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Epoxy Composite Reinforced with Bacterial Cellulose and Multi-Walled Carbon Nanotubes: Mechanical Properties and Flame Retardancy Performance

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Abstract

This study investigates the mechanical properties and flame retardancy of epoxy-based nanocomposites reinforced with bacterial cellulose (BC) and multi-walled carbon nanotubes (MWCNTs). The optimal performance was achieved with a composite containing 5 wt% BC and 0.5 wt% MWCNTs. In terms of mechanical properties, this composition exhibited superior tensile strength, flexural strength, compressive strength and impact resistance compared to other combinations. Moreover, the flame retardancy of the nanocomposite was significantly enhanced, with a limiting oxygen index (LOI) of 29.3 % and a burn rate of 16.02 mm/min. The results are attributed to the unique synergy between BC and MWCNTs, the primary components of the nanocomposite. BC, with its natural fiber structure and excellent mechanical properties, provides rigidity and strong interactions with the epoxy matrix. MWCNTs, owing to their nano-scale structure, contribute to both mechanical reinforcement and flame retardancy. This combination improves the uniformity and dispersion of the reinforcing phase within the epoxy matrix, leading to enhanced mechanical properties and flame resistance. When the BC/MWCNTs epoxy nanocomposite was further reinforced with fiberglass fabric at the optimal composition (5 wt% BC, 0.5 wt% MWCNTs), it demonstrated even higher flame retardancy, with an LOI of 30.8 % and a UL-94V rating of V1, classifying it as a highly flame-retardant material. Given these outstanding properties, the BC/MWCNTs epoxynanocomposite has potential applications not only in various industrial sectors such as aerospace, automotive and construction but also in the medical and environmental fields, where materials with high durability and flame resistance are crucial. The BC/MWCNTs material system not only demonstrates its advantages as a reinforcement in composites but also brings great prospects when fabricated into membrane form. These applications open up many new directions of development in the fields of environment, energy, biomedicine and industry, creating a solid foundation for research and practical applications.

Keywords: Bacterial cellulose, Epoxy, Flame-retardant, Nanocomposites, Environmental, Multi-walled carbon nanotubes, Limiting oxygen index

Introduction

Currently, there is a growing demand for multifunctional, sustainable, and high-performance composite materials, particularly in fields such as wearable electronics, automotive, aerospace and construction. In response to this, researching and developing new types of materials has become an urgent task. One promising research direction is the use of bacterial cellulose (BC), a natural polymer with excellent mechanical properties, as a reinforcement for composite materials. Several studies have shown that BC can be successfully integrated with carbon nanotubes (CNTs) to create composites with electromagnetic interference (EMI) shielding properties and good thermal insulation, meeting the stringent requirements of high-tech applications [1]. One study improved the properties of epoxy composites by incorporating cellulose nanocrystals (CNCs). The results showed that adding 5 % CNC to the epoxy system increased tensile strength by 20 % and tensile modulus by 15 %, while maintaining good electrical

insulation properties [2]. This demonstrates the significant potential of using renewable resource-based composites to not only minimize environmental impact but also ensure high performance in applications [3]. In addition, research on insulating materials based on aramid fibers, mica, and nanofibrillated cellulose (NFC) has achieved promising results. Notably, a composite system containing 50 % NFC showed a substantial improvement in electrical insulation and thermal stability, indicating great potential for applications requiring high thermal stability and fire resistance in harsh environments [4]. Other studies have focused on enhancing the mechanical properties and fire resistance of poly(lactic acid) (PLA) by combining it with CNTs. Results showed that adding 3 % CNT to PLA increased the tensile strength of the composite by 25 %, while also significantly improving fire resistance, with the oxygen index increasing from 21 to 28 % [5]. For epoxy composites, integrating nanofillers such as graphene, hexagonal boron nitride (h-BN) and MXene has led to significant improvements in mechanical properties and corrosion resistance. For instance, research indicated that adding 2 % graphene to epoxy increased tensile strength by 30 % and tensile modulus by 25 %, while also improving fire resistance with a 15 % reduction in burn time [6]. Studies have also shown that increasing the cellulose fiber content in epoxy composites can enhance tensile strength by up to 40 %, although some limitations regarding phase adhesion remain [8]. Furthermore, using aerogels based on bacterial cellulose nanofibrils (bCNF) as templates has demonstrated superior fire resistance and thermal insulation. When using silsesquioxane as a precursor, the thermal conductivity of the composite decreased by up to 20 %, while fire resistance improved significantly, with burn rate reduced to less than 5 mm/min [9]. Finally, recent research has successfully developed environmentally friendly epoxy nanocomposites based on cellulose nanofibers and vanillin epoxy, featuring outstanding mechanical, thermal insulation and UV resistance properties. For example, a nanocomposite system with 3 % cellulose nanofiber improved tensile strength by up to 30 % and enhanced UV resistance with a 15 % reduction in absorption [10]. The combination of long cellulose fibers with vanillin-based epoxy also created a green composite material with 20 % higher mechanical strength and superior fire resistance compared to conventional epoxy systems, providing a crucial foundation for high-performance structural applications [11].

Epoxy resins are widely used as matrix materials in composite systems due to their exceptional properties. They exhibit excellent mechanical strength, chemical resistance and thermal stability, making them suitable for high-performance applications. The ability to cure at room temperature and form strong adhesive bonds with various reinforcements further enhances their versatility. Moreover, epoxy resins have low shrinkage during curing, which contributes to dimensional stability in composite structures.

However, epoxy also has some limitations. It is inherently brittle, which can lead to reduced toughness in certain applications. Additionally, the material's flammability and smoke production during combustion pose safety concerns, particularly in fields requiring high flame retardancy. Addressing these drawbacks often involves the incorporation of reinforcements, such as bacterial cellulose and multi-walled carbon nanotubes, to enhance both mechanical and flame-retardant properties, as demonstrated in this research [12]. Epoxy resins are versatile materials widely utilized in various industrial applications due to their exceptional mechanical, thermal and electrical properties. Their adaptability makes them suitable for diverse uses such as laminated circuit boards, electronic component encapsulation, surface coatings, potting, fiber reinforcement and adhesives. However, their inherent brittleness, low impact resistance, delamination and limited fracture toughness restrict their performance in high-demand applications. These challenges can be addressed through modifications to improve their properties. Recent advancements in epoxy technology, including the development of modified and bio-based epoxy resins, have expanded their applications, particularly in the fabrication of natural fiber-reinforced composites and nanocomposites. These innovations have enhanced the mechanical and thermal performance of epoxy-based materials, making them more viable for industrial use (Saba *et al.* [13]).

This research emphasizes bacterial cellulose (BC) as a significant additive to enhance the mechanical properties of epoxy composites because BC provides unique benefits that complement those of carbon nanotubes (CNTs). While CNTs alone are known for

their exceptional mechanical reinforcement, challenges such as agglomeration and limited interaction with the epoxy matrix can reduce their effectiveness. BC, a natural polymer with a high surface area, remarkable tensile strength and abundant hydroxyl groups, improves the dispersion of CNTs and strengthens the interfacial bonding with the epoxy matrix. This combination of BC and CNTs allows for a synergistic effect, addressing limitations and optimizing mechanical properties. The study also prioritizes fire retardance improvement as a critical goal. Epoxy's inherent flammability limits its high-performance applications, making flame retardance enhancements essential. The research should provide detailed parameters and mechanisms contributing to the observed fire retardance improvements, offering deeper insights into how BC and CNTs interact with the epoxy matrix under thermal conditions [14,15].

Although there have been studies on BC or CNTs individually as reinforcing agents, research combining both as a disperse phase remains limited. Comparing the outcomes of this study with previous works would highlight the advantages of the dual-reinforcement approach and its novelty. Furthermore, the objective of this research - to develop epoxy composites with enhanced mechanical and fire retardance properties - should be clarified in the introduction and conclusion, including its potential applications. Specific uses, such as aerospace, automotive or electronic components, would shape the discussion on how the property improvements align with the functional requirements of these fields. By addressing these aspects, the study could present a more comprehensive and application-oriented perspective.

From the published studies, it is evident that enhancing the mechanical and fire resistance properties of composite materials by combining natural fibers such as bacterial cellulose (BC) with nanomaterials like carbon nanotubes (CNTs) has garnered significant interest. However, there are still gaps that need to be addressed to optimize these material systems. Specifically, while many studies have successfully combined cellulose nanocrystals (CNCs) or other fibers with epoxy to improve tensile strength, hardness and fire resistance, there is limited extensive research on integrating BC with multi-walled carbon nanotubes (MWCNTs) in epoxy composites to evaluate comprehensive fire resistance properties. Combining BC with MWCNTs not only holds the potential for significant improvements in mechanical properties but could also create a material system with high fire resistance, suitable for industrial applications requiring stringent safety and thermal durability. Many current studies primarily focus on assessing the mechanical properties or thermal conductivity of composite materials, but research on the fire resistance mechanisms when integrating BC/MWCNTs into epoxy remains limited. This opens up a necessary research direction to develop epoxy composite materials reinforced with BC/MWCNTs, not only optimizing mechanical properties but also enhancing fire resistance, meeting the increasing demands in fields such as electronics, construction, and aerospace. Filling these gaps is crucial for advancing the development of epoxy composite systems reinforced with BC and MWCNTs. This research will not only contribute to improving existing material properties but also open new opportunities for applying high-performance, environmentally friendly composite materials in industry. The BC/MWCNTs material system is not only effective in composite fabrication but also has great potential when developed into a membrane form. With the porous nanostructure of BC and the superior conductivity of MWCNTs, this membrane can be applied in water purification and environmental treatment, removing heavy metals and pollutants, as well as desalinating brackish water. In addition, the BC/MWCNTs membrane is also suitable as an ion-conducting membrane in fuel cells, supercapacitors, pressure and gas sensors, as well as flexible electronic devices. In biomedicine, this membrane can be used as an antibacterial bandage, drug delivery or tissue regeneration support. In particular, the BC/MWCNTs membrane is also promising in renewable energy, such as a conductive membrane for solar cells, contributing to sustainable development and technological modernization.

Materials and methods

Materials

Epikote 240 is a Bisphenol A epoxy resin supplied by Shell Chemicals (USA), with an epoxy group content of 24.6 %, an epoxy equivalent weight of 185 - 196, and a viscosity of 0.7 - 1.1 Pa·s at 25 °C. Diethylenetriamine

(DETA), used as a curing agent, is supplied by Dow Chemicals (USA). **Nata-de-coco** is a product of bacterial cellulose (*Acetobacter xylinum*), produced by fermenting coconut water or coconut milk. It has a nanofibrous structure, high purity, excellent mechanical strength and good water-holding capacity. Besides being a food ingredient, nata-de-coco is used as an eco-friendly source of cellulose for producing composites and biopolymers. Nata-de-coco, sourced from Minh Tam Coconut Company in Ben Tre, Vietnam, exhibits a dry content comprising 10 wt%. Notably, 90 wt% of the total weight of nata-de-coco consists of water content. Nata-de-coco Vietnam with a dry content of 10 wt%, 90 wt% of nata-de-coco is water. Ethanol (Pure alcohol with 99.5 to 99.6 % alcohol by volume), NaOH (99 % purity) and acetone were purchased from Sigma Aldrich (Vietnam). MWCNTs with a diameter of 40 - 45 nm and a length of around 3 μm was provided by Showa Denko Japan Co.

