International Journal of Nanoelectronics and Materials
IJNeaM
ISSN 1985-5761 | E-ISSN 2232-1535

Exploring bamboo nanocellulose aerogel: a review on electromagnetic absorption in the application of EMI shielding

Tuan Mohamad Farhan Tuan Mohd Marzuki [a], Mohd Syahir Anwar Hamzah [a], Nadirul Hasraf Mat Nayan [b], Huda A Majid [b] *, Noor Azwan Shairi [c], Najib Al-Fadhali [d], and Dian Widi Astuti [e]

[a]*Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Pagoh Higher Education Hub, 84600 Pagoh, Johor, Malaysia*
[b]*Research Centre for Applied Electromagnetic, Institute of Integrated Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, Malaysia*
[c]*Centre for Telecommunication Research and Innovation (CeTRI), Fakulti Teknologi dan Kejuruteraan Elektronik dan Komputer (FTKEK), Universiti Teknikal Malaysia Melaka (UTeM), Melaka, Malaysia*
[d]*Electrical Engineering Technology, Alfred State College of Technology, State University of New York, NY 14802, United States*
[e]*Department of Electrical Engineering, Faculty of Engineering, Universitas Mercu Buana, Indonesia*
∗Corresponding author. Tel.: +6013-702 5675; e-mail: mhuda@uthm.edu.my

Received 09 May 2025, Revised 01 August 2025, Accepted 14 August 2025

ABSTRACT

Bamboo nanocellulose (BNC), a biopolymer derived from renewable biomass, is recognized for its impressive mechanical strength, thermal stability, and biodegradability, making it an excellent choice for high-performance composite materials. Bamboo nanocellulose is transformed into lightweight, porous aerogels by undergoing alkali processing, delignification, and lyophilization, alongside other chemical and mechanical methods. These aerogels are a long-term and versatile framework for incorporating graphene oxide (GO), a material noted for its tunable electrical conductivity and outstanding electromagnetic absorption capabilities. Graphene oxide (GO) improves the aerogel's electrical conductivity and electromagnetic wave absorption. With its tunable reduction state and outstanding conductive capabilities, GO integrates synergistically with bamboo nanocellulose via hydrothermal synthesis and in situ polymerization, resulting in a hierarchical structure that enhances EMI shielding effectiveness. The resulting BNC-GO aerogels have high electrical conductivity, thermal stability, and absorption-dominated electromagnetic shielding. Recent research has highlighted the efficiency of BNC-GO aerogels, with several measuring methodologies and electromagnetic wave absorption testing showing its strong shielding effectiveness over a wide frequency range. These findings emphasize the potential of bamboo nanocellulose as a sustainable matrix for graphene oxide-based composites, paving the way for eco-friendly, next-generation EMI shielding materials.

Keywords: *Electromagnetic shielding, Nanocellulose, Graphene oxide aerogel*

1. INTRODUCTION

The increasing prevalence of electromagnetic interference (EMI) from modern electronic devices and wireless communication systems has generated a critical demand for effective shielding materials. The EMI phenomenon happens when unwanted signals affect electronic devices. This is a significant problem in areas with many electronic devices because it reduces signal quality. Researchers have extensively investigated composite materials that are lightweight, sustainable, and capable of delivering high shielding effectiveness, particularly for applications requiring flexibility and adaptability across varying electromagnetic frequencies [1, 2]. Traditional metal and metallic composites' high density, low mechanical flexibility, corrosiveness, and time-consuming and costly manufacturing expenses limit their use as EMI shielding materials. Thus, composites with carbon, polymeric, and ceramic matrices are currently the primary focus of modern EMI shielding materials [3]. Among these materials, aerogels—highly porous, ultra-lightweight structures—have garnered significant attention due to their unique structural and functional properties. Due to their structure, aerogels are good candidates for EMI shielding materials. Graphene oxide (GO) aerogels demonstrate excellent electrical conductivity and high surface area, enabling efficient EMI absorption and minimal reflection, which is essential in mitigating secondary EMI issues in sensitive electronics [4]. Combined with natural polymers like nanocellulose derived from bamboo, these aerogels form efficient composites in EMI shielding that are eco-friendly and renewable. Bamboo nanocellulose (BNC) contributes to the composite's mechanical robustness and flexibility, making it ideal for applications requiring structural stability and functional adaptability in various EMI conditions [5].

This review paper examines recent advancements in developing and applying bamboo nanocellulose and graphene oxide aerogels for EMI shielding. It emphasizes the fabrication methods, structural properties, and mechanisms by which these composites achieve high shielding effectiveness, focusing on integrating reduced graphene oxide to enhance conductivity and electromagnetic absorption. Additionally, this review addresses measurement approaches in structured, highlighting key materials, frequency ranges, absorption performance, and offering insights into their efficacy and potential for standardization across the field. By synthesizing current research, this review outlines the performance potential of these sustainable, high-performance composites. It identifies knowledge gaps and future directions for optimizing bamboo nanocellulose and graphene oxide aerogels in EMI shielding applications. However, it highlights nanocellulose's critical roles in creating high-performance EMI shields with various forms, as shown in Figure 1.

2. FUNDAMENTALS OF BAMBOO NANOCELLULOSE-GRAPHENE OXIDE (BNC-GO) AEROGEL

Bamboo nanocellulose-graphene oxide (BNC-GO) aerogel is a lightweight, porous composite material that integrates bamboo-derived nanocellulose with graphene oxide (GO). This innovative material combines bamboo nanocellulose's structural integrity and environmental sustainability with graphene oxide's exceptional electrical conductivity and electromagnetic absorption capabilities. The aerogel's hierarchical structure, created through freeze-drying and chemical cross-linking methods, enhances its functionality by providing a high surface area, interconnected pores, and tunable electrical properties. BNC-GO aerogels are particularly significant as they address the growing need for eco-friendly materials in advanced applications, such as EMI shielding, thermal insulation, and flexible electronics.

By leveraging the renewable and biodegradable nature of bamboo nanocellulose and the multifunctionality of GO, BNC-GO aerogels represent a sustainable alternative to traditional synthetic materials, offering high performance while reducing environmental impact.

2.1. Bamboo Nanocellulose (BNC)

Bamboo nanocellulose exhibits several molecular and structural properties that render highly suitable for electromagnetic interference (EMI) shielding applications [6]. Firstly, the high aspect ratio and extensive surface area of bamboo nanocellulose fibers significantly enhance their interaction with electromagnetic waves, facilitating effective absorption and dissipation of these waves [7]. Additionally, bamboo nanocellulose's hierarchical and porous structure promotes multiple reflections and scattering of electromagnetic waves, thereby improving the overall shielding effectiveness [8]. The material's lightweight and flexible nature further contributes to its suitability for applications where weight and flexibility are critical, such as in wearable electronics. Moreover, as a natural material, bamboo nanocellulose is biodegradable and environmentally friendly, offering a sustainable alternative to traditional EMI shielding materials [9].

2.2. Properties of Nanocellulose

Plant cell walls contain cellulose, which may be easily extracted from natural resources using various physicochemical techniques. Cellulose, which was once used to make paper and furniture, is now widely used in multiple commercial applications. It has recently attracted interest as an environmentally acceptable and sustainable energy source for producing conductive polymeric materials [10]. Cellulose significantly improves mechanical qualities, EM wave attenuation, and dielectric permittivity when added to polymer composites [11].

