetic properties. The resultant composites had an *SE of 47.2 dB and a specific SE of 363 dB/cm* (Meng et al., 2024). These systems demonstrate that combining biochar's porous scaffold with high-aspect-ratio conductive fillers yields high performance even at moderate filler loads.

3.3 Biochar + MXenes

Two-dimensional MXene materials (e.g., Ti_3C_2Tx) exhibit ultrahigh conductivity, and when combined with biochar, yield effective 3D conductive networks and excellent shielding properties. One study found that MXene-coated biochar composites had >60 dB SE at low filler loading due to strong interfacial coupling and layered conductive pathways (Hu et al., 2024). High conductivity, tunable surface terminations, and synergy with the porous structure of biochar enable absorption-dominated shielding(Wang et al., 2019).

3.4 Biochar + Magnetic Nanoparticles / Metal-Biochar Composites

Incorporating magnetic or metallic nanoparticles into the biochar matrix introduces magnetic loss mechanisms (natural resonance and eddy-current losses) in addition to dielectric/conductive losses.

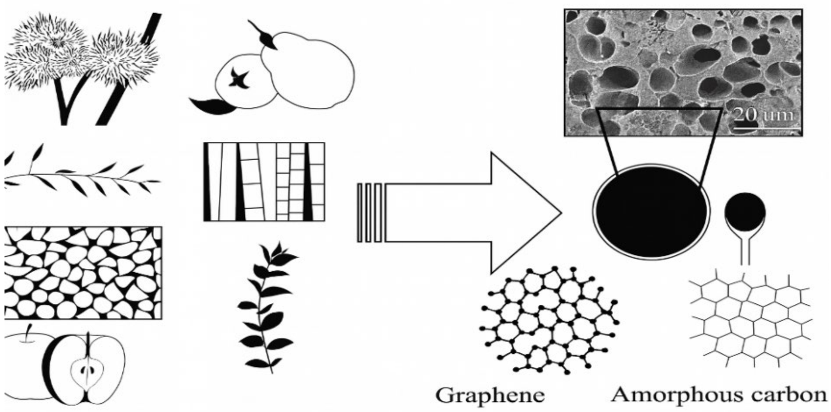

Figure 2: Different starting materials (Ricinus communis outer shell, bamboo, wood, apple, and quince stillage, olive tree pruning, eucalyptus) in biochar production, at various temperatures, usually in an oxygen-controlled atmosphere, lead to the production of porous materials with domains with graphene and amorphous carbon.

For example, Fe_3O_4-biochar composites demonstrated strong absorption-based shielding due to the synergy of magnetic and dielectric losses. Ni-biochar nanocomposites exhibited broadband absorption (2-18 GHz) driven by interfacial polarisation and conductive network formation(Marinković et al., 2025). These systems offer higher absorption contributions and improved impedance matching.

Table 1: Biochar-based composites

No.	Biochar Source & Treatment	Nanofiller	Matrix	Thickness (mm)	Frequency Band	SE_T (dB)	Key Mechanism	Ref.
1.	Drywall panels coated with commercial wood biochar	-	Drywall panels	10	18GHz	25	vertical and horizontal polarization	(Savi et al., 2022)
1.	Olive tree pruning biochar (~600°C)	Carbon black (20 wt%)	PFTE binder	0.1-0.5	1–3 GHz	39	Conductive network & porosity	(Nikolopoulos et al., 2023b)
2.	Gypsum + biochar (various wt%)	—	Gypsum matrix	10	4.9GHz		Porosity + carbon loss	(Natalio et al., 2020b)
3.	Biochar + Fe_3O_4	Fe_3O_4 nanoparticles	Polymer	-	2-18 GHz	40.15	Magnetic + dielectric loss	(Sparavigna, 2023)
4.	cashew shell biochar	carbon fibre	epoxy resin	-	18	-48.6	Electrical conductivity & layered network	(Babu et al., 2023)

