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Advancing Sustainable Materials: The Role of Modified Bacterial Cellulose in Modern Technology

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ABSTRACT

Bacterial cellulose (BC), a naturally derived biopolymer synthesized by certain bacteria, has emerged as a material of immense scientific and industrial interest due to its unique structural and functional properties. This review provides a comprehensive analysis of the modification strategies applied to bacterial cellulose and their impact on the material's morphological characteristics and application potential. The discussion encompasses various forms of modified cellulose, including micro fibrillated cellulose (MFC), microcrystalline cellulose (MCC), networked cellulose, nanocrystalline cellulose (NCC), cellulose-carbon nanotube composites, and cellulose-clay composites. Each form is examined in terms of its production techniques, structural attributes, and functional properties, highlighting how these modifications enhance BC's mechanical, electrical, thermal, and barrier performance. Special emphasis is placed on the morphological transformations induced by these modifications and their implications for specific applications, ranging from biomedical engineering and energy storage to environmental remediation and sustainable packaging. Emerging trends, such as the integration of artificial intelligence in material design, bioinspired structures, and sustainable production methods, are also explored, underscoring the transformative potential of bacterial cellulose in addressing contemporary global challenges. By synthesizing current knowledge and identifying key research gaps, this review aims to provide a roadmap for future innovations in the field, positioning bacterial cellulose as a cornerstone material for creating sustainable, high-performance, and multifunctional systems.

KEYWORDS: Bacterial Cellulose, Nanocrystalline Cellulose, Cellulose-Carbon Nanotube Composites, Sustainable Materials, Morphological Modification

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I. INTRODUCTION

Bacterial cellulose (BC) is a distinctive biopolymer produced by specific bacteria, notably Gluconacetobacter xylinus, via a regulated biosynthetic mechanism. In contrast to plant-derived cellulose, which frequently includes hemicellulose and lignin, bacterial cellulose (BC) is synthesized in a pure form, rendering it a desirable material for diverse scientific and industrial uses (Potivara & Phisalaphong, 2019; Rahmayetty et al., 2022; Zou et al., 2019). The structural composition of BC comprises linear β-(1→4)-linked D-glucose chains that aggregate into a three-dimensional nanofibrous network, yielding exceptional mechanical properties, including high tensile strength, crystallinity, and a notable surface area-to-volume ratio (Zou et al., 2019; Kamal et al., 2022). Bacterial cellulose's notable advantages include its biocompatibility and non-toxic characteristics, facilitating its widespread application in biomedical fields such as tissue engineering, wound healing, and drug delivery systems (Meng et al., 2019; Pacheco et al., 2017; Gao et al., 2020). The hydrophilic properties of BC enable it to retain water surpassing 90% of its weight, hence increasing its appropriateness for certain applications (Meng et al., 2019). Additionally, BC demonstrates superior thermal stability and chemical resistance, allowing it to endure extreme climatic conditions without considerable deterioration (Zou et al., 2019; Kamal et al., 2022). The intrinsic features of BC render it both versatile and amenable to many modification strategies designed to augment its functioning (Meng et al., 2019; Frone et al., 2018).

The morphological attributes of bacterial cellulose significantly influence its possible applications. The elevated porosity and connectedness of the BC network enhance effective mass transport, rendering it a desirable scaffold for composite materials (Zou et al., 2019; Kamal et al., 2022). The facile functionalization of bacterial cellulose via chemical, physical, or enzymatic methods facilitates the development of hybrid materials with improved mechanical, electrical, or thermal characteristics (Meng et al., 2019; Wasim et al., 2020). Modifications, including the integration of nanoparticles or alternative polymers, have demonstrably enhanced the mechanical properties and functionality of BC, broadening its applicability to fields such as electronics, energy storage, and environmental remediation (Meng et al., 2019; Wasim et al., 2020; Betlej et al., 2021). Recent years have witnessed a surge in interest in bacterial cellulose, propelled by the demand for sustainable and eco-friendly products. British Columbia, as a renewable resource, offers a viable substitute for synthetic polymers, especially in sectors seeking to diminish their carbon emissions (Potivara & Phisalaphong, 2019; Rahmayetty et al., 2022; Zou et al., 2019). The production process of BC, dependent on microbial fermentation, is environmentally sustainable and may be modified to employ waste substrates, thereby supporting circular economy activities (Potivara & Phisalaphong, 2019; Rahmayetty et al., 2022; Zou et al., 2019). Improvements in bioprocessing technologies and the genetic modification of cellulose-producing bacteria have greatly enhanced the scalability of bacterial cellulose production, rendering it a

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feasible choice for extensive applications (Potivara & Phisalaphong, 2019; Rahmayetty et al., 2022; Zou et al., 2019).