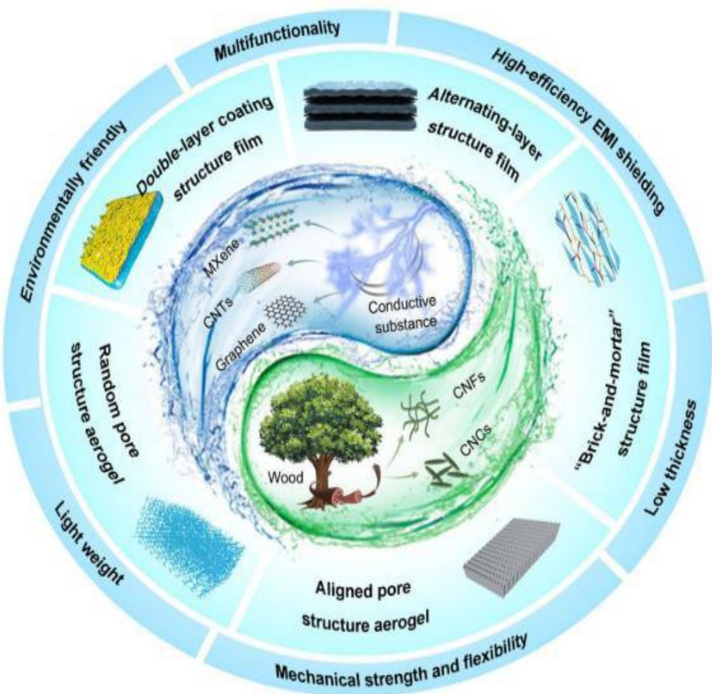

Figure 1. Schematic illustration of the nanocellulose-assisted preparation of composites for EMI shielding application [12]

Cellulose is a standard natural material given its abundance, low density, degradability, potential for sustainable energy, strong mechanical strength, and low abrasive qualities [13]. It is a long-chain polymer with β-D glucose units connected by glycosidic bonds [14]. Cellulose is produced from membrane complexes, also known as terminal complexes (TCs) [15] form fibrous structures called microfibrils that range in width from 2 to 20 nm, depending on their biological origin. These structures aggregate regularly along the chain direction due to intermolecular hydrogen bonds and hydrophobic interactions [16].

Synthetic cellulose, derived from bacterial nanocellulose (BNC), exists in nanofibrils, nanocrystals, and nanoyarns. Cellulose nanocrystals (CNCs), resembling basic nanofibers, typically range from 50 to 200 nm or more in size. Additionally, nanocellulose can be broadly categorized into three main types: (i) cellulose nanocrystals, also known as cellulose nanowhiskers, which are made by acid hydrolysis of natural cellulose and then mechanically agitating the leftovers in water to create stiff, rod-like nanocrystals [17], (ii) Microfibrillated celluloses (MFCs) are made by mechanically breaking down cellulose/water slurries, either with or without energy-diminishing help from cellulase treatment or partial carboxymethylation [18], and (iii) cellulose nanofibrils produced by physically dissolving the oxidized celluloses in water after they have been oxidized using 2,2,6,6-tetramethylpiperidine-1-oxy radical (TEMPO) [19].

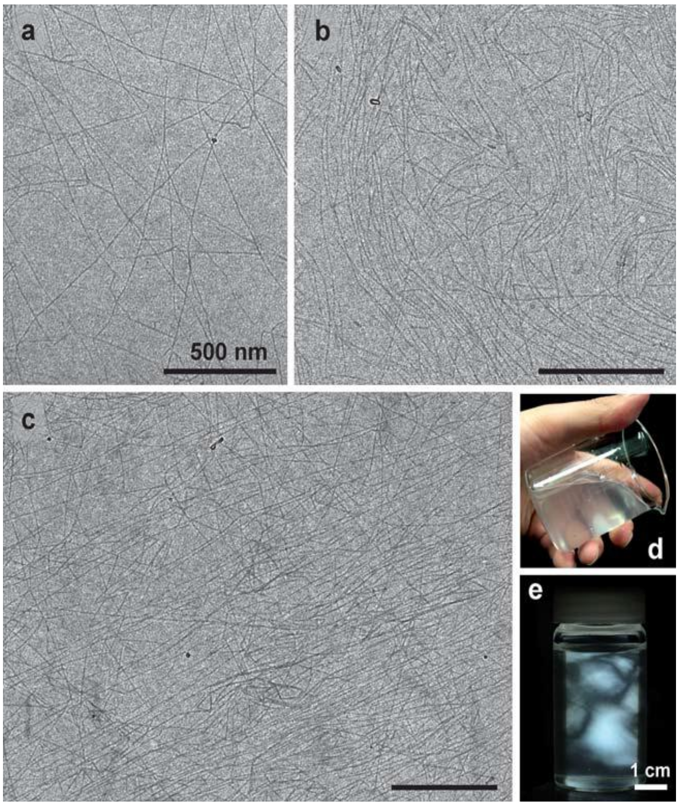

Figure 2. TEM images (a-c) dried dispersion of TEMPO-oxidized hardwood cellulose obtained by diffraction-contrast in bright-field mode with low-dose exposure, (d) insets depict a typical dispersion, and (e) between cross polarizations [19, 20].

2.3. Nanocellulose in Aerogels Application

Nanocellulose (NC) is a promising material for aerogel applications due to its unique mechanical and structural properties. NC aerogels' remarkable lightweight nature and high porosity (over 90%) make them ideal for various applications, including medical devices and sensors. NC's fibrous nanostructure aids in developing linked three-dimensional networks that preserve low density while enhancing mechanical strength. Furthermore, BNC's abundance of hydroxyl groups permits various chemical alterations, which enable the aerogel's characteristics to be tailored to specific application needs. These aerogels are further positioned as sustainable substitutes for conventional synthetic materials due to NC's biocompatibility and biodegradability, opening the door for creative material science and engineering [21].

2.4. Role of Graphene Oxide (GO) in BNC Aerogels

Graphene oxide (GO) enhances the performance of bamboo nanocellulose (BNC) aerogels by improving their microwave absorption capabilities. When added, GO forms a lightweight, three-dimensional porous structure that aids in efficient microwave dissipation. The study indicates that GO concentration is key in determining the resulting composite aerogels' electromagnetic characteristics and absorption efficiency. Specifically, the optimal microwave dissipation capability was achieved at a GO concentration of 1.5 mg/mL, where the minimum reflection loss reached –50.42 dB at a thickness of 2.47 mm. This indicates that the addition of GO not only improves the mechanical strength and stability of BNC aerogels but also broadens their adequate absorption bandwidth, making them suitable for applications in mitigating electromagnetic radiation and enhancing material performance in various technological fields [22].

3. METHODS FOR FABRICATING BNC-GO AEROGELS

Different fabrication techniques affect the aerogel's structure and performance. The most common methods are hydrothermal synthesis, chemical crosslinking, and freeze-drying. These methods impact the aerogel's structure and performance, with comparisons highlighting their effectiveness in optimizing properties for applications such as EMI shielding.

3.1. Techniques for Integrating Nanocellulose and GO

The hydrothermal synthesis method efficiently produces bamboo nanocellulose-graphene oxide (BNC-GO) aerogels by combining GO and nanocellulose in a solution—often with a reducing agent such as ascorbic acid—and treating the mixture under high temperature and pressure in a Teflon-lined autoclave. The conditions promote the reduction of GO, restoring its conductive sp^2 carbon network, referring to the arrangement of carbon atoms with trigonal planar geometry and delocalized π-electrons, and enhance its interaction with nanocellulose to form a porous, interconnected structure [23].

This method improves the uniform distribution of GO and prevents agglomeration, resulting in aerogels with high mechanical strength, excellent electrical conductivity, and significant electromagnetic interference (EMI) shielding performance. Hydrothermal synthesis is also eco-friendly, avoiding hazardous chemicals, and allows precise control of aerogel properties by adjusting reaction conditions [23, 24], as depicted in Figure 3.