Preparation method

Preparation of BC/MWCNTs/epoxy nanocomposite

The BC/MWWCNTs nanocomposite membrane fabrication process is carried out according to the process shown in **Figure 1**. In this study, 5 samples of epoxy-based nanocomposites were prepared, including Epoxy/5 % BC, Epoxy/0.5 % MWCNTs, Epoxy/5 % BC/0.25 % MWCNTs, Epoxy/5 % BC/0.5 % MWCNTs and Epoxy/5 % BC/0.75 % MWCNTs (**Table 1**).

Table 1 Fabrication process of BC/MWCNTs/epoxy nanocomposite membrane material.

No	Material symbol	% Mass, BC	% Mass, MWCNTs
1	Epoxy/5 % BC	5	0.00
2	Epoxy/0.5 % MWCNTs	0	0.50
3	Epoxy/5 % BC/0.25 % MWCNTs	5	0.25
4	Epoxy/5 % BC/0.5 % MWCNTs	5	0.50
5	Epoxy/5 % BC/0.75 % MWCNTs	5	0.75

The process of isolating bacterial cellulose (BC) from nata de coco using a suspension of slaked lime NaOH at a concentration of 0.3 M

Isolation process of bacterial cellulose (BC) from nata de coco using 0.3 M NaOH typically involves the following steps: (1) Processing of nata de coco: Nata de coco is first cut into small pieces or ground to increase its surface area. It is then soaked in a 0.3M NaOH solution for 24 to 48 h. During this soaking process, NaOH breaks down unwanted organic compounds, such as proteins, lipids and biological impurities remaining from fermentation, which helps to remove these contaminants and facilitates the isolation of bacterial cellulose (BC). (2) Rinsing and neutralization: After soaking, the nata de coco is removed and thoroughly rinsed several times with water to eliminate any residual NaOH. Then, the nata de coco can be soaked in a weak acid solution, such as acetic acid or citric acid, with a concentration of approximately 0.1 to 0.2 M, to neutralize any remaining NaOH and adjust the pH to a neutral level. (3) Isolation of bacterial cellulose: Once the treatment and rinsing processes are complete, BC is recovered by blending the nata de coco in distilled water using a blender, and then replacing the water with medical alcohol. The resulting mixture is subjected to ultrasonic stirring for 30, 45 and 60 min at room temperature. Afterward, the mixture is vacuum filtered to obtain BC in the form of a thin membrane, which is then air-dried to produce pure BC (**Figure 1**).

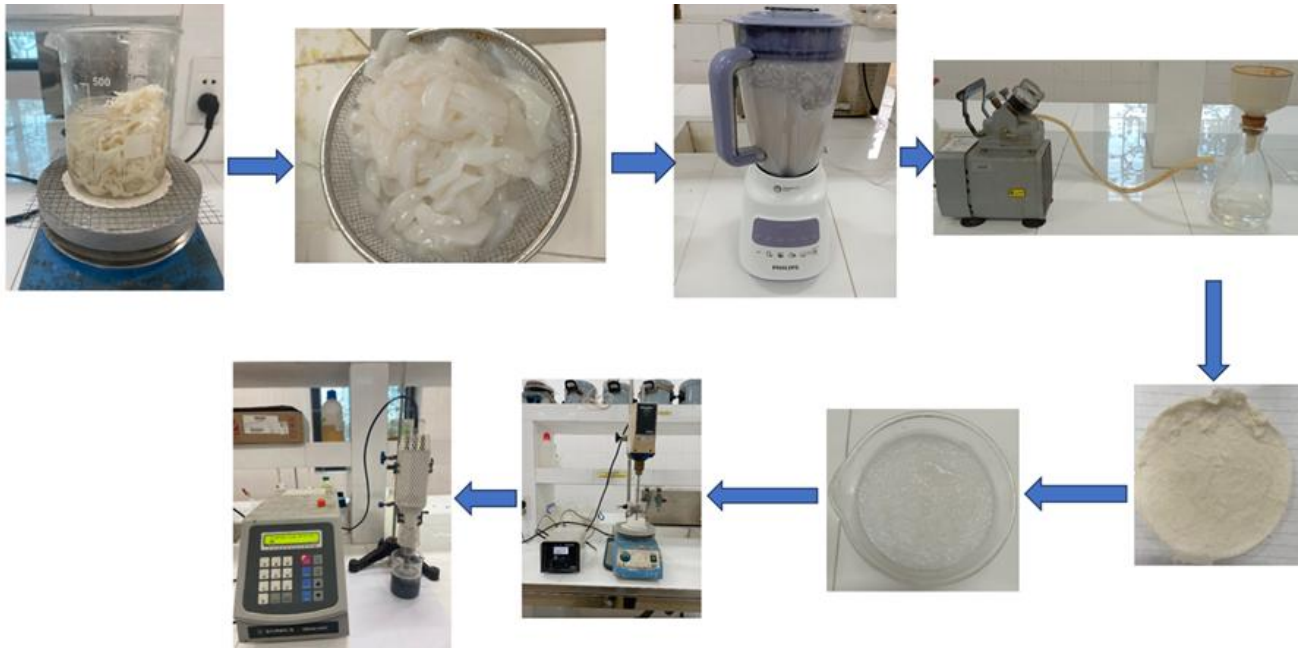


Figure 1 BC/MWCNTs/epoxy nanocomposite membrane fabrication process.

The fabrication process of the epoxy nanocomposite reinforced with BC and MWCNTs

The fabrication process of the epoxy nanocomposite reinforced with BC and MWCNTs involves the following steps: (1) Mixing: Initially, a mixture of epoxy, bacterial cellulose (BC) and multi-walled carbon nanotubes (MWCNTs) is mechanically stirred at 80 °C for 3 h at a speed of 3,000 rpm. (2) Ultrasonic mixing: After mechanical stirring, the mixture undergoes ultrasonic mixing at room temperature for 30, 45 and 60 min to ensure even dispersion of the components. (3) Defoaming: The mixture is then subjected to vacuum degassing to remove air bubbles, improving the quality and homogeneity of the material. (4) Adding curing agent: The curing agent DETA is added to the mixture at a weight ratio of epoxy to DETA of 100/14. (5) Curing and stabilization: The material, after being thoroughly mixed with the curing agent, is cured at 80 °C for 3 h, followed by stabilization for 7 days. (6) Analysis and measurement: Finally, the nanocomposite material is tested for mechanical properties, flame retardancy and analyzed using scanning electron microscopy (SEM) for surface structure characterization (**Figure 1**).

Characterizations

The sample morphology was analyzed by scanning electron microscopy (S-4800 FE-SEM- Field Emission Scanning Electron Microscopy, Hitachi, Japan). The FE-SEM images were captured the fractured sample surface with a high resolution. The samples were coated with Pt with a thickness of less than 10 nm under the mode of I equal to 30 mA, with a deposition time of 30 s. Tensile strength was tested according to the ISO 527-1993 standard using an INSTRON 5582-100kN machine (USA) at a tensile speed of 5 mm·min^{-1} under controlled conditions (25 °C and 75 % humidity). Fourier Transform Infrared (FTIR) spectra were recorded on an FTS 2000 FTIR (Varian) using KBr tablets prepared by compressing KBr powder mixed with the BC sample. Thermal mass analysis (TGA) was performed by using DTG-60H, Shimadzu (Japan) with a heating rate of 10 °C·min^{-1} under 20 cm^3·min^{-1} of air environment condition at the Department Physical Chemistry, Faculty of Chemistry, Hanoi National University of Education. Flame retardancy was assessed through Limiting Oxygen Index (LOI) tests (JIS K720 standard) using samples of 150×6.5×3 mm³ and Horizontal (UL-94HB) and Vertical Burning (UL-94V) tests (ASTM D635-12 standard) with standard bar specimens of 125 ± 5 mm in length, 13 ± 0.5 mm in width and 3.0 ± 0.2 mm in thickness. The flame retardant and oxygen limit tests were conducted at the Polymer Materials Research Center, Hanoi University of Technology, Vietnam.

Results and discussion

Study on the production of bacterial cellulose from coconut jelly biomass by chemical method using NaOH combined with ultrasonic stirring

SEM structural morphology

Studying the structural morphology of bacterial cellulose (BC) before and after treatment is an important part of understanding and improving the properties of this material. Before treatment, BC has a natural fibrous structure with impurities such as lignin, hemicellulose, protein and other polysaccharides attached, reducing the mechanical and chemical properties of the material. The morphology of untreated BC often shows fibers covered by layers of impurities, making the cellulose fibers heterogeneous and less stable (**Figure 2**).

After NaOH treatment and ultrasonic stirring, BC fibers become cleaner and retain their natural fibrous structure. NaOH hydrolyzes ester and glycosidic bonds in organic compounds, removing impurities bound to cellulose fibers, while ultrasonic stirring breaks the chemical bonds of impurities, cleaning the surface of cellulose fibers. This study helps us better understand the cleaning process and improve the properties of materials, opening up many potential applications for BC in various fields, from biomedicine to industry, and increasing the ability of fibers to interact with other chemicals. When BC (bacterial cellulose) is treated with NaOH and ultrasonic stirring, the resulting fibers have a cleaner structure because this treatment removes impurities and unwanted components. NaOH is a strong alkaline solution that hydrolyzes ester and glycosidic bonds in organic compounds, including impurities such as lignin, hemicellulose and proteins. This hydrolysis process removes impurities bound to the cellulose fibers, resulting in a cleaner structure (**Figures 2** and **3**).

Ultrasonic stirring, with high ultrasonic energy, creates microwaves and microbubbles in the solution, which enhance the hydrolysis and fiber cleaning process. These microwaves and microbubbles have the ability to break chemical bonds and reduce the size of the impurity particles, making them easier to remove from the cellulose fibers. When BC is not chemically treated, natural impurities remain attached to the cellulose fibers. These impurities can include lignin, hemicellulose, proteins and other polysaccharides. These impurities make the cellulose fibers unclean, affecting the mechanical and chemical properties of the material (**Figure 3**).

The role of ultrasonic stirring in enhancing the properties of materials, particularly in the formation of bacterial cellulose nanofibers, is crucial and warrants a deeper discussion. Ultrasonic stirring employs high-frequency sound waves to induce rapid vibrations and cavitation in the liquid medium. This mechanical energy helps break down larger aggregates and promotes the dispersion of particles or fibers at the nanoscale. In the case of bacterial cellulose (BC) nanofibers, ultrasonic stirring significantly influences their morphology and structure, ensuring that they are well-dispersed, uniform, and exhibit desirable properties such as high surface area and improved mechanical strength. The ultrasonic energy facilitates the disintegration of cellulose aggregates and the breakdown of any entanglements between fibers, leading to the formation of individual nanofibers. This effect is critical for producing BC with the desired structural integrity and consistency. As confirmed by the scanning electron microscopy (SEM) images in **Figures 2 - 4**, ultrasonic stirring enhances the formation of BC nanofibers with a more uniform and well-defined structure compared to samples that were not subjected to this treatment. The SEM images clearly illustrate the increased alignment, smaller diameter and better dispersion of the nanofibers after the ultrasonic treatment, showcasing its pivotal role in optimizing the morphology of BC.