This review intends to deliver a thorough examination of bacterial cellulose modification techniques and their effects on the material's morphological properties. This study investigates different modified cellulose types, such as microfibrillated cellulose (MFC), microcrystalline cellulose (MCC), networked cellulose, nanocrystalline cellulose (NCC), cellulose-carbon nanotube composites, and cellulose-clay composites, to clarify how structural modifications affect material properties and expand application possibilities. Particular attention will be directed towards the morphological alterations caused by these adjustments and their ramifications for specific applications. This exploration aims to emphasize the versatility of bacterial cellulose as a platform material and its potential to tackle modern challenges across several fields.

II. MICRO FIBRILLATED CELLULOSE

Microfibrillated cellulose (MFC), or nano fibrillated cellulose (NFC), is a cellulose-derived substance distinguished by its distinctive fibrillar architecture, with individual fibrils measuring between 5 and 100 nanometers in diameter and extending into the micrometer range. This hierarchical structure is attained via the mechanical disintegration of cellulose fibers, leading to a densely entangled network of nanoscale fibrils. The elevated aspect ratio of MFC enhances its remarkable mechanical capabilities, including as tensile strength and stiffness, which may compete with those of steel, while being considerably lighter (Ballner et al., 2016; Pinkl et al., 2017). Moreover, MFC's extensive surface area, frequently surpassing 100 m^2/g, promotes robust interactions with adjacent matrix, rendering it an efficient reinforcing agent in composite materials (Pinkl et al., 2017). The manufacture of MFC entails several essential stages, commencing with the identification of a suitable cellulose source. Bacterial cellulose is frequently favored for its superior purity and crystallinity; nevertheless, plant-derived materials like wood pulp, cotton linters, and agricultural byproducts are also extensively utilized (Silviana & Susanti, 2019; Jarvis, 2017). The primary cellulose fibers undergo pretreatment operations aimed at increasing their sensitivity to fibrillation. The pretreatments may encompass chemical techniques such as acid hydrolysis, alkali treatment, or TEMPO-mediated oxidation, which alter the cellulose surface and diminish its crystallinity, consequently weakening hydrogen bonding among cellulose chains and facilitating mechanical disintegration of the fibers (Li et al., 2022; Silveira et al., 2016).

Mechanical fibrillation is the fundamental process in MFC manufacturing, utilizing diverse approaches that offer unique benefits in terms of efficiency, energy consumption, and fibril quality. High-pressure homogenization is a prevalent technique in which cellulose suspensions undergo significant shear forces and pressure fluctuations, efficiently disaggregating cellulose fibers into discrete fibrils while maintaining their structural integrity (Ballner et al., 2016). Additional methods comprise grinding, employing mechanical attrition, and ultrasonication, utilizing sound cavitation to rupture cellulose fibers. Although ultrasonication requires less energy, it is typically constrained to small-scale production because of its reduced processing capacity (Ballner et al., 2016). Cry crushing, which entails freezing followed by mechanical fragmentation, has emerged as a potential technique for creating MFC with minimal chemical intervention (Ballner et al., 2016). The morphological attributes of MFC are intricately linked to its production parameters, particularly the degree of fibrillation, which influences surface area exposure and, in turn, the material's reactivity and interaction with other constituents in composite systems. Highly fibrillated MFC typically demonstrates a gel-like consistency resulting from a dense, entangled network, but partially fibrillated versions may preserve certain fibrous traits (Li et al., 2022; Silveira et al., 2016). Crystallinity, affected by the source material and processing conditions, is a crucial characteristic. Increased crystallinity generally enhances mechanical characteristics but may diminish flexibility and processability (Li et al., 2022; Silveira et al., 2016).

Surface chemistry is essential in determining the functioning of MFC. Throughout manufacture, functional groups like carboxyl, hydroxyl, or sulfate moieties may be included via chemical modifications, improving MFC's dispersibility in diverse mediums and facilitating covalent interaction with other substances. TEMPO-oxidized MFC, characterized by a high density of carboxyl groups, has enhanced colloidal stability and compatibility with hydrophilic matrices, rendering it especially appropriates for use in coatings, films, and hydrogels (Li et al., 2022). The adaptability of MFC production methods enables the customization of its features to satisfy application needs, underscoring its promise in various technological domains, such as biological applications and structural composites (Teles et al., 2021; Silviana & Susanti, 2019). MFC is an exceptionally adaptable material possessing outstanding mechanical qualities and a distinctive fibrillar structure that