Next, the **chemical crosslinking** is commonly used to fabricate bamboo nanocellulose-graphene oxide (BNC-GO) aerogels by creating covalent bonds between nanocellulose and graphene oxide (GO). Using crosslinking agents like epichlorohydrin (ECH), hydroxyl groups in nanocellulose react with GO under alkaline conditions to form a stable, three-dimensional network. This process enhances the mechanical strength, stability, and uniform dispersion of GO within the cellulose matrix [22].

The crosslinked structure improves the aerogel's electrical conductivity and electromagnetic wave absorption, making it ideal for EMI shielding applications. It stabilizes the porous framework, contributing to lightweight and thermally insulating properties. This technique is straightforward, scalable, and efficient; nevertheless, reaction conditions must be optimized to balance mechanical and functional performance.

Other than that, the **freeze-drying** method is commonly used to fabricate bamboo nanocellulose-graphene oxide (BNC-GO) aerogels, creating lightweight, porous structures with high surface area. In this process, the BNC-GO suspension is frozen at low temperatures (–50°C to –80°C) and then placed in a vacuum, where the ice sublimates, leaving behind a porous aerogel [25, 26].

This technique preserves the aerogel's interconnected pore network, which is essential for applications like electromagnetic interference (EMI) shielding and adsorption. Adjusting freezing conditions, such as freezing rate and direction, allows control over porosity and density, improving mechanical strength and thermal insulation properties. Although freeze-drying produces high-performance aerogels with minimal shrinkage, the method can be time-intensive and energy-consuming, posing challenges for large-scale production [26, 27].

3.2. Comparison of Methods for BNC-GO Integration

The comparison of hydrothermal synthesis, chemical crosslinking, and freeze-drying methods for bamboo nanocellulose-graphene oxide (BNC-GO) aerogel fabrication highlights their unique strengths and limitations, offering valuable guidance for selecting the appropriate technique based on specific application requirements.

Scalability: Chemical crosslinking demonstrates greater scalability among the three methods due to its relatively simple process and lower equipment requirements. In contrast, hydrothermal synthesis and freeze-drying methods involve high-temperature and pressure conditions or energy-intensive vacuum operations, limiting their feasibility for large-scale production.

Eco-Friendliness: Hydrothermal synthesis and freeze-drying avoid excessive use of chemical reagents, but they are less eco-friendly due to their high energy consumption. Chemical crosslinking, despite being more scalable, may pose environmental concerns due to the use of crosslinking agents, which could introduce chemical residues.

Customization: Hydrothermal synthesis offers superior control over the reduction state of graphene oxide (GO) and facilitates the creation of a uniform, conductive

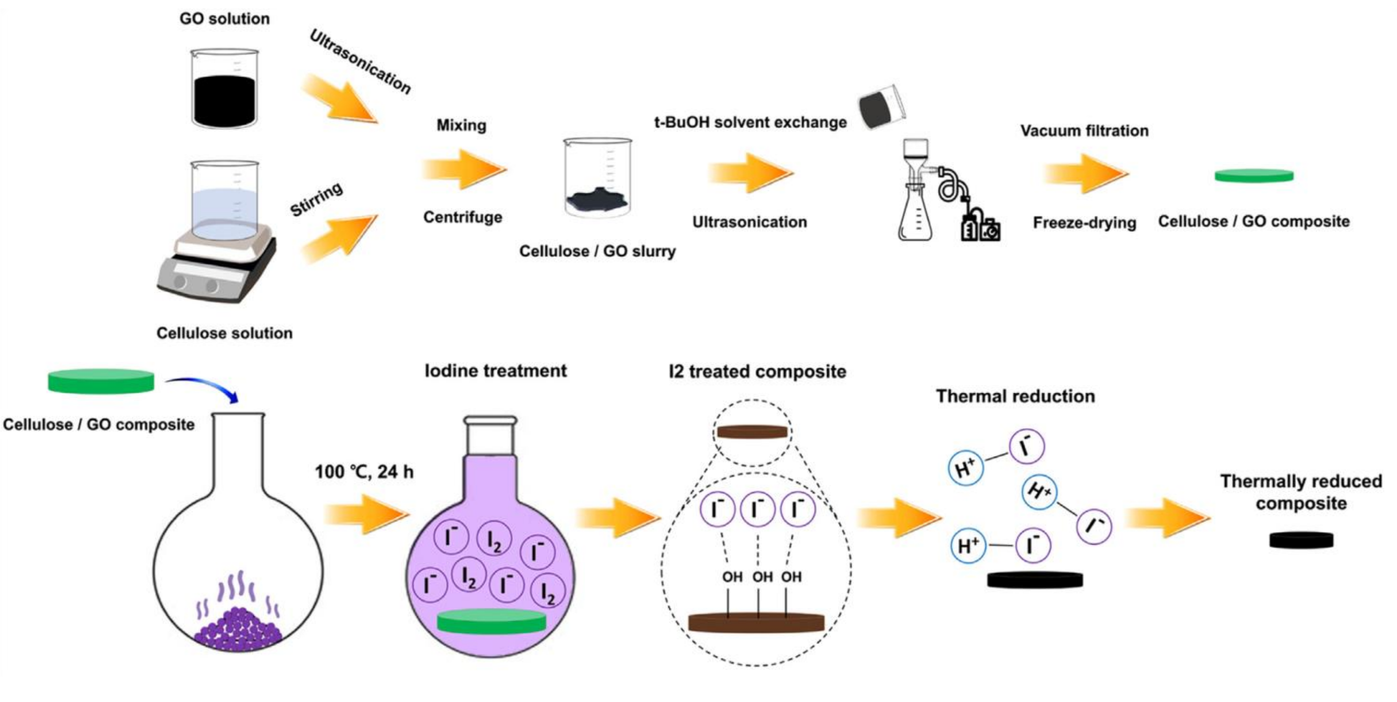

Figure 3. Schematic illustration of composite fabrication [23]

network within the aerogel. Chemical crosslinking is particularly effective in enhancing structural stability, making it suitable for applications requiring high mechanical performance. On the other hand, freeze-drying excels at preserving the porous structure, providing high surface area and lightweight properties.

Cost and Time: Freeze-drying is the most time-intensive and energy-demanding method, which could hinder its practical application on an industrial scale. Chemical crosslinking is faster and more cost-effective, but additional steps may be required to optimize the reaction conditions. While precise, hydrothermal synthesis involves significant energy input and specialized equipment, impacting its cost-effectiveness.

Overall, the choice of method depends on the desired balance between scalability, environmental impact, and specific performance requirements, with each method offering distinct advantages for the fabrication of high-performance BNC-GO aerogels. As in Table 1, customization refers to controlling material structure by adjusting reaction conditions.

4. CHARACTERIZATION OF BNC-GO AEROGELS

The structural and morphological properties of bamboo nanocellulose-graphene oxide (BNC-GO) aerogels are crucial for their functionality, particularly in electromagnetic interference (EMI) shielding and thermal insulation applications. These aerogels feature a hierarchical, three-dimensional porous network that combines the lightweight nature and high surface area of nanocellulose with the electrical conductivity and electromagnetic wave absorption capabilities of graphene oxide (GO). The uniform dispersion of GO sheets within the nanocellulose matrix is achieved through controlled fabrication processes such as freeze-drying, hydrothermal synthesis, and chemical crosslinking, which prevent GO aggregation and enhance composite performance [28].

Techniques such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM) reveal the intricate interconnected pore structures and the well-distributed GO sheets within the matrix, contributing to the material's mechanical stability and porosity. These structural features are further confirmed by Fourier Transform Infrared (FTIR) spectroscopy and X-ray diffraction (XRD), which demonstrate strong interactions between nanocellulose and GO, as well as increased crystallinity and alignment [29].