In addition to structural improvements, ultrasonic stirring can enhance the interaction between BC and other materials, such as functional additives or reinforcing agents, which are often necessary for the development of advanced composites or hybrid materials. The ability to control the dispersion of BC nanofibers effectively, especially in composite formulations, leads to superior mechanical properties and performance in various applications, such as in biodegradable films, energy storage devices, and environmental applications. Thus, ultrasonic stirring provides an efficient and effective method to manipulate the structural properties of BC, ensuring that it meets the specific requirements for advanced applications.

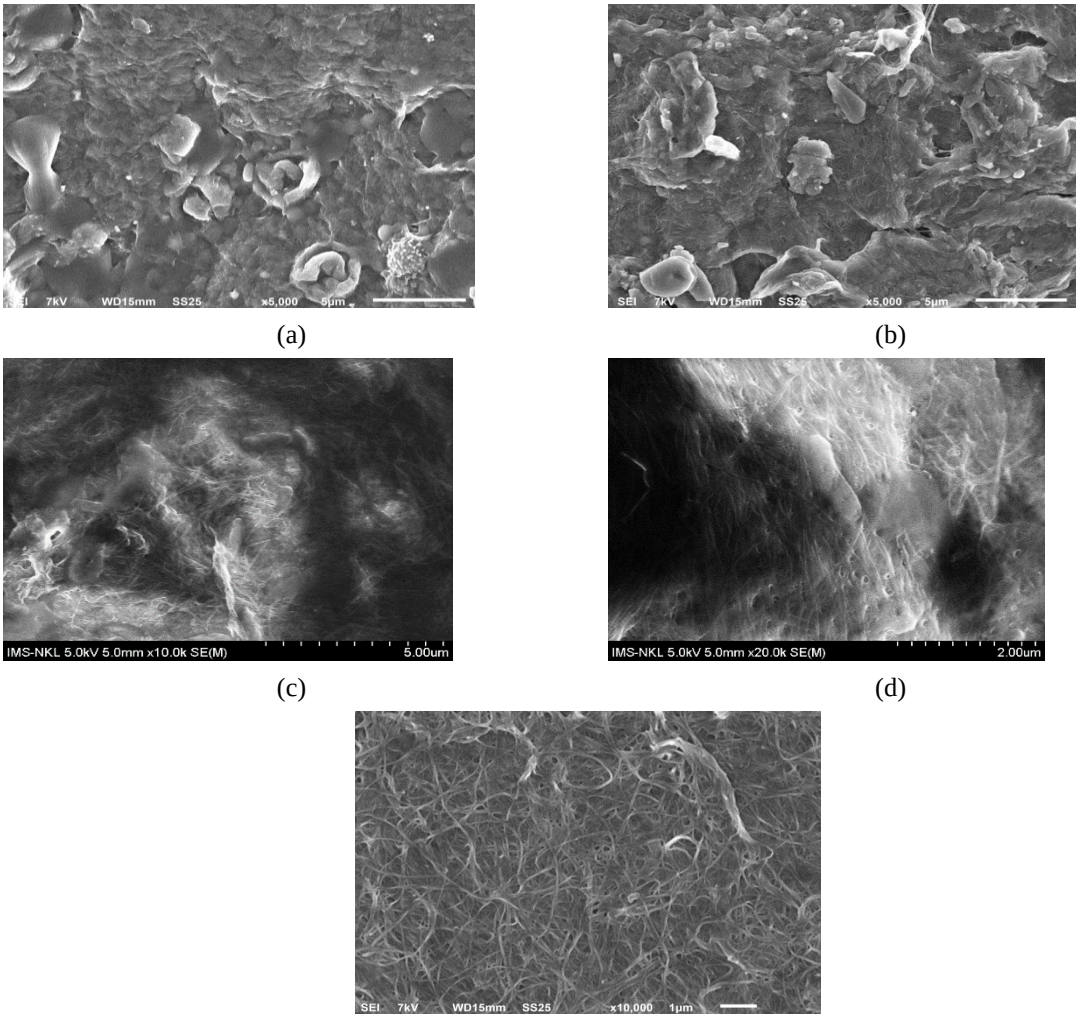


Figure 2 SEM images of BC membranes prepared under different ultrasonic stirring conditions: (a) BC no ultrasound; (b) BC ultrasonically stirred for 30 min; (c) BC was sonicated for 30 min and treated with 0.3 M NaOH; (d) BC was sonicated for 45 min and treated with 0.3 M NaOH; (e) BC was sonicated for 60 min and treated with 0.3 M NaOH.

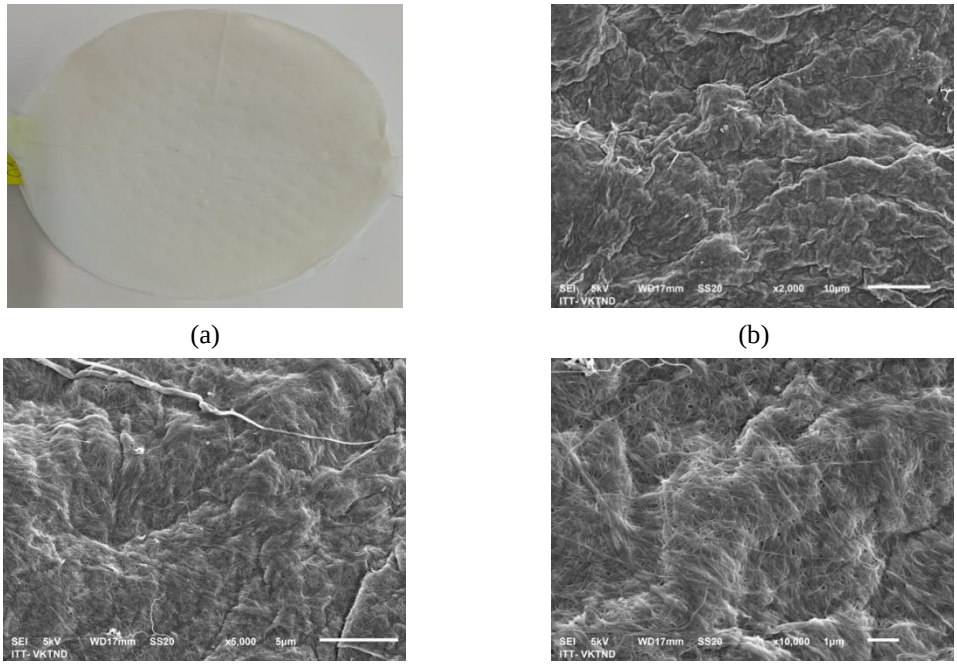


Figure 3 SEM image of bacterial cellulose (BC) membrane at different resolutions, when treated with 0.3 M NaOH, 60 min of ultrasound; (a) bacterial cellulose membrane, (b) resolution ×2,000, (c) resolution ×5,000 and (d) resolution ×10,000.

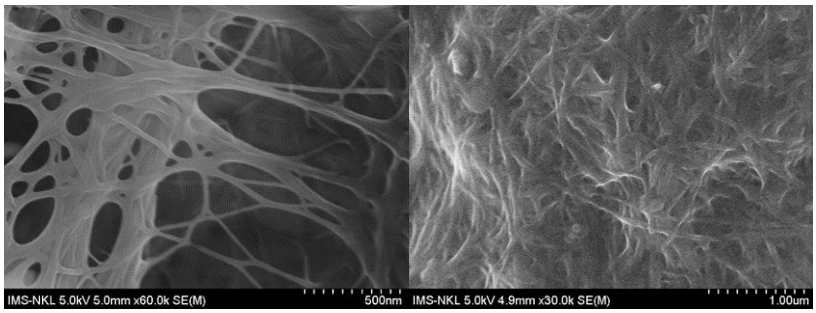


Figure 4 SEM images of BC membranes at 30.0 and 60.0 k magnification, 60 min of sonication.

The removal of impurities through chemical treatment and ultrasonic stirring enhances the mechanical properties of cellulose fibers, such as tensile strength, toughness and chemical resistance. In addition, the cleaner structure of cellulose fibers after treatment also increases the ability of the fibers to interact with other chemicals, improving the ability to reinforce and bond with other materials in composite applications. In summary, the treatment of BC with NaOH and ultrasonic stirring is an important process to purify cellulose fibers, remove impurities and improve the properties of the material, thereby opening up many potential applications in industrial and biomedical fields.

In the production of bacterial cellulose from coconut jelly, NaOH (sodium hydroxide) plays an important role. First, NaOH is used to separate lignin and hemicellulose from coconut fibers by breaking the chemical bonds between them and cellulose. This helps to purify the raw materials and facilitate the subsequent synthesis of cellulose. Next, NaOH is added to the culture medium to increase the alkalinity, raising the pH to around 8 - 9. The alkaline environment provides ideal conditions for cellulose-synthesizing bacteria, helping them grow and produce cellulose efficiently. Finally, NaOH also plays a role in removing other unwanted impurities and bacteria during the treatment process, ensuring the purity of the final product, bacterial cellulose. Thanks to this multi-faceted role, NaOH plays

an indispensable role in the coconut jelly processing to obtain bacterial cellulose.

From **Figures 2** - **4**, it can be seen that the bacterial cellulose membrane has a unique and clean natural structure, with characteristic features such as the interweaving of cellulose fibers and the flexibility of the cellulose network. This is the result of the natural biological process by which bacteria synthesize cellulose in the culture medium. One of the most important characteristics of bacterial cellulose membranes is the diversity in structural morphology. The structure of bacterial cellulose membranes varies from gel to fibrous, from fragments to continuous fragments, depending on the environmental conditions and manufacturing process. This creates a wide range of structures and shapes that the membrane can take, affecting its mechanical and chemical properties. The structure of bacterial cellulose membranes is a tightly organized cellulose fiber network, with cellulose fibers intertwined and linked together through hydrogen bonds. This tight organization creates a stable environment and high strength for the membrane, while also providing the membrane with the flexibility to adapt to changing environmental conditions. The cellulose fibers in the membrane are small in size and nano-sized, which contributes to increased flexibility and interaction with other molecules in the system. The interweaving of cellulose fibers also creates a large contact surface between the membrane and the surrounding environment, enhancing the ability to absorb and interact with substances in the environment. In summary, bacterial cellulose membranes have a natural, clean structure, with interwoven, looped fibers, creating a flexible and stable medium for applications in many fields such as medical, environmental and industrial.