4. EMI Shielding Mechanisms in Biochar-Based Composites

The overall shielding effectiveness (SE_T) of an EMI(S) shielding material is the sum of three components: shielding effectiveness due to reflection (SE_R), absorption (SE_A), and multiple internal reflections (SE_M)(M. S. et al., 2025).

$$SE_T = SE_A + SE_R + SE_M$$

Key mechanisms relevant to biochar-based composites:

1. **Reflection**: Occurs at the interface when there is impedance mismatch; reliant on high conductivity and free charge carriers(Geetha et al., 2009).
2. **Absorption**: Energy dissipated within the material by dielectric loss (dipoles, heteroatoms), magnetic loss (magnetic fillers), and conduction loss (ohmic heating)(Saini et al., 2009).
3. **Multiple internal reflections (MIR)**: Occurs in porous structures where scattered waves undergo repeated reflection/absorption before exiting; porous biochar structures enhance MIR, thereby boosting absorption(Orasugh et al., 2022).
4. **Impedance matching**: Matching material and free-space impedances reduces reflection and improves absorption by increasing penetration into the absorber layer-dominated shielding, which is an important goal for biochar composites that combine dielectric and magnetic properties(Ott & Ott, 2009).
5. **Synergistic filler interactions**: In hybrid systems (e.g., biochar + graphene/MXene + magnetic particles), the combination of conduction paths, heterointerfaces, and magnetic domains results in increased dielectric and magnetic losses, as well as interfacial polarization.

Thus, the porous architecture of biochar facilitates multiple scattering, increasing the path length of waves and promoting absorption rather than merely reflection. The incorporation of conductive nanofillers creates percolative networks, enhancing conduction losses and electromagnetic attenuation. Magnetic fillers further contribute via natural resonance and eddy current losses.

5. Current Challenges

While biochar-based nanocomposites appear promising for EMI shielding, they face several challenges, such as raw biochar often lacking adequate conductivity; consequently, hybridisation is required, increasing complexity. To achieve high SE, relatively high filler contents may degrade mechanical/thermal properties or increase cost. The uniform dispersion of nanofillers within biochar-matrix composites remains challenging, particularly at an industrial scale. More research is needed on oxidation resistance, moisture ingress, thermal cycling, and mechanical fatigue, particularly in outdoor or wearable applications. Different measurement methods, frequency bands, and sample geometries make benchmarking challenging. Standard protocols are necessary.

6. Future developments

It involves producing biochar with controlled porosity and high graphitisation using customised biomass and activation. Charge transfer and interfacial polarisation can be improved by precisely controlling the interface chemistry (functionalization) between biochar and nanofillers. Biochar-nanocomposite foams and buildings can be produced via additive manufacturing (3D printing). Incorporating multifunctionality in smart composites, such as EMI shielding, thermal control, and structural strength. Large-scale manufacturing studies and life-cycle assessment are necessary to move from laboratory to industrial settings. Wider frequency bands should be investigated as new shielding solutions are needed for 5G and 6G.

7. Conclusions

Biochar-based nanocomposites represent a compelling class of sustainable materials for electromagnetic interference shielding, combining porous carbon architectures, low density, and strong compatibility with conductive and magnetic nanofillers. Biochar-carbon black systems achieve ~39 dB in the 1-3 GHz band(Nikolopoulos et al., 2023c), while MXene-modified biochar composites exceed 60 dB with low filler loading(Hu et al., 2024). Fe_3O_4-loaded biochar yields ~40 dB over 2-18 GHz(Sparavigna, 2023), and cashew-shell biochar/carbon-fibre epoxy reaches −48.6 dB at microwave frequencies(Babu et al., 2023). The synergistic effects of biochar and graphene, CNTs, MXenes, and magnetic nanoparticles result in increased conductivity, interfacial polarisation, and absorption-dominated behaviour. To enable widespread application, remaining obstacles, such as the restricted intrinsic conductivity of raw biochar, dispersion homogeneity, and testing standardisation, must be addressed. Nonetheless, developments in interface architecture and scalable processing have established biochar-based composites as a green, high-performance substrate for next-generation EMI shielding applications.

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