The tailored pore structure and high degree of uniformity facilitate multiple internal reflections and scattering of electromagnetic waves, enhancing absorption efficiency. This structural design significantly improves the aerogel's mechanical resilience, electrical conductivity, and thermal stability, making BNC-GO aerogels highly suitable for advanced multifunctional applications in sustainable engineering [30]. Recent studies summarize key structural and morphological findings on bamboo-derived nanocellulose and graphene oxide aerogels, highlighting processing transformations, with results and citations detailed in Table 2.

Key studies provide valuable insights into the structural and functional properties of bamboo nanocellulose-graphene oxide (BNC-GO) aerogels. Zhao *et al.* used SEM and Raman spectroscopy to reveal the aerogel's interconnected pores and uniform GO dispersion, which improve surface area and EMI shielding performance [28]. They also highlighted the partial reduction of GO, restoring its conductive sp^2 carbon networks. Fan *et al.* employed TEM and TGA to confirm the even distribution of GO within the nanocellulose matrix, enhancing conductivity and structural stability [29]. Their findings also showed improved thermal resistance, making the aerogels suitable for high-temperature applications. Xu *et al.* used XRD and FTIR to analyze crystallinity and bonding, showing more substantial nanocellulose alignment and better thermal properties [30]. They also highlighted improved mechanical strength due to strong interfacial bonding and GO dispersion. Together, these studies demonstrate the role of advanced characterization techniques in optimizing BNC-GO aerogels for applications like EMI shielding and thermal management.

Figure 4 shows the XRD analysis of different bamboo-derived materials. The peaks at 16.28° and 22.38° of intensity confirm the presence of cellulose structure, while the 26.88° peak corresponds to amorphous silicon dioxide, SiO_2 [29].

Table 1. Comparison of methods for integrating bamboo nanocellulose and GO

Method	Process	Advantages	Limitations
Hydrothermal Synthesis	GO and nanocellulose are mixed with a reducing agent and heated at high temperatures and pressure in an autoclave.	• Enhances GO reduction and conductivity • Promotes strong interactions between components • Facilitates uniform GO dispersion and porous network formation	• Requires high energy input for temperature and pressure • Limited scalability due to equipment constraints
Chemical Crosslinking	Covalent bonds are formed between nanocellulose and GO using crosslinkers like epichlorohydrin under controlled conditions.	• Improves mechanical stability • Provides consistent dispersion of GO in the matrix • Customizable for specific applications	• Use of crosslinking agents may limit eco-friendliness • Optimization of reaction conditions is required for the desired performance
Freeze-Drying	The BNC-GO suspension is frozen and sublimated under vacuum, preserving the porous structure.	• Produces lightweight, highly porous aerogels • Maintains structural integrity • Effective for applications needing high surface area	• Time-intensive process • High energy consumption • May require optimization to reduce production cost

Table 2. Recent studies of various characterization techniques used to analyze the BNC-GO aerogels

Reference	Characterization Technique	Purpose	Key Findings
Zhao *et al.*, 2021	Scanning Electron Microscopy (SEM)	Observes surface morphology and pore structure	Revealed hierarchical, interconnected pores with uniform dispersion of GO sheets are critical for mechanical stability and high surface area.
	Raman Spectroscopy	Assesses the reduction state of GO	Demonstrated partial reduction of GO, restoring sp^2 networks for better conductivity, essential for EMI shielding applications.
	Electrical Conductivity Tests	Evaluates conductivity for EMI shielding applications	Confirmed a significant increase in conductivity with GO addition, achieving absorption-dominated EMI shielding performance.
Fan *et al.*, 2017	Transmission Electron Microscopy (TEM)	Analyzes nanostructure and GO distribution	Confirmed homogeneous distribution of GO in the nanocellulose matrix, improving conductivity and structural integrity.
	Thermogravimetric Analysis (TGA)	Measures thermal stability	Displayed improved thermal resistance of BNC-GO aerogels compared to pure nanocellulose, attributed to GO inclusion.
Xu *et al.*, 2021	Fourier Transform Infrared (FTIR) Spectroscopy	Identifies chemical interactions between components	Indicated successful integration and bonding between nanocellulose and GO, with characteristic peaks confirming functionalization.
	X-ray Diffraction (XRD)	Assesses the reduction state of GO and evaluates the crystallinity and alignment of components [30]	Show enhanced crystallinity and alignment of nanocellulose, contributing to improved thermal stability and structural properties.
	Mechanical Testing	Tests tensile strength and resilience	Highlighted enhanced mechanical robustness due to the strong interfacial bonding and uniform GO dispersion.

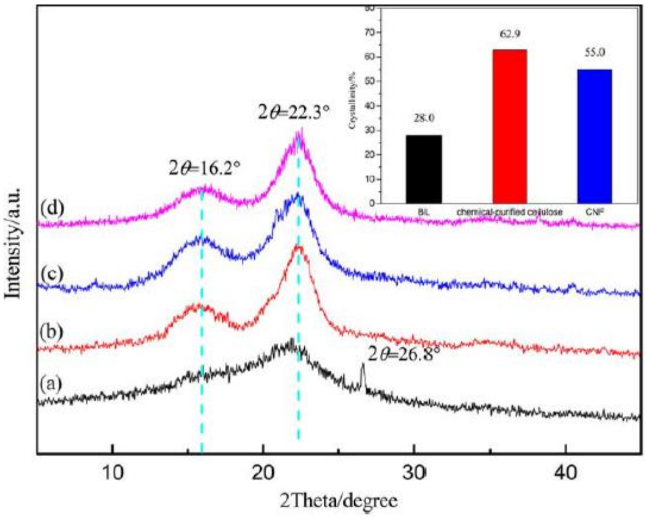

Figure 4. XRD patterns of (a) bamboo leaf, (b) chemical-purified cellulose, (c) CNF, and (d) the silanized modified CNF aerogel [29]

4.1. Thermal and Electrical Characterization

Bamboo CNC-GO aerogels' thermal and electrical properties are critical parameters that directly influence their suitability and performance across various application domains, particularly in thermal insulation, electromagnetic shielding, and advanced electronics. The following sections outline the principal findings and factors impacting these characteristics.

4.1.1. Thermal Conductivity

CNC-GO aerogels generally exhibit low thermal conductivity due to their porous architecture. Key factors affecting this property include the density of the aerogel network, the degree of GO reduction, and thermal interface resistance between the aerogel components. Yin *et al.* highlight that the hierarchical structure within these materials introduces multiple thermal interfaces, impeding phonon transport and enhancing thermal insulation. Such structures allow for controlled heat dissipation, a valuable trait for high-performance thermal insulation and management materials [1, 31].

4.1.2. Thermal Stability

Thermal stability is a critical parameter for CNC-GO aerogels, especially in applications where materials are exposed to variable temperatures. Studies indicate that these composites maintain stability up to approximately 200°C, beyond which cellulose degradation may begin [4]. Compared to pure cellulose, CNC-GO aerogels demonstrate enhanced thermal resistance due to GO's stabilizing influence, which allows for reversible thermal expansion and contraction while preserving structural integrity under thermal cycling. When reduced, CNC-GO aerogels can exhibit Joule heating, which converts electrical energy into heat as current passes through a conductive material. As demonstrated in studies by Yin *et al.*, these aerogels respond rapidly to applied voltage, providing uniform heat distribution across the material and maintaining stable heating performance across multiple cycles [1].

4.1.3. Electrical Conductivity

The graphene oxide (GO) content and the reduction process significantly influence the electrical conductivity of CNC-GO aerogels. Cao *et al.* reported that post-reduction treatments restore the sp^2 carbon networks within GO, establishing conductive pathways that enhance electron transport across the aerogel structure [2]. This improvement is reflected in the increased conductivity values, which can reach several hundred S/m, indicate a range of electrical conductivity when optimally processed. Additionally, incorporating conductive additives further elevates the conductivity, aligning with findings that show the importance of conductive networks in boosting EMI shielding effectiveness [5].