IR properties

When bacterial cellulose (BC) is treated with NaOH, its Fourier-transform infrared (FTIR) spectrum shows significant changes in chemical structure. Before treatment, the hydroxyl (-OH) groups appear as a broad and strong peak around 3,300 - 3,500 cm^{-1}, indicating the presence of hydrogen bonding between hydroxyl groups within the cellulose. After treatment with NaOH, this peak may become narrower and decrease in intensity due to the removal of some free hydroxyl groups and hydrogen bonds. The C-H groups of cellulose, appearing in the range of 2,900 - 3,000 cm^{-1}, may also exhibit changes in intensity or shape due to the removal of some methyl and methylene groups. The C-O-C groups, related to glycosidic linkages, appear around 1,000 - 1,150 cm^{-1} and may show reduced intensity or shifts after treatment, indicating the breakdown or alteration of these linkages. The presence of carbonyl (C=O) groups may increase around 1,700 - 1,750 cm^{-1} if new carbonyl groups form due to reactions with NaOH or oxidation. Finally, the C-O-H groups, appearing around 1,100 - 1,200 cm^{-1}, may also change in intensity and shape after treatment. These changes reflect alterations in the chemical structure of BC due to NaOH treatment, leading to improved mechanical and chemical properties of the BC (**Figure 5**).

The combination of chemical treatment with NaOH and ultrasonic waves can have significant effects on the material's properties. Ultrasound, by generating high and low-pressure waves, not only increases the dispersion of the material in the solution but also helps break down the bonds between molecules and functional groups on the material's surface. This enhanced dispersion facilitates more effective contact and reaction of NaOH with the material's surface, leading to changes in its chemical structure. These effects can result in alterations in the material's structure, such as changes in the arrangement of functional groups, adjustments in the density of functional groups, or even the formation of new structures. These changes will be reflected in the FTIR spectrum (**Figure 5**) through shifts and changes in the intensity of absorption peaks, indicating modifications in the chemical and structural properties of the material after treatment.

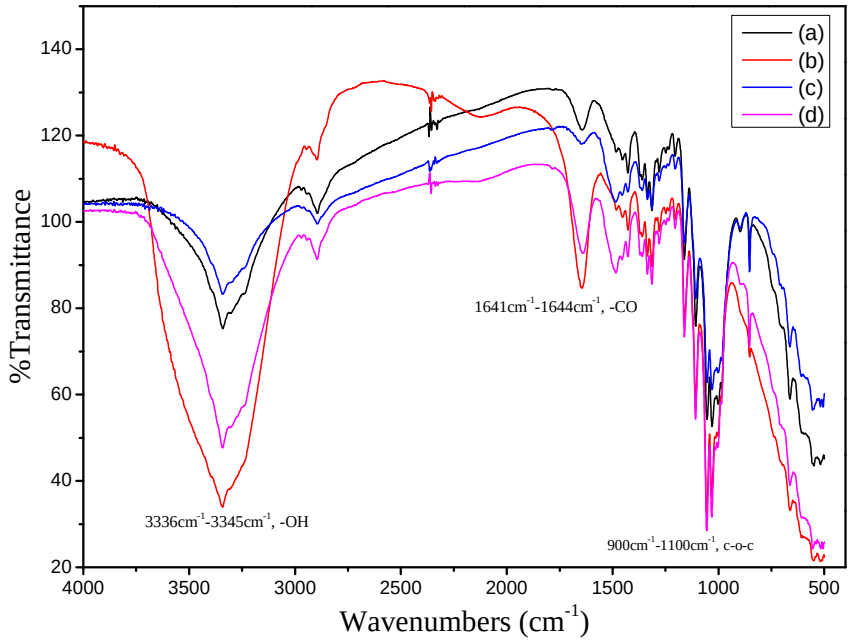


Figure 5 IR properties of BC when prepared under different conditions: (a) BC was sonicated for 45 min and treated with 0.3M NaOH, (b) BC with no ultrasound, (c) BC was sonicated for 60 min and treated with 0.3 M NaOH and (d) BC was sonicated for 30 min and treated with 0.3 M NaOH.

When treating materials with a 0.3 M NaOH solution and applying ultrasound for different durations (30, 45 and 60 min), FTIR spectra show a decrease in absorption intensity as the ultrasound time increases. This decrease can be explained by the enhanced effectiveness of the chemical reaction between NaOH and the functional groups on the material's surface with longer ultrasound exposure, due to increased contact and chemical reaction. Ultrasound, by generating high and low-pressure waves, helps break chemical bonds and improve the dispersion of the material in solution. This leads to a reduction in the intensity of absorption peaks associated with the reacted functional groups. The use of ultrasound not only enhances the efficiency of the chemical reaction but also reduces processing time and improves product quality, while also making the dissolution and dispersion of components more effective.

Structural morphology of nanocomposite materials on epoxy system reinforced with MWCNTs/bacterial cellulose (BC)

The structural morphology of the epoxy resin-based nanocomposite reinforced with bacterial cellulose (BC) and multi-walled carbon nanotubes (MWCNTs) can be thoroughly analyzed through Scanning Electron Microscopy (SEM). The SEM images provide critical insights into the interaction dynamics and interfacial bonding among the various constituents within the composite system, highlighting the crucial role that these interactions play in determining the overall properties of the material.

In examining the SEM images, a noteworthy aspect is the close interaction between the epoxy resin and the reinforcing agents, BC and MWCNTs. This effective wetting of the epoxy resin with both BC and MWCNTs is visually evident, illustrating how the resin penetrates and coats the surfaces of these nanofillers. Such intimate contact is paramount as it fosters improved interfacial bonding, which directly correlates with enhanced mechanical performance. The presence of strong interfacial bonds is instrumental in distributing stress across the composite, thereby minimizing localized failure and enhancing overall structural integrity. Moreover, the SEM images reveal that both BC and MWCNTs are uniformly dispersed within the epoxy matrix without any signs of agglomeration or separation. This uniform dispersion is critical for achieving a stable composite structure, as it ensures that the reinforcing components are effectively integrated

into the resin, leading to improved load transfer during mechanical loading. The homogeneity observed in the distribution of these nanofillers significantly contributes to the enhancement of material properties, such as strength and toughness (**Figure 6**).

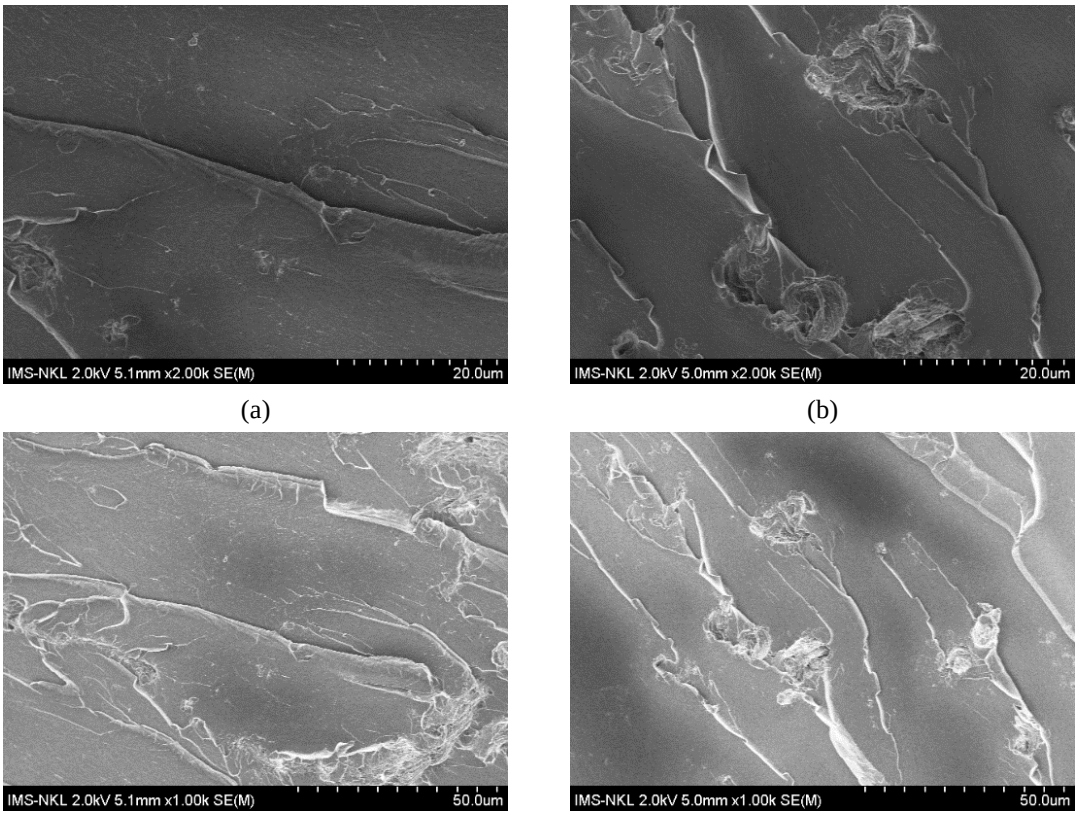


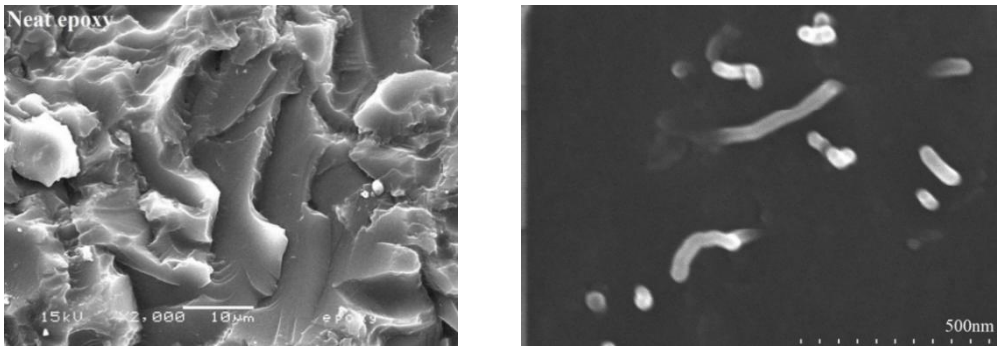
Figure 6 SEM images of epoxy nanocomposite materials with BC/MWCNTs: (a) −5 % BC; (b) −5 % BC, 0.25 % MWCNTs; (c) −5 % BC, 0.5 % MWCNTs; (d) −5 % BC, 0.75 % MWCNTs.

The nano-scale dimensions of the reinforcing agents, particularly the 45 - 57 nm size range of the nano-phases, play a pivotal role in augmenting the performance characteristics of the composite. The smaller the size of the reinforcing agents, the larger the surface area available for interaction with the epoxy matrix. This increased contact area facilitates more effective bonding and distribution of stress, which is essential for improving the mechanical properties of the material. Additionally, the presence of MWCNTs, known for their excellent mechanical strength and electrical conductivity, further enhances the composite's overall performance, making it suitable for various applications requiring high strength-to-weight ratios.

