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AI-Powered Innovation in Waste-Derived Nanocomposite Electromagnetic Absorbers: Toward A Sustainable Future

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The rapid advancement of wireless communication systems, including 5G/6G networks, autonomous vehicles, radar systems, and dense Internet of Things (IoT) environments, has intensified global concerns regarding electromagnetic interference (EMI) and pollution issues. This swift technological development has surpassed the progress in creating electromagnetic (EM) wave-absorbing materials that are high-performing, lightweight, cost-effective, and environmentally sustainable. Traditional absorbers, typically composed of ferrites, metal powders, carbon black, or layered composites, often encounter challenges such as high density, limited absorption bandwidth, complex synthesis processes, and dependence on nonrenewable resources. As we transition into an era characterized by digital saturation and heightened environmental awareness, the field of materials science must innovate to develop multifunctional EM absorbers that minimize their ecological impacts. Nanocomposites derived from waste materials, in conjunction with artificial intelligence (AI), present a promising solution to this problem.

For instance, a D-fructose-derived porous carbon (DPC) combined with Co_3O_4 nanoparticles demonstrated enhanced microwave absorption, achieving reflection losses between –60 and –63.7 dB, a significant reduction in the frequency of maximum RL (from 16.9 GHz to 9.2 GHz), and effective absorption over a broad coating thickness range of 2.78–4.84 mm, illustrating the potential of biomass-derived carbon composites as sustainable, lightweight, and high-performance EM absorbers [1].

Another study reported a simple liquid–liquid phase separation approach to synthesize polyimide-based porous carbon/cobalt nanoparticle composites (PPC/Co). The resulting coral-like porous structure enhanced impedance matching and microwave attenuation through the synergistic effect of carbon-induced dielectric loss and Co nanoparticle–induced magnetic loss. The optimized composite (PPC/Co-700) achieved a minimum reflection loss of −59.85 dB (30 wt%, 3.42 mm) and an effective absorption bandwidth of 6.24 GHz (30 wt%, 2.78 mm), demonstrating a facile strategy for developing high-performance EM absorbers [2].

Cellulose-based carbon aerogels decorated with FeCo nanoparticles (FeCo@CCA) exhibited enhanced EM wave absorption due to uniform nanoparticle dispersion, porous structure–induced multi-reflection, and synergistic magnetic and dielectric losses, achieving a minimum reflection loss of −49.5 dB and a maximum effective absorption bandwidth of 10.88 GHz [3].

These findings support the feasibility of developing sustainable, lightweight, and efficient EM absorbers based on waste or biomass precursors. When coupled with AI-guided optimization, such materials hold potential for rapid discovery of next-generation absorbers balancing performance and environmental sustainability.

Recent studies have separately demonstrated two key strategies for developing high-performance electromagnetic absorbers: (i) recycling electronic waste to obtain metal or metal-oxide nanoparticles, and (ii) combining biomass-derived porous carbon with magnetic or metallic fillers to achieve strong microwave absorption. While these approaches have been successfully validated individually, the integration of e-waste-derived nanoparticles within biomass-derived carbon matrices remains largely unexplored. This pathway represents a promising potential strategy for creating sustainable, lightweight, and broadband electromagnetic absorbers, but a complete experimental realization of this approach has not yet been reported.

Despite recent advancements, the development of high-performance electromagnetic absorbers from waste materials remains challenging because of the inherent complexities of these systems. The efficacy of these absorbers is contingent upon the nonlinear interactions of various factors, including the composition, microstructure, filler shape, carbonization temperature, defect density, magnetic response, conductivity, and absorber thickness. Traditionally, optimization has depended on slow empirical trial-and-error methods, which are becoming increasingly obsolete. Artificial intelligence (AI), particularly machine learning (ML), is poised to transform the design, prediction, and optimization of functional materials.

Machine learning has demonstrated strong capability in predicting the electromagnetic performance of absorber materials by capturing nonlinear relationships between composition, structure, and reflection-loss behavior. These models not only enable accurate forward prediction but also support inverse design, allowing optimized multilayer or metamaterial absorbers to be identified with significantly reduced computational cost [4, 5].

Integrating artificial intelligence with waste-derived materials enables accelerated design of sustainable electromagnetic absorbers. Physics-informed and explainable machine-learning models, such as adversarial autoencoders, can optimize performance and reveal underlying mechanisms, including dipole polarization, magnetic resonance, and conduction losses [6].

Future research leveraging AI could accelerate the development of such integrated systems.

The field is moving toward autonomous “self-driving” laboratories, where AI-driven models propose materials, robotic systems manage synthesis, and high-throughput measurements iteratively refine predictive models. This closed-loop approach can drastically shorten discovery timelines from years to months and enable the rapid development of ultralight, broadband, thermally stable, and sustainable electromagnetic absorbers from waste, suitable for advanced communication, satellite shielding, aerospace, and wearable electronics [7].

To realize this vision, stronger interdisciplinary collaboration among materials scientists, environmental engineers, AI researchers, sustainability experts, and industry stakeholders is essential.

The establishment of standardized open-access databases, expansion of explainable machine learning frameworks, and integration of life-cycle assessment (LCA) metrics into materials

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optimization models are essential for advancement in this domain. The convergence of AI-driven design with waste valorization represents both a scientific breakthrough and an ethical and environmental imperative that must be addressed. This comprehensive approach offers a promising pathway for developing sustainable, circular, and high-performance electromagnetic absorbers capable of addressing the challenges of the coming decades.

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