4.2. Synergistic Effects of NC and GO in Improving Mechanical and Functional Performance

Integrating nanocellulose (NC) and graphene oxide (GO) in aerogels significantly improves mechanical and functional properties due to their synergistic interactions. Nanocellulose, known for its high tensile strength, flexibility, and biodegradability, provides structural reinforcement, while GO contributes to electrical conductivity and electromagnetic absorption. The strong interfacial bonding between NC and GO enhances load transfer, preventing structural collapse and improving mechanical resilience under stress [32, 33].

Additionally, the porous architecture formed by nanocellulose facilitates uniform GO dispersion, which is crucial for maintaining conductivity and shielding effectiveness. Studies have also demonstrated that GO nanosheets create a continuous conductive network within the nanocellulose matrix, enabling superior electromagnetic interference (EMI) shielding while preserving lightweight and flexible properties [34].

The combination of NC and GO further enhances thermal stability, as GO reduces cellulose degradation by forming protective layers that resist high-temperature conditions [32, 35]. These synergistic effects make NC-GO aerogels highly suitable for multifunctional applications, particularly in EMI shielding, flexible electronics, and thermal management.

4.3. Electromagnetic Absorption and Shielding Performance

Electromagnetic absorption and shielding performance are critical metrics for evaluating the effectiveness of bamboo CNC-GO aerogels in minimizing electromagnetic interference (EMI). The ability of these aerogels to absorb and attenuate electromagnetic waves relies heavily on the composition, structure, and conductive pathways formed by the nanocellulose and graphene oxide components. Recent studies underline the importance of standardized testing methods to assess these materials' shielding efficiency and absorption characteristics, ensuring reliable performance in applications where EMI mitigation is essential.

4.4. Electromagnetic Wave Absorption Testing

Electromagnetic wave absorption testing is crucial for evaluating the performance of nanocellulose-graphene oxide (GO) composites in applications related to electromagnetic interference (EMI) shielding. The testing typically involves measuring the aerogel samples' reflection loss and absorption characteristics across a range of frequencies, often utilizing a vector network analyzer. The basic principles and testing methods of electromagnetic shielding and absorption for cellulose-based composites have been discussed in [36]. Recent studies have demonstrated that the incorporation of GO into bacterial nanocellulose (BNC) aerogels significantly enhances their microwave absorption capabilities [31]. For instance, optimal reflection loss values were achieved at specific GO concentrations, indicating a strong relationship between the filler content and the electromagnetic properties of the composite. The results show that the structural integrity and porosity of the aerogels play a pivotal role in their ability to dissipate electromagnetic waves effectively. Furthermore, the synergistic effects of BNC contribute to improved conductivity and dielectric properties, which are essential for achieving high-performance EMI shielding. These findings underscore the potential of BNC-GO composites in developing advanced materials for electronic applications requiring efficient electromagnetic wave absorption.

4.5. Relevance of BNC-GO Aerogels for EMI Shielding Applications

The integration of bamboo nanocellulose (BNC) with graphene oxide (GO) into aerogel composites has emerged as a promising strategy for electromagnetic interference (EMI) shielding applications. According to Wang *et al.*, Anisotropic carbon aerogels fabricated from cellulose nanofiber/graphene oxide composites demonstrate

Table 3. Presents key insights into electromagnetic wave absorption testing, comparing different materials and their absorption efficiency

References	Material Composition	Testing Frequency Range (GHz)	Adequate Absorption Bandwidth (GHz)	Testing Type
Yan *et al.*, 2024	CNF/Ti_3C_2Tx/PLA Composite	2–18 GHz	5.6 GHz	Vector Network Analyzer (VNA)
Amini *et al.*, 2025	3D-Printed Cellulosic Constructs with PEDOT	Variable, optimized at 8-12 GHz	Wideband Absorption (Over 6 GHz)	Free-space Measurement
Cao *et al.*, 2015	Ultrathin Graphene-Based Composites	Broadband, optimized at 2–18 GHz	Covers the entire 2–18 GHz range	Waveguide Measurement
Gogoi & Borah, 2017	Biopolymer-Based EMI Shielding	1–10 GHz	Optimized for specific applications	Coaxial Line Method
Xu *et al.*, 2024	Fe_3O_4/CMC/GO Composite	2–18 GHz	6.10–8.52 GHz	Resonant Cavity Method

remarkable EMI shielding effectiveness, achieving an absolute shielding effectiveness of 23,628 dB $cm^2\ g^1$ with an ultralow density of 3 mg cm^3 [37]. The layered interconnected structure, obtained through bidirectional freezing and carbonization, provides excellent mechanical properties with 97% compression recovery after 300 cycles and creates an effective network for electromagnetic wave attenuation. The effectiveness of these composites is further supported by Yuan *et al.* [38], who demonstrated that cellulose nanofiber-based composites with graphene can achieve superior EMI shielding effectiveness of 50.5 dB in the X-band frequency range, with an impressive absorption coefficient of 0.87 and absorption rate of 98.7%. This high absorption-dominated shielding mechanism is attributed to forming highly efficient asymmetric conductive network structures within the cellulose nanofiber's matrix [38].

Additionally, Zhang *et al.* reported that the combination of nanocellulose-derived carbon fibers with graphene layers in aerogel structures can achieve an adequate absorption bandwidth of 6.16 GHz and a minimum reflection loss of −70.44 dB, even at a low filler loading of 3 wt% [39]. These remarkable performances demonstrate that BNC-GO aerogels offer exceptional EMI shielding capabilities and present a sustainable and lightweight solution for advanced electronic applications, making them particularly attractive for next-generation portable and wearable devices where performance and weight considerations are crucial.

4.6. Comparative Analysis with Conventional Materials

Conventional EMI shielding materials, such as metals like copper and aluminum, typically offer high shielding effectiveness (SE > 50–100 dB) due to their excellent electrical conductivity and reflectivity. However, their high density, rigid structure, and susceptibility to corrosion limit their use in flexible and lightweight electronic applications [9, 40].

In comparison, bamboo nanocellulose–graphene oxide (BNC–GO) aerogels demonstrate sound absorption values in the range of approximately 20–60 dB [41], depending on GO content, aerogel structure, and fabrication methods, while maintaining ultralight densities (often below 0.1 g/cm^3) and excellent mechanical flexibility [42]. The porous architecture of these aerogels promotes absorption-dominated shielding mechanisms through multiple internal reflections and dielectric losses, which contrast with metals that primarily rely on reflection.

Compared with commercial polymer-based composites—such as carbon-fiber/polymer or graphene/polymer composites—BNC-GO aerogels offer a renewable and biodegradable alternative. Although some polymer nanocomposites achieve higher SE (> 70–90 dB), these typically require high filler loading (e.g., > 10 wt%), leading to increased cost and reduced material flexibility [43]. Overall, BNC–GO aerogels offer a compelling compromise between shielding performance, ultralight weight, sustainability, and flexibility, making them competitive candidates for next-generation EMI shielding materials.

4.7. Electromagnetic Shielding Performance Assessment

The electromagnetic interference (EMI) shielding effectiveness of nanocellulose-based materials demonstrates significant variation across different architectural designs and material compositions, with values ranging from 22.6 dB to 85 dB across recent studies. Li *et al.* achieved the highest EMI shielding effectiveness of 84–85 dB using meter-scale MXene/graphene oxide@monstera nanocellulose core-shell nanofiber textiles, demonstrating unprecedented ultra-broadband performance covering both gigahertz (8.2–26.5 GHz) and terahertz (0.3–1.5 THz) frequency ranges at a thickness of only 185 μm [44].