Furthermore, the inclusion of BC and MWCNTs also contributes to the fire resistance of the composite. The inherent properties of these nanofillers, combined with the epoxy matrix, help to create a barrier that slows down the spread of flames and reduces smoke emission during combustion. This characteristic is increasingly vital in applications where fire safety is a paramount concern. In conclusion, the SEM analysis of the epoxy resin-based nanocomposite reinforced with BC and MWCNTs provides compelling evidence of the critical roles played by component interaction, dispersion uniformity, and nano-scale reinforcement in enhancing the mechanical properties and fire resistance of the material.

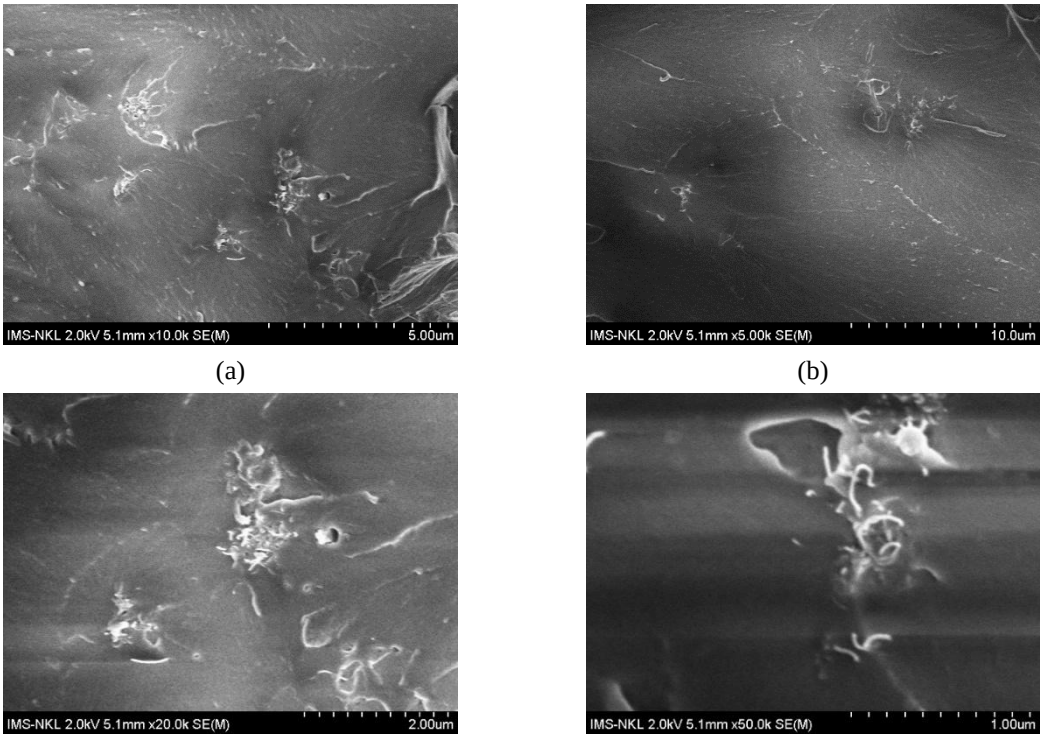
The close interaction and effective wetting of the epoxy resin with the nanofillers lead to a robust, homogeneous, and stable composite structure, positioning this nanocomposite as a promising candidate for advanced applications across various industries. The synergistic effects of BC and MWCNTs within the

epoxy matrix not only underscore the potential of utilizing bio-based materials but also highlight the advancements in nanocomposite technology aimed at achieving superior performance characteristics (**Figures 7** and **8**).



(a) (b)

Figure 7 SEM images of epoxy polymer and BC/MWCNTs nanocomposite; (a) epoxy polyme and (b) epoxy/MWCNTs 0.5 %.



(a) (b)

(c) (d)

Figure 8 SEM images of epoxy nanocomposite materials with BC/MWCNTs: (a) −5 % BC; (b) −5 % BC, 0.25 % MWCNTs; (c) −5 % BC, 0.5 % MWCNTs; (d) −5 % BC, 0.75 % MWCNTs.

Structural morphology of nanocomposite materials on epoxy system reinforced with MWCNTs/bacterial cellulose (BC)/glass fiber (GF)/epoxy

This shows that BC and MWCNTs have a great impact on the matrix material, enhancing the interaction between the resin-fiberglass interface. For materials without the participation of BC and MWCNTs, on the fiber surface, the resin is peeled and peeled off. BC (bacterial cellulose) and MWCNTs (Multi-Walled Carbon Nanotubes) are additives with special properties that help enhance the mechanics and properties of composite materials. BC has the ability to form a

crystalline cellulose fiber network with a large surface area, helping to enhance the mechanical connection between the components in the composite.

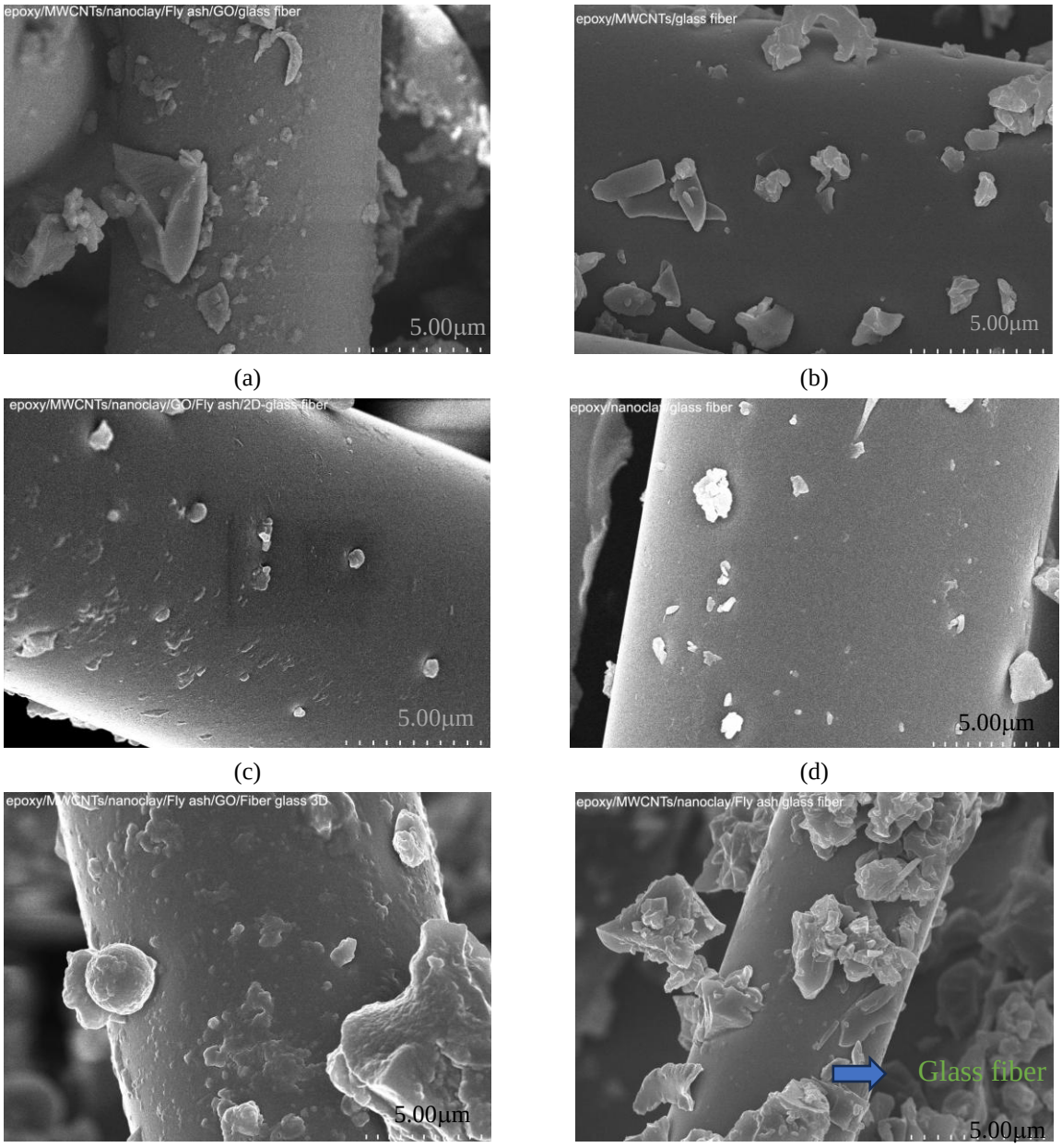


Figure 9 Structural morphology of epoxy-based composite materials reinforced with woven glass fibers containing BC, MWCNTs: (a) Epoxy/0.5 % MWCNTs; (b) epoxy/glass fiber; (c) epoxy/5 % BC; (d) 5 % BC, 0.25 % MWCNTs; (e) 5 % BC, 0.5 % MWCNTs; (f) 5 % BC, 0.75 % MWCNTs.

MWCNTs, with high mechanical strength and electrical conductivity, act as nanotubes that bridge the glass fiber and epoxy resin, enhancing the mechanical properties and strength of the material. The FE-SEM results clearly show that the combination of BC and MWCNTs significantly improved the adhesion and interaction between glass fibers and epoxy resin, enhancing the strength and properties of the composite materials. This is of great significance in the development of advanced composite materials, used in applications requiring high strength and superior mechanical properties. By adding BC and MWCNTs,

composite materials can achieve higher performance, enhanced strength, stiffness and load-bearing capacity, opening up many application possibilities in industrial and engineering fields (**Figure 9**).

TGA thermal properties

In the TGA (Thermogravimetric Analysis) of BC (bacterial cellulose) extracted from nata de coco using a 0.3 M NaOH solution (**Figure 10**), the thermal stability of the samples shows significant differences depending on the ultrasound duration.

Specifically, as the ultrasound duration increases from 30 to 60 min, the thermal stability of the bacterial cellulose also increases significantly. This improvement can be explained through several key mechanisms. First, ultrasound helps to break down the network structure of bacterial cellulose, increasing the surface area for interaction. As a result, the NaOH solution can penetrate deeper into the cellulose structure, enhancing its ability to react with unwanted organic compounds. This not only aids in the removal of impurities but also promotes chemical reactions that create more thermally stable products. Second, longer ultrasound durations can lead to changes in the molecular structure of bacterial cellulose. The uniform dispersion and mechanical effects from the ultrasound waves can weaken certain bonds within the cellulose structure, resulting in a more stable material.