In comparison, Wang *et al.* reported an EMI SE of 37.59 dB in the X-band using bamboo cellulose nanofiber (BCNF)/silver nanoparticles multilayer films combined with reduced graphene oxide/multi-walled carbon nanotubes, achieving a superior thickness-normalized shielding effectiveness (SE/d) of 729 dB mm^{-1} [45]. Zhang *et al.* demonstrated exceptional performance in carbon aerogel systems derived from cellulose nanofiber/reduced graphene oxide-glucose composites, achieving 67.5 dB EMI SE with an absorption-dominant mechanism showing 97.5% absorption loss ratio [46].

Meanwhile, traditional approaches such as those employed by Chen *et al.*, using nickel/reduced graphene oxide/cellulose nanofiber composite papers, yielded more modest results of 22.6 dB [47], highlighting the significant performance enhancement achieved through advanced architectural designs. The electrical conductivity values also vary considerably, from 99 S m^{-1} in Pickering emulsion-based systems Wang *et al.*, to an exceptional 6.4×10^3 S m^{-1} in core-shell nanofiber textiles, indicating that architectural optimization plays a crucial role in achieving superior electromagnetic shielding performance [48]. Table 4 depicts the comparative performance analysis of nanocellulose-based EMI shielding materials.

4.8. Critical Assessment

Despite the remarkable progress demonstrated in nanocellulose-based EMI shielding materials, several critical research gaps persist that limit the widespread adoption and optimization of these sustainable alternatives. The most significant challenge lies in the lack of standardized measurement protocols and reporting standards, as evidenced by the inconsistent frequency ranges tested across studies, varying thickness normalization methods, and different approaches to characterizing absorption versus reflection mechanisms [49, 50]. While Li *et al.* demonstrated ultra-broadband performance across gigahertz and terahertz frequencies, most studies focus exclusively on X-band measurements, limiting comparative analysis and practical applicability

Table 4. Comparative performance metrics of nanocellulose-based EMI shielding materials

References	Material System	EMI SE (dB)	Frequency Range (GHz)	Conductivity (S/m)
Li *et al.*, 2025	MXene/GO@MC core-shell nanofiber	84–85	8.2–26.5 GHz, 0.3–1.5 THz	6.4×10^3
Wang *et al.*, 2025	BCNF/AgNPs + rGO/MWCNTs multilayer	37.59	X-band	High
Zhang *et al.*, 2024	CNF/rGO-glucose carbon aerogel	67.5	X-band	-
Wang *et al.*, 2021	CNF/RGO/NBR Pickering emulsion	25.81	X-band	99
Chen *et al.*, 2020	Ni/RGO/CNF composite paper	22.6	-	1,664

across diverse electromagnetic environments [44]. Long-term durability and environmental stability represent another critical gap, with limited studies addressing the performance degradation under cyclic loading, temperature variations, humidity exposure, and chemical environments that these materials would encounter in real-world applications [44].

Wang *et al.* provided some insight into cyclic performance, showing only a 2.51% decrease in EMI shielding efficacy after 5000 cycles, but comprehensive accelerated aging studies and environmental stress testing remain largely unexplored [48]. The scalability challenge is particularly pronounced, as demonstrated by the contrast between Li *et al.*'s meter-scale fabrication achievement and the predominantly laboratory-scale demonstrations in other studies, indicating a significant gap between material innovation and industrial manufacturing readiness [44]. Furthermore, the mechanistic understanding of structure-property relationships remains incomplete, with insufficient theoretical modeling and predictive capabilities to guide rational material design. Hassan *et al.* identified the need for a comprehensive understanding of electromagnetic absorption mechanisms, while the correlation between nanocellulose crystallinity, interfacial interactions, and electromagnetic properties requires systematic investigations [49]. Additionally, the integration of multifunctional properties, as demonstrated by Li *et al.* with simultaneous EMI shielding, infrared stealth, Joule heating, and stress-sensing capabilities, presents optimization challenges that require multi-objective design strategies and trade-off analysis between competing functionalities [44]. Table 5 is constructed with an approach to the limitations of these technologies in standard practices in high-quality review papers.

5. CHALLENGES AND FUTURE DIRECTION

Despite significant advancements in bamboo nanocellulose-graphene oxide (BNC-GO) aerogels for electromagnetic interference (EMI) shielding applications, several challenges must be addressed to enhance their performance and scalability. One major limitation is the scalability and cost-effectiveness of the synthesis process. Methods such as hydrothermal synthesis, chemical crosslinking, and freeze-drying require precise control over reaction conditions, which increases production costs and limits large-scale manufacturing potential [51]. Additionally, achieving uniform dispersion of graphene oxide (GO) within the nanocellulose matrix remains a challenge, as GO tends to aggregate, reducing its conductive pathways and shielding efficiency [29]. Another concern is long-term stability and durability, particularly under extreme environmental conditions such as high humidity and temperature fluctuations, which can degrade the aerogel structure and alter its EMI shielding properties over time [34].

Future research should optimize fabrication techniques to enhance these aerogels' mechanical robustness and

Table 5. Technological challenges in standard practice in high-quality review papers

Gap Category	Specific Gaps Identified	Research Priority
Standardization	• Inconsistent EMI measurement protocols • Varying frequency ranges tested • Different thickness normalization methods	High
Mechanistic Understanding	• Limited structure-property correlations • Insufficient absorption mechanism studies • Missing theoretical modeling	High
Durability & Stability	• Long-term performance under environmental stress • Cyclic loading effects • Chemical stability assessments	High
Scalability	• Industrial-scale production methods • Cost-effectiveness analysis • Quality control in large-scale manufacturing	Medium
Multifunctionality Integration	• Trade-offs between different properties • Optimization strategies for multi-purpose materials • Integration with electronic systems	Medium

conductivity while ensuring eco-friendly and cost-effective production. Additionally, exploring multifunctional properties, such as thermal management and self-healing capabilities, could expand the applications of BNC-GO aerogels beyond EMI shielding, making them suitable for use in flexible electronics, aerospace, and next-generation wearable devices. The development of green reduction methods for GO and the integration of other conductive nanomaterials may further enhance the performance of these aerogels, paving the way for sustainable and high-performance EMI shielding solutions in the future. In addition to modifying the polymer's qualities, new materials must be created and investigated to meet the demand [52].

6. CONCLUSION

Bamboo nanocellulose-graphene oxide (BNC-GO) aerogels have emerged as promising sustainable materials for electromagnetic interference (EMI) shielding. These aerogels achieve high porosity, thermal stability, and excellent shielding effectiveness by combining nanocellulose's lightweight, biodegradable structure with graphene oxide's conductivity and electromagnetic absorption properties (GO). Fabrication methods such as hydrothermal synthesis, chemical crosslinking, and freeze-drying have successfully enhanced their structural integrity and performance. Characterization techniques, including SEM, TEM, FTIR, and XRD, confirm their strong mechanical properties and optimized dielectric behavior. Despite their potential, challenges remain in scalability, cost-efficiency, and long-term stability, which require further improvements. Future research should focus on large-scale production, structural durability, and multifunctional applications, such as thermal management and flexible electronics. Overall, BNC-GO aerogels are a lightweight, eco-friendly solution for EMI shielding. They have potential uses in electronics and industry but need further improvements for large-scale production.

ACKNOWLEDGMENTS

This research was supported by the Ministry of Higher Education (MoHE) Malaysia through the Fundamental Research Grant Scheme (FRGS/1/2023/TK07/UTHM/03/2).

REFERENCES

[1] Y. Yin, Q. He, H. Hu, M. Shen, Z. Wu, and M. Shi, “MXene based aerogel composite with thermal camouflage and electromagnetic wave absorption performance,” *Journal of Alloys and Compounds*, vol. 971, p. 172482, 2024, doi: 10.1016/j.jallcom.2023.172482.

[2] K. Cao, W. Ye, Y. Zhang, Z. Chen, R. Zhao, and W. Xue, “Fabrication of MOF-rGO aerogels to enhance electromagnetic wave absorption by adjusting the morphology and structure of MOFs by electron transfer,” *Chemical Engineering Journal*, vol. 489, p. 151384, 2024, doi: 10.1016/j.cej.2024.151384.

[3] D. Jiang *et al.*, “Electromagnetic Interference Shielding Polymers and Nanocomposites - A Review,” *Polymer Reviews*, vol. 59, no. 2, pp. 280–337, 2019, doi: 10.1080/15583724.2018.1546737.

[4] L. Quan *et al.*, “Electromagnetic properties of graphene aerogels made by freeze-casting,” *Chemical Engineering Journal*, vol. 428, p. 131337, 2022, doi: 10.1016/j.cej.2021.131337.

[5] J. Li *et al.*, “Multifunctional antimony tin oxide/reduced graphene oxide aerogels with wideband microwave absorption and low infrared emissivity,” *Composites Part B: Engineering*, vol. 231, p. 109565, 2022, doi: 10.1016/j.compositesb.2021.109565.

[6] Z. Cai and H. Zhang, “The effect of carboxymethylation on the macromolecular conformation of the (1→3)-β-D-glucan of curdlan in water,” *Carbohydrate Polymers*, vol. 272, p. 118456, 2021, doi: 10.1016/j.carbpol.2021.118456.

[7] O.-G. Dragos-Pinzaru *et al.*, “CoPt Nanowires with Low Pt Content for the Catalytic Methanol Oxidation Reaction (MOR),” *ACS Applied Nano Materials*, vol. 5, no. 6, pp. 8089–8096, 2022, doi: 10.1021/acsanm.2c01234.

[8] J. Andrzejewski, A. K. Mohanty, and M. Misra, “Development of hybrid composites reinforced with biocarbon/carbon fiber system. The comparative study for PC, ABS and PC/ABS based materials,” *Composites Part B: Engineering*, vol. 200, p. 108319, 2020, doi: 10.1016/j.compositesb.2020.108319.

[9] Y. Shi *et al.*, “Advanced Functional Electromagnetic Shielding Materials: A Review Based on Micro-Nano Structure Interface Control of Biomass Cell Walls,” *Nano-Micro Letters*, vol. 17, no. 1, p. 3, 2025, doi: 10.1007/s40820-024-01494-2.

[10] T. Sun *et al.*, “Interactions of Alginate-Deferoxamine Conjugates With Blood Components and Their Antioxidation in the Hemoglobin Oxidation Model,” *Frontiers in Bioengineering and Biotechnology*, vol. 8, 2020, doi: 10.3389/fbioe.2020.00053.

[11] J. T. Orasugh, L. T. Temane, and S. S. Ray, “Nanocellulose-based conductive composites: A review of systems for electromagnetic interference shielding applications,” *International Journal of Biological Macromolecules*, vol. 277, p. 133891, 2024, doi: 10.1016/j.ijbiomac.2024.133891.

[12] Z. Zeng, J. Qiao, R. Zhang, J. Liu, and G. Nyström, “Nanocellulose-assisted preparation of electromagnetic interference shielding materials with diversified microstructure,” *SmartMat*, vol. 3, no. 4, pp. 582–607, 2022, doi: 10.1002/smm2.1118.

[13] X. Cao *et al.*, “Cellulose-based functional hydrogels derived from bamboo for product design,” *Frontiers in Plant Science*, vol. 13, 2022, doi: 10.3389/fpls.2022.958066.

[14] T. T. M. Thu, R. A. Moreira, S. A. L. Weber, and A. B. Poma, “Molecular Insight into the Self-Assembly Process of Cellulose Iβ Microfibril,” *International Journal of Molecular Sciences*, vol. 23, no. 15, p. 8505, Jul. 2022, doi: 10.3390/ijms23158505.

[15] S. Iwamoto, A. N. Nakagaito, and H. Yano, “Nano-fibrillation of pulp fibers for the processing of

transparent nanocomposites," *Applied Physics A*, vol. 89, no. 2, pp. 461–466, 2007, doi: 10.1007/s00339-007-4175-6.

[16] F.-X. Collard and J. Blin, "A review on pyrolysis of biomass constituents: Mechanisms and composition of the products obtained from the conversion of cellulose, hemicelluloses and lignin," *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 594–608, 2014, doi: 10.1016/j.rser.2014.06.013.

[17] Y. Habibi, L. A. Lucia, and O. J. Rojas, "Cellulose Nanocrystals: Chemistry, Self-Assembly, and Applications," *Chemical Reviews*, vol. 110, no. 6, pp. 3479–3500, 2010, doi: 10.1021/cr900339w.

[18] M. Henriksson, G. Henriksson, L. A. Berglund, and T. Lindström, "An environmentally friendly method for enzyme-assisted preparation of microfibrillated cellulose (MFC) nanofibers," *European Polymer Journal*, vol. 43, no. 8, pp. 3434–3441, 2007, doi: 10.1016/j.eurpolymj.2007.05.038.

[19] A. Isogai, T. Saito, and H. Fukuzumi, "TEMPO-oxidized cellulose nanofibers," *Nanoscale*, vol. 3, no. 1, pp. 71–85, 2011, doi: 10.1039/C0NR00583E.

[20] T. Saito *et al.*, "Individualization of Nano-Sized Plant Cellulose Fibrils by Direct Surface Carboxylation Using TEMPO Catalyst under Neutral Conditions," *Biomacromolecules*, vol. 10, no. 7, pp. 1992–1996, 2009, doi: 10.1021/bm900414t.

[21] M. Panahi-Sarmad, N. Alikarami, T. Guo, M. Haji, F. Jiang, and O. J. Rojas, "Aerogels based on Bacterial Nanocellulose and their Applications," *Small*, vol. 20, no. 44, 2024, doi: 10.1002/smll.202403583.

[22] R. Shu, L. Xu, and Y. Guan, "Preparation of cellulose derived carbon/reduced graphene oxide composite aerogels for broadband and efficient microwave dissipation," *Journal of Colloid and Interface Science*, vol. 675, pp. 401–410, 2024, doi: 10.1016/j.jcis.2024.07.026.

[23] J. Kim and J. Kim, "Pyrolyzed cellulose/rGO aerogel composites via I2 treatment and silane surface functionalization with highly improved through-plane thermal conductivity and EMI shielding effectiveness," *Journal of Materials Research and Technology*, vol. 26, pp. 2782–2795, 2023, doi: 10.1016/j.jmrt.2023.08.083.

[24] B. C. Moggio, R. Bergamasco, C. M. G. Andrade, and L. B. R. Aylon, "On the Analysis of Cryogels and Xerogels Using Cellulose Nanofibers and Graphene Oxide," *Polymers*, vol. 15, no. 18, p. 3833, 2023, doi: 10.3390/polym15183833.

[25] N. Zhang *et al.*, "Graphene Oxide Enhanced Nanocellulose/Chitosan Biodegradable Aerogel Pad for Fresh Pork Preservation," *Food and Bioprocess Technology*, vol. 17, no. 12, pp. 4768–4780, 2024, doi: 10.1007/s11947-024-03406-z.

[26] V. T. Nguyen *et al.*, "High-performance hydrophobic aerogel based on nanocellulose, graphene oxide, polyvinyl alcohol, and hexadecyltrimethoxysilane: Structure, properties, and applicability," *Journal of Environmental Chemical Engineering*, vol. 12, no. 4, p. 113215, 2024, doi: 10.1016/j.jece.2024.113215.