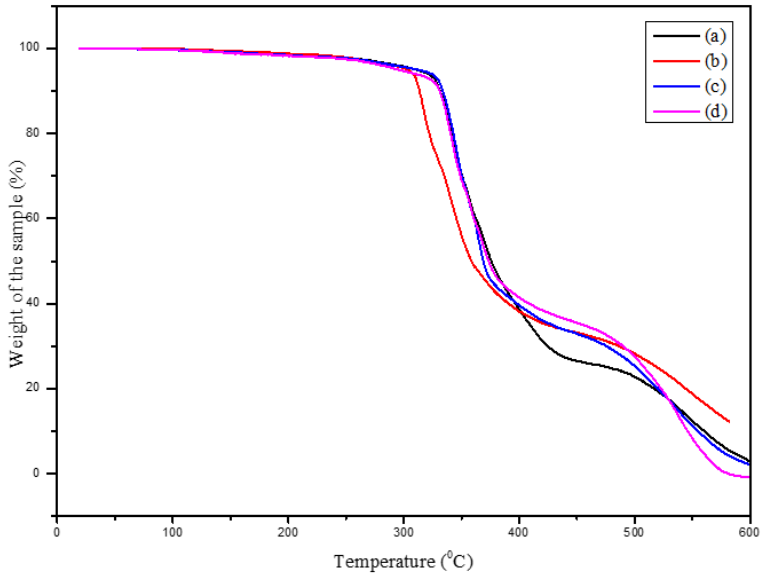


Figure 10 TGA thermal properties of BC: (a) BC was sonicated for 45 min and treated with 0.3 M NaOH; (b) BC no ultrasound; (c) BC was sonicated for 60 min and treated with 0.3 M NaOH; (d) BC was sonicated for 30 min and treated with 0.3 M NaOH.

This contributes to an improved thermal resistance, allowing it to maintain its physical and chemical properties when exposed to high temperatures. Additionally, after the ultrasound process, the removal of impurities is carried out more effectively. These impurities can reduce the thermal stability of the material, and their complete removal through rinsing and neutralization significantly enhances the thermal resistance of the BC. In summary, increasing the ultrasound duration from 30 to 60 min not only improves thermal stability but also enhances the overall quality of the bacterial cellulose extracted from nata de coco. The changes in structure, combined with the removal of impurities, create a BC product with better thermal resistance, opening up broader applications in fields such as biomaterials, healthcare and food (**Figure 11**).

Mechanical properties of nanocomposite materials on epoxy system reinforced with MWCNTs/bacterial cellulose (BC)

The nano composite material based on epoxy resin, reinforced with bacterial cellulose (BC) and multi-walled carbon nanotubes (MWCNTs), has shown a

significant improvement in mechanical properties. Research indicates that the presence of either BC or MWCNTs enhances the mechanical characteristics of the material. Notably, the combination of both additives creates a strong synergistic effect, leading to a substantial increase in strength.

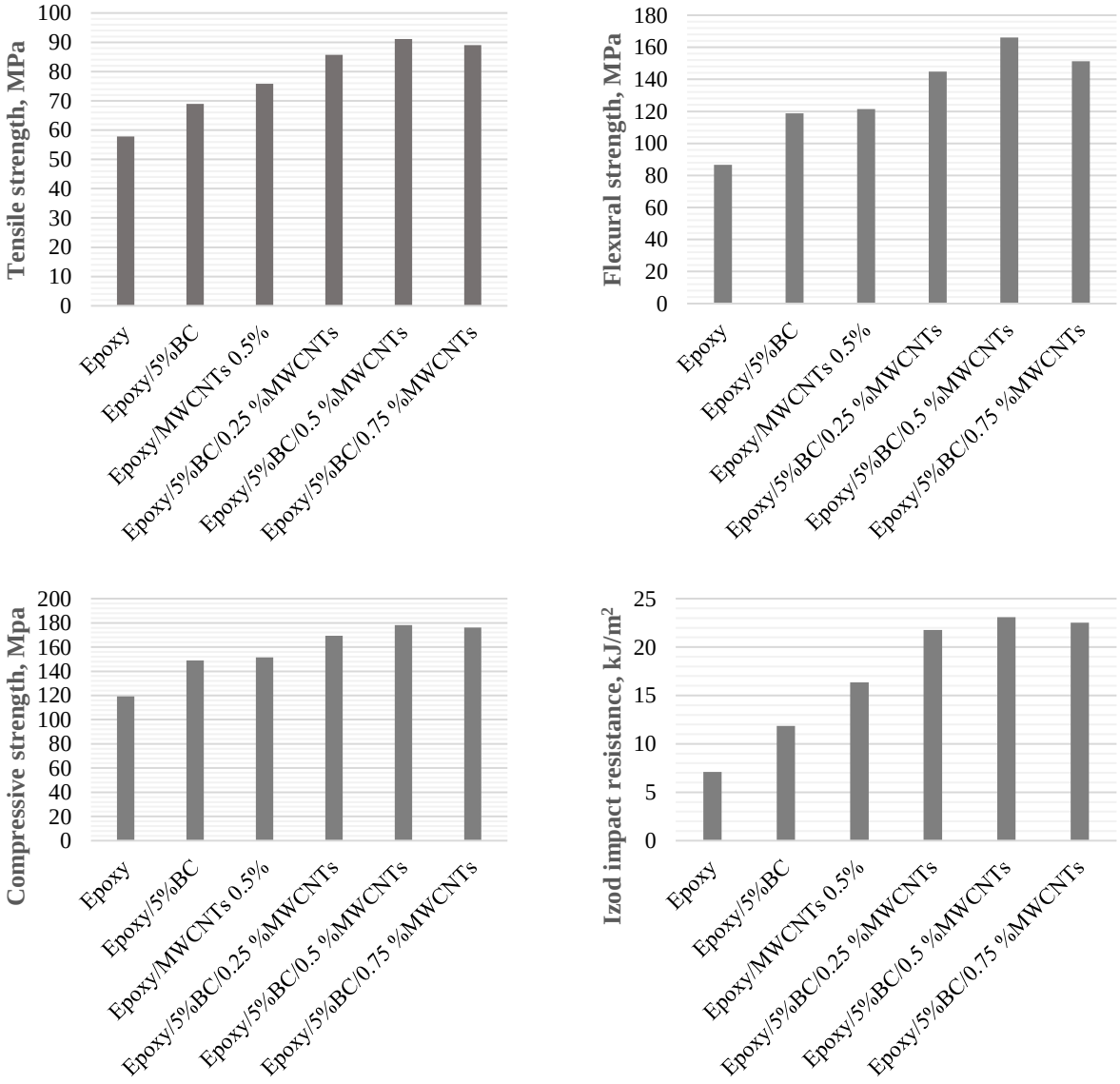


Figure 12 Mechanical properties of nanocomposite materials on epoxy system reinforced with MWCNTs/bacterial cellulose (BC).

The optimal ratio identified is 5 % by weight of BC combined with 0.5 % by weight of MWCNTs, yielding impressive values for mechanical strength: Tensile strength reaches 91.09 MPa, flexural strength is 166.05 MPa, compressive strength is 178.06 MPa, and Izod impact strength is 23.09 kJ/m^2. These results not only confirm the ability to improve the mechanical properties of the composite material but also open new avenues for developing stronger, lighter materials suitable for various industrial and construction applications. The combination of BC and MWCNTs is seen as a potential solution for creating green and environmentally friendly materials. Specifically, the Epoxy/5 % BC/0.5 % MWCNTs material exhibits superior mechanical strength due to the optimal combination of BC and MWCNTs. This ratio maximizes the advantages of both, creating a robust network of connections within the epoxy matrix. This synergistic effect enhances load-bearing capacity, while the uniform dispersion of the components improves the

microstructure of the material. In contrast, other ratios such as 0.25 or 0.75 % MWCNTs, or using only BC, do not achieve the same level of strength due to ineffective interactions or a lack of one of the key components (**Figure 12**).

Flame retardant properties of nanocomposite materials on epoxy system reinforced with MWCNTs/bacterial cellulose (BC)

The use of nano composite materials based on epoxy resin reinforced with bacterial cellulose (BC) and multi-walled carbon nanotubes (MWCNTs) is an effective method to improve the fire-retardant properties of the material. The results indicate that the presence of either BC or MWCNTs additives enhances the fire-retardant characteristics of the material, and when both types of additives are combined, the synergistic effect between them significantly increases the fire resistance of the material. At a combination ratio of 5 % by weight of BC and 0.5 % by weight of MWCNTs, the material achieves the best fire-retardant performance, as measured by the Limiting Oxygen Index (LOI) and burning rate. LOI is the percentage of oxygen in the air required to sustain combustion, and a higher LOI indicates better fire resistance. A slower burning rate also suggests that the material has better fire resistance in the event of an incident. The improvement in fire-retardant properties when combining BC and MWCNTs can be explained by the interactions between the components in the composite system. BC has the ability to absorb moisture and create a protective layer on the surface of the material, minimizing the exposure between the material and oxygen, thus reducing the likelihood of combustion. MWCNTs, with their nano structure and good electrical conductivity, can also form a char layer and slow down the burning process of the material. The combination of BC and MWCNTs creates a synergistic effect, enhancing the fire-retardant properties of the composite material and making it a widely applicable safe choice in various fields such as construction, transportation and electronics (**Table 2**, **Figure 13**).

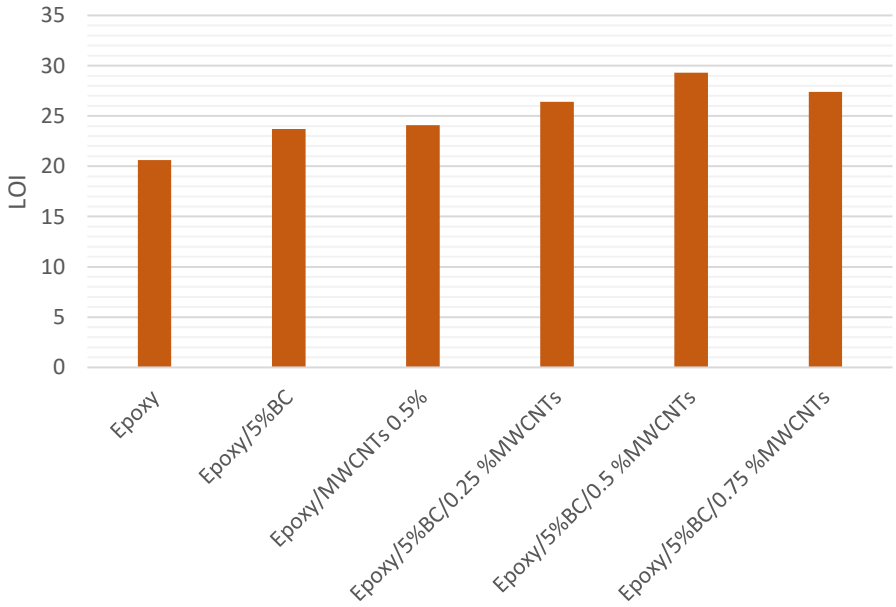


Figure 13 Flame retardant properties of MWCNTs/bacterial cellulose (BC) materials through LOI index.

The results from the data table indicate that the addition of MWCNTs to the epoxy and 5 % bacterial cellulose (BC) mixture improved the fire resistance of the materials. All samples containing MWCNTs achieved a UL-94 rating of V-2, demonstrating good fire resistance, which is a notable difference compared to the samples without MWCNTs. The burning times for these samples ranged from 31 to 36 s, with the sample containing 0.25 % MWCNTs (Sample 3) having the longest burning time (36 s), suggesting that the concentration of MWCNTs may affect the burning rate. However, all samples with MWCNTs exhibited

dripping, which could increase the risk of fire spread. Therefore, while MWCNTs enhance fire resistance, optimizing their concentration is necessary to achieve a balance between fire performance and controlling the dripping phenomenon.

Table 2 Flame retardant properties of MWCNTs/bacterial cellulose (BC) materials through UL-94V.

No	Sample	UL-94 Rating	No	Sample
1	Epoxy/5 % BC	-	-	-
2	Epoxy/MWCNTs 0.5 %	-	-	-
3	Epoxy/5 % BC/0.25 % MWCNTs	V-2	36.35	Yes
4	Epoxy/5 % BC/0.5 % MWCNTs	V-2	31.24	Yes
5	Epoxy/5 % BC/0.75 % MWCNTs	V-2	34.67	Yes

Mechanical properties of nanocomposite materials on epoxy system reinforced with MWCNTs/bacterial cellulose (BC)/glass fiber

The results of the mechanical properties presented in **Figure 14** indicate that epoxy-based composite materials reinforced with a combination of nano bacterial cellulose (BC) and Multi-Walled Carbon Nanotubes (MWCNTs), along with fiberglass, achieve significantly higher mechanical strength compared to epoxy-based composites that contain only BC or MWCNTs reinforced with fiberglass. Notably, when varying the MWCNTs content from 0.25 to 0.75 % by weight, the mechanical properties reach their peak at 0.5 % MWCNTs. At this optimal concentration, the tensile strength is recorded at 379.07 MPa, the flexural strength at 390.86 MPa, the compressive strength at 355.03 MPa, and the impact strength at 168.15 kJ/m^2. This demonstrates the effective synergy between BC and MWCNTs in enhancing the overall mechanical performance of the composite material, highlighting the potential for utilizing these nanomaterials in advanced composite applications.

At the 0.5 % MWCNTs combination ratio, the mechanical strength of the composite material achieves its best values for several reasons. Firstly, at this level, MWCNTs can disperse uniformly within the epoxy matrix, optimizing the interactions between the nano fibers and the resin matrix, thereby improving the overall mechanical properties. Secondly, MWCNTs have excellent load-bearing capacity, and at this ratio, they can fully utilize their strength without causing blockages or defects in the material. Furthermore, the addition of MWCNTs not only increases the tensile strength but also enhances the stiffness and flexural strength of the composite.

The 0.5 % ratio may be optimal for reinforcing properties without compromising the material's ductility. Finally, when combined with bacterial cellulose, this ratio creates a synergistic reinforcement effect, where both additives work together to optimize mechanical properties. In summary, 0.5 % MWCNTs is the optimal ratio that maximizes the mechanical properties of the composite material.

From this result, it can be seen that the combination of BC and MWCNTs in the epoxy matrix has created a synergistic effect, which significantly enhances the mechanical properties of the composite material. BC provides a crystalline cellulose fiber network with a large surface area, which improves the bonding and dispersion of the components in the composite material. MWCNTs, with their excellent mechanical and electrical properties, not only enhance the strength of the material but also improve its resistance to force and impact.

The mechanical enhancement at 0.5 wt% MWCNTs content can be explained by the optimal dispersion of nanotubes in the epoxy matrix, forming a strong bonding network between the composite components. At lower MWCNTs content, the dispersion is not enough to produce the optimal strengthening effect, while at higher content, agglomeration may occur, reducing the strengthening effect.

This result not only confirms the important role of BC and MWCNTs in improving the mechanical properties of composite materials but also provides important guidance on optimizing the MWCNTs content to achieve the best mechanical properties. This

opens up opportunities for the development of advanced composite materials with high performance, applied in industrial and engineering fields requiring high strength and stability.

When increasing the MWCNTs content to 0.75 %, the mechanical strengths of the composite materials tend to decrease. This can be explained by the agglomeration of MWCNTs when the concentration increases. At 0.5 % MWCNTs content, the nanotubes are evenly dispersed in the epoxy resin matrix, creating a strong bonding network between the resin molecules and glass fibers, thereby enhancing the mechanical strength of the material. However, when the MWCNTs content increased to 0.75 %, the nanotubes began to agglomerate together, forming MWCNTs clusters instead of being evenly dispersed.

This agglomeration phenomenon reduced the contact surface area between the MWCNTs and the epoxy matrix, reducing the reinforcing effect of the nanotubes. The MWCNTs clusters created weak points in the composite structure, reducing the ability to transmit force and disperse stress in the material. This resulted in a decrease in the tensile strength, flexural strength, compressive strength and impact strength of the composite.

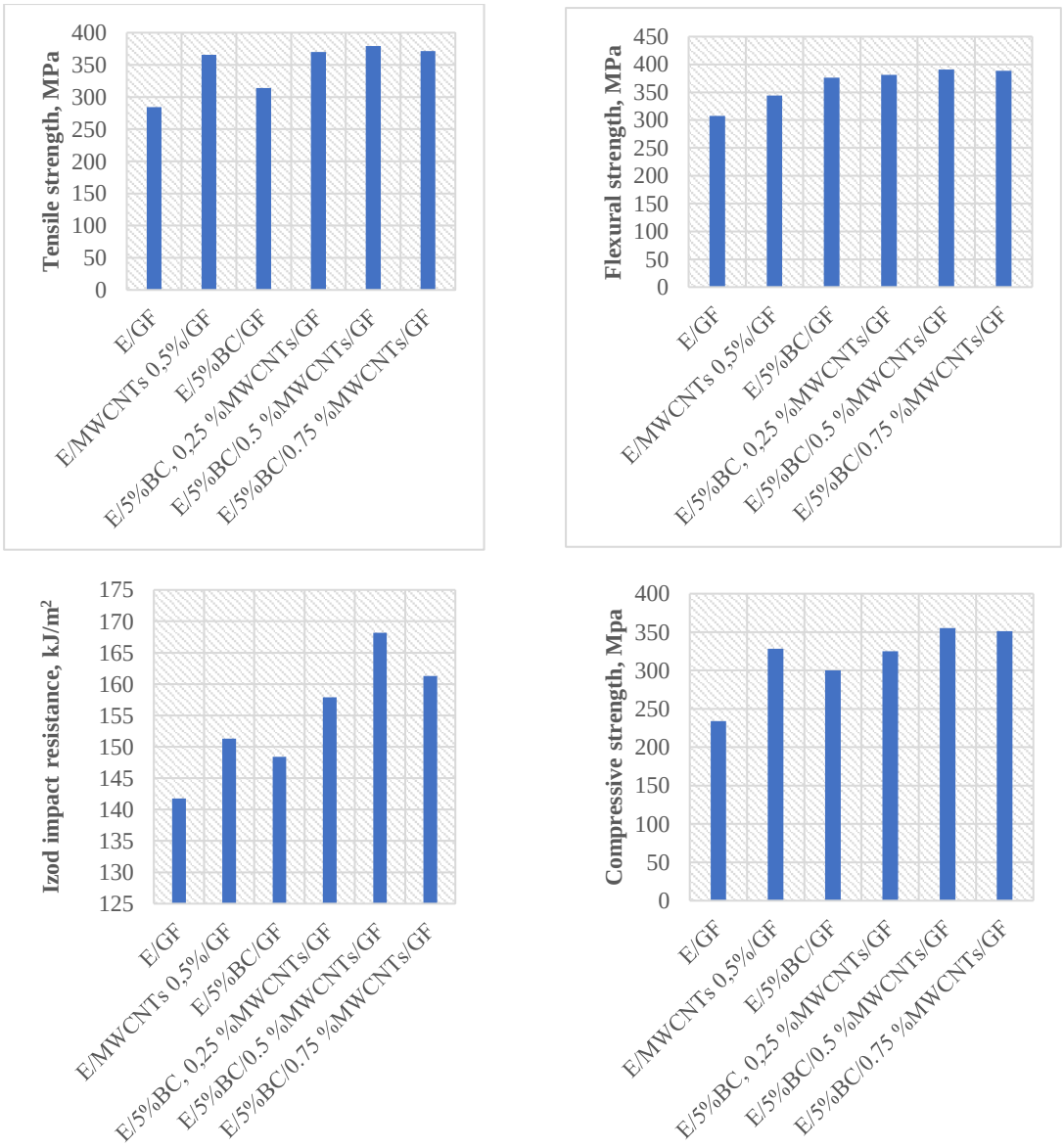


Figure 14 Mechanical properties of materials: Epoxy/glass fiber (GF) = E/GF; E/MWCNTs 0.5 %/GF; E/5 % BC/GF; E/5 % BC, 0.25 % MWCNTs/GF; E/5 % BC/0.5 % MWCNTs/GF; E/5 % BC/0.75 % MWCNTs/GF.

In addition, the MWCNTs clusters can create voids and defects in the epoxy matrix, reducing the uniformity and continuity of the material structure. These defects can become the initiation points of cracks and fractures, reducing the overall mechanical strength of the composite.

This result emphasizes the importance of controlling the MWCNTs content and dispersion during the fabrication of composite materials to optimize mechanical properties. Maintaining the uniform dispersion of MWCNTs at the optimal concentration (0.5 %) achieved the best improvement in the mechanical strength of the material.

According to the results presented in **Figure 14**, the mechanical strength of the composite material peaks at 0.5 % MWCNTs content but decreases at lower (0.25 %) or higher (0.75 %) concentrations. The primary reason for this decline is agglomeration and reduced compatibility of the nanomaterials with the epoxy matrix. When the MWCNTs content exceeds 0.5 %, uniform dispersion in the epoxy becomes challenging, leading to agglomeration, as clearly shown in SEM images in **Figures 6** and **8**. These MWCNT clusters act as weak points within the material's structure, reducing stress transfer efficiency and overall mechanical properties. Furthermore, agglomeration hinders wetting and compatibility between BC, MWCNTs and the epoxy matrix, impairing chemical and mechanical bonding between phases. Therefore, controlling dispersion and improving compatibility are crucial to optimizing the reinforcing potential of BC and MWCNTs in composite materials.

Flame retardant properties

Regarding the flame retardant properties, the epoxy composite material containing 5 % bacterial cellulose (BC) and 0.5 % multi-walled carbon nanotubes (MWCNTs) reinforced with fiberglass (GF) exhibits the best flame retardant characteristics. Specifically, the Limited Oxygen Index (LOI) reaches 31.8 %, indicating that this material has superior fire resistance, achieving a V1 rating according to the UL 94HB standard. A high LOI value signifies that the material can self-sustain in an environment with low oxygen concentration, thereby reducing the risk of fire during use. However, when the MWCNTs content is increased to 0.75 %, the flame retardant properties of the material tend to decrease, as shown in **Table 3**. This reduction may be due to changes in the structure and properties of the composite when the MWCNTs content exceeds the optimal level, leading to a diminished fire resistance. Therefore, controlling the MWCNTs ratio is crucial for maintaining and optimizing the flame retardant properties of the epoxy composite materia

Table 3 Flame retardant properties of composite materials.

Sample	LOI	UL-94V
Epoxy/Glass fiber (GF) = E/GF	27.6	-
E/0.5 % MWCNTs/GF	28.9	-
E/3 % BC/GF	30.3	V_2
E/3 % BC, 0.25 % MWCNTs/GF	30.7	V_1
E/3 % BC, 0.5 % MWCNTs/GF	31.8	V_1
E/3 % BC, 0.75 % MWCNTs/GF	31.6	V_1

At a concentration of 0.5 %, MWCNTs create a uniformly dispersed network within the epoxy matrix, in combination with bacterial cellulose (BC), to form a protective layer on the composite surface during combustion. This protective layer can prevent the infiltration of oxygen, thereby reducing the burn rate. The network also possesses good heat dissipation properties, helping to lower the surface temperature and inhibit the thermal degradation of the epoxy resin, which enhances the flame retardant characteristics of the material. However, when the MWCNTs content is increased to 0.75 %, the agglomeration of MWCNTs begins to occur, creating weaknesses in the protective network. Clusters of MWCNTs that are not uniformly dispersed can reduce heat dissipation and surface protection, leading to decreased flame retardant efficiency. The combination of BC and MWCNTs at a 0.5 % concentration represents the optimal level, but

when it exceeds this threshold, the dispersion becomes uneven, causing agglomeration and creating voids, which diminish the protective efficacy and fire resistance of the material. These results indicate that optimizing the content of components in the composite material is crucial for achieving the best mechanical properties and flame retardant characteristics. Controlling the ratios of additives not only impacts flame resistance but also determines the overall performance of the composite material.

SEM images of ash residue of materials after evaluating flame retardant properties

The results of SEM imaging of the remaining burnt carbon residue of the material samples after LOI and UL The 94V testing results, as illustrated in **Figure 15**, provide significant insights into the structural integrity and performance characteristics of the materials under evaluation. In particular, the comparative analysis between the coal samples with and without the incorporation of nano additives reveals stark differences in structural morphology and resilienc.

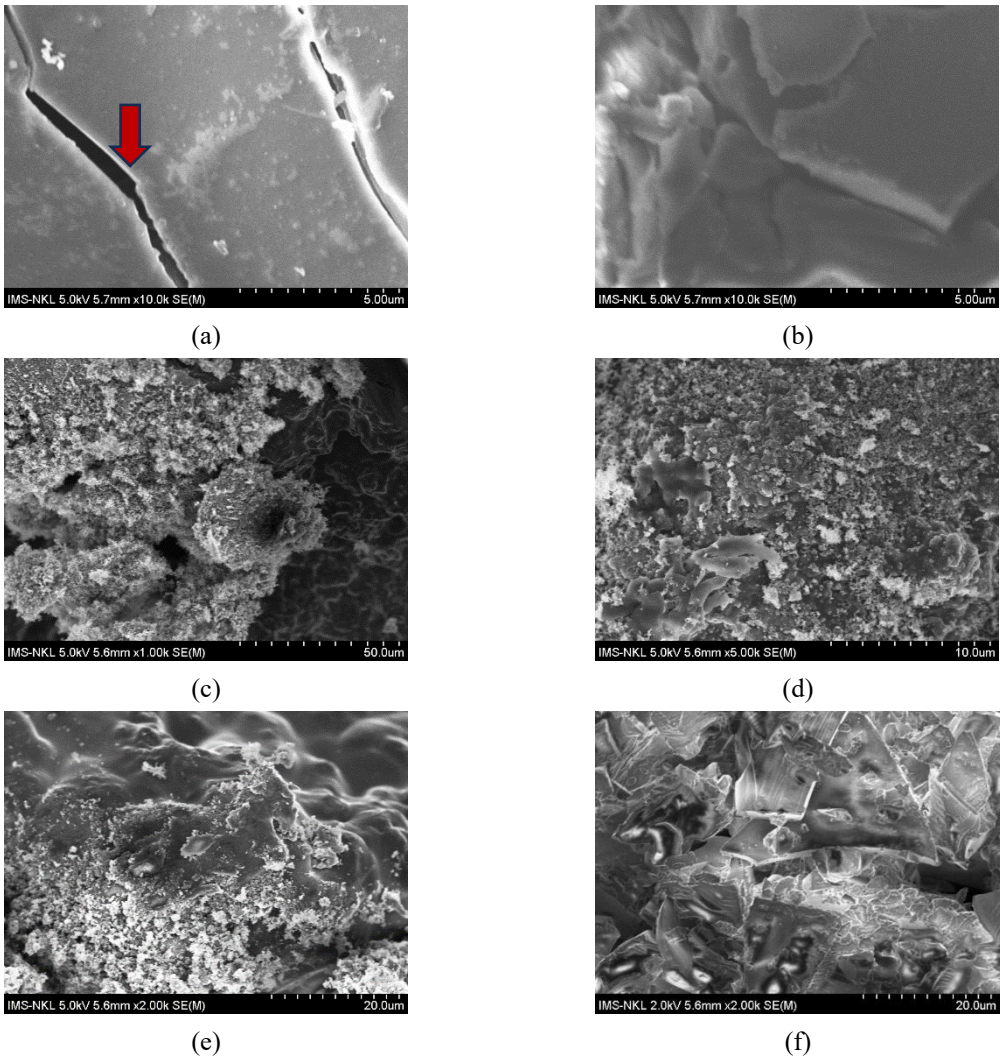


Figure 15 SEM images of the carbon residue after testing the combustion properties of the composite materials: (a) Epoxy; (b) epoxy/BC; (c): epoxy/BC 3 %/MWCNTs 0.25 %; (d) epoxy/BC 3 %/MWCNTs 0.75 %; (e) epoxy/BC 3 %/MWCNTs 0.5 %; (f) epoxy/MWCNTs 0.5 %.

For the material sample devoid of any nano additives, the SEM images depict a porous structure, characterized by numerous cracks and voids. This porosity is indicative of a weaker bond within the matrix, leading to compromised mechanical properties and a higher susceptibility to thermal degradation. The presence of cracks suggests that the material may not withstand high-temperature applications, thereby

limiting its potential use in demanding environments. In contrast, the coal sample that includes both bacterial cellulose (BC) and multi-walled carbon nanotubes (MWCNTs) showcases a markedly different structure, particularly at the optimal ratio of 5 % BC combined with 0.5 % MWCNTs. The SEM images clearly illustrate a solid and robust structure, devoid of the porosity and cracking observed in the untreated sample. This enhancement in structural integrity can be attributed to the synergistic effects of BC and MWCNTs on the epoxy resin matrix.

Bacterial cellulose, with its unique nanofiber structure, plays a crucial role in enhancing the overall properties of the composite. The nanofibers of BC significantly improve the dispersion of the matrix, allowing for a more uniform distribution of the reinforcing agents throughout the epoxy resin. This uniformity is critical for creating a strong interfacial bond between the matrix and the fillers, thus facilitating an efficient load transfer during mechanical stress. Additionally, BC contributes to the material's heat resistance and tensile strength, effectively acting as a reinforcement that mitigates thermal degradation.

On the other hand, multi-walled carbon nanotubes (MWCNTs) are renowned for their exceptional mechanical strength and thermal conductivity. When incorporated into the epoxy matrix, MWCNTs enhance heat transfer and thermal resistance, contributing to a more effective dissipation of heat. This is particularly advantageous in high-temperature applications, where maintaining structural integrity is essential. The high aspect ratio of MWCNTs further aids in reinforcing the matrix, thereby reducing the likelihood of crack formation and propagation under thermal stress.

The combination of BC and MWCNTs at the optimal ratio creates a cohesive and resilient bonding network within the composite. This enhanced bonding structure not only improves mechanical properties but also plays a pivotal role in fire resistance. The tight interconnection between the components serves to prevent the formation and propagation of cracks when exposed to high temperatures, thereby maintaining the structural integrity of the material.

Furthermore, the improved bonding network significantly reduces outgassing, a phenomenon that can lead to increased flammability. By minimizing the release of volatile compounds during thermal exposure, the composite exhibits enhanced flame retardant properties. This reduction in flammability is crucial for applications where safety is a priority, as it helps to mitigate the risks associated with fire hazards.

In conclusion, the findings from the 94V testing underscore the transformative impact of incorporating BC and MWCNTs into the epoxy resin matrix. The optimal combination of 5 % BC and 0.5 % MWCNTs results in a material that not only exhibits superior mechanical properties but also enhanced flame retardant characteristics. This balance of properties ensures that the composite maintains its structural integrity even when subjected to high temperatures, thereby broadening its applicability across various demanding environments. As such, the integration of these nano additives into the composite presents a promising avenue for the development of advanced materials that meet the rigorous standards required in modern applications.

The key components influencing the flame retardancy of the composite in this study are bacterial cellulose (BC) and carbon nanotubes (CNTs). BC, with its nanofiber structure and large surface area, contributes to forming a protective char layer during combustion, reducing fire and heat propagation. CNTs, when uniformly dispersed in the composite, create a 3-dimensional network that enhances thermal stability and limits heat transfer. The interaction between BC and CNTs can produce a synergistic effect, significantly improving flame retardancy. However, poor dispersion of CNTs may reduce the flame-retardant efficiency, making the control of their dispersion process critical. Additionally, flame-retardant additives (if included), such as phosphorus-based compounds or ammonium polyphosphate, can further enhance flame retardancy by forming a protective layer or releasing non-combustible gases. Indicators such as LOI and UL-94 tests clearly demonstrate the effectiveness of each component, with samples containing well-dispersed CNTs typically achieving higher flame-retardant performance.

Conclusions

The results showed that the nanocomposite material at the incorporation ratio of 5 wt% bacterial cellulose (BC) and 0.5 wt% multi-walled carbon nanotubes (MWCNTs) achieved the best performance in mechanical and flame retardant properties. In the

mechanical dimension, this material exhibited the best tensile strength, flexural strength, compressive strength and impact strength compared to other incorporation ratios. Meanwhile, in the flame retardant aspect, the material at this ratio had the highest flame retardant ability, which was demonstrated by the minimum oxygen index of 29.3 % and the flame retardant rate of 16.02 mm/min. This result was the result of the unique combination of BC and MWCNTs, the 2 main components of the nanocomposite material. BC, with its natural fiber structure and good mechanical properties, provided rigidity and good interaction with the epoxy resin matrix. MWCNTs, with their nano-shape and structure, provide mechanical reinforcement and fire resistance to the material. This combination improves the homogeneity and dispersion of the reinforcement phase in the epoxy resin matrix, thereby enhancing the mechanical properties and fire resistance of the nanocomposite material.

Epoxy resin-based nanocomposite materials with BC and MWCNTs present simultaneously when reinforced with glass fabric, with a combination ratio of 5 % BC, 0.5 % MWCNTs, the material has a flame retardancy at LOI 30.8 % and UL-94V at V1, which is a good fire retardant material. With such superior properties, BC/MWCNTs nanocomposite materials can not only be applied in many industrial fields such as aerospace, automobile, construction, but also have great potential in the medical and environmental fields, where materials with high strength and good fire resistance are required.

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Data availability

The data used to support the findings of this study are included within the article. The authors declare that there is no conflict of interest regarding the publication of this paper.

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