[27] Z. Zheng *et al.*, "Cellulose/nanocarbon composite based multifunctional aerogels for thermal management," *Materials Today Communications*, vol. 38, p. 107701, 2024, doi: 10.1016/j.mtcomm.2023.107701.

[28] B. Zhao *et al.*, "Advances in electromagnetic shielding properties of composite foams," *Journal of Materials Chemistry A*, vol. 9, no. 14, pp. 8896–8949, 2021, doi: 10.1039/D1TA00417D.

[29] B. Fan *et al.*, "Natural cellulose nanofiber extracted from cell wall of bamboo leaf and its derived multifunctional aerogel," *Polymer Composites*, vol. 39, no. 11, pp. 3869–3876, 2018, doi: 10.1002/pc.
24419.

[30] X. Zhang, H. Wang, Z. Cai, N. Yan, M. Liu, and Y. Yu, "Highly Compressible and Hydrophobic Anisotropic Aerogels for Selective Oil/Organic Solvent Absorption," *ACS Sustainable Chemistry & Engineering*, vol. 7, no. 1, pp. 332–340, 2019, doi: 10.1021/acssuschemeng.8b03554.

[31] D. Yin *et al.*, "Flexible mille-feuille structure electromagnetic interference shielding film with excellent thermal conductivity and Joule heating," *Nano Research*, vol. 17, no. 5, pp. 4544–4554, 2024, doi: 10.1007/s12274-023-6387-2.

[32] M. Li, X. Wang, R. Zhao, Y. Miao, and Z. Liu, "A novel graphene-based micro/nano architecture with high strength and conductivity inspired by multiple creatures," *Scientific Reports*, vol. 11, no. 1, p. 1387, 2021, doi: 10.1038/s41598-021-80972-8.

[33] T. C. Mokhena *et al.*, "Recent advances on nanocellulose-graphene oxide composites: a review," *Cellulose*, vol. 31, no. 12, pp. 7207–7249, 2024, doi: 10.1007/s10570-024-06055-9.

[34] D. Xu, S. Wang, L. A. Berglund, and Q. Zhou, "Surface Charges Control the Structure and Properties of Layered Nanocomposite of Cellulose Nanofibrils and Clay Platelets," *ACS Applied Materials & Interfaces*, vol. 13, no. 3, pp. 4463–4472, 2021, doi: 10.1021/acsami.0c18594.

[35] L. Nguyen Dang and J. Seppälä, "Electrically conductive nanocellulose/graphene composites exhibiting improved mechanical properties in high-moisture condition," *Cellulose*, vol. 22, no. 3, pp. 1799–1812, 2015, doi: 10.1007/s10570-015-0622-2.

[36] Y. Ma *et al.*, "Recent Advances of Application and Structural Design of Cellulose-Based Composites for EMI Shielding," *Polymer Reviews*, vol. 64, no. 3, pp. 872–897, 2024, doi: 10.1080/15583724.2024.2335504.

[37] L. Wang, H. Shen, H. Zhang, D. Xu, and J. Zhou, "Fabrication of anisotropic carbon aerogels from cellulose nanofiber/graphene oxide composites for electromagnetic interference shielding," *Journal of Alloys and Compounds*, vol. 980, p. 173505, 2024, doi: 10.1016/j.jallcom.2024.173505.

[38] M. Yuan *et al.*, "Electromagnetic asymmetric films comprise metal organic frameworks derived porous carbon for absorption-dominated electromagnetic interference shielding," *Composites Part B: Engineering*, vol. 233, p. 109622, 2022, doi: 10.1016/j.compositesb.2022.109622.

[39] R. Zhang *et al.*, "Ultralight aerogel sphere composed of nanocellulose-derived carbon nanofiber and graphene for excellent electromagnetic wave absorption," *Nano Research*, vol. 16, no. 5, pp. 7931–7940, 2023, doi: 10.1007/s12274-023-5521-5.

[40] L. William. Zahner, *Copper, brass, and bronze surfaces : a guide to alloys, finishes, fabrication and maintenance in architecture and art*. John Wiley & Sons, Inc., 2020.

[41] S. Hu *et al.*, "Fe_3O_4 nanoparticles encapsulated in single-atom Fe–N–C towards efficient oxygen reduction reaction: Effect of the micro and macro pores," *Carbon*, vol. 162, pp. 245–255, 2020, doi: 10.1016/j.carbon.2020.02.059.

[42] C. Wan and J. Li, "Graphene oxide/cellulose aerogels nanocomposite: Preparation, pyrolysis, and application for electromagnetic interference shielding," *Carbohydrate Polymers*, vol. 150, pp. 172–179, 2016, doi: 10.1016/j.carbpol.2016.05.051.

[43] R. K. Bheema, G. J, K. Bhaskaran, A. Verma, M. Chavali, and K. C. Etika, "A review on recent progress in polymer composites for effective electromagnetic interference shielding properties – structures, process, and sustainability approaches," *Nanoscale Advances*, vol. 6, no. 23, pp. 5773–5802, 2024, doi: 10.1039/D4NA00572D.

[44] Y. Li *et al.*, "Meter-Scale Wearable Multifunctional Core-Shell Nanofiber Textiles for Ultra-Broadband Electromagnetic Interference Shielding and Infrared Stealth," *Advanced Materials*, vol. 37, no. 15, 2025, doi: 10.1002/adma.202501485.

[45] L. Wang, D. Xu, and J. Zhou, "Multilayer composite films with enhanced electromagnetic interference shielding and thermal management properties based on bamboo cellulose nanofibers," *Carbohydrate Polymers*, vol. 354, p. 123309, 2025, doi: 10.1016/j.carbpol.2025.123309.

[46] J. Zhang *et al.*, "High-Compressive, Elastic, and Wearable Cellulose Nanofiber-Based Carbon Aerogels for Efficient Electromagnetic Interference Shielding," *ACS Applied Materials & Interfaces*, vol. 16, no. 13, pp. 16612–16621, 2024, doi: 10.1021/acsami.3c16559.

[47] Z. Chen, Q. Zhang, W. Meng, Z. Wang, X. Han, and J. Pu, "Nickel-reduced graphene oxide-cellulose nanofiber composite papers for electromagnetic interference shielding," *BioResources*, vol. 15, no. 1, pp. 814–824, 2019, doi: 10.15376/biores.15.1.814-824.

[48] Y. Wang *et al.*, "Fabrication of Cellulose Nanofiber/Reduced Graphene Oxide/Nitrile Rubber Flexible Films Using Pickering Emulsion Technology for Electromagnetic Interference Shielding and Piezoresistive Sensor," *Macromolecular Materials and Engineering*, vol. 306, no. 6, 2021, doi: 10.1002/mame.202100070.

[49] M. W. Hassan, T. M. Elshazly, and D. Ponnamma, "Cellulose-inspired approaches to sustainable EMI shielding materials: A comprehensive review," *International Journal of Biological Macromolecules*, vol. 273, p. 132920, 2024, doi: 10.1016/j.ijbiomac.2024.132920.

[50] H. Yang *et al.*, "Nanocellulose-graphene composites: Preparation and applications in flexible electronics," *International Journal of Biological Macromolecules*, vol. 253, p. 126903, 2023, doi: 10.1016/j.ijbiomac.2023.126903.

[51] X. Zhao *et al.*, "Soft fibers with magnetoelasticity for wearable electronics," *Nature Communications*, vol. 12, no. 1, p. 6755, 2021, doi: 10.1038/s41467-021-27066-1.

[52] P. Kumar, U. Narayan Maiti, A. Sikdar, T. Kumar Das, A. Kumar, and V. Sudarsan, "Recent Advances in Polymer and Polymer Composites for Electromagnetic Interference Shielding: Review and Future Prospects," *Polymer Reviews*, vol. 59, no. 4, pp. 687–738, 2019, doi: 10.1080/15583724.2019.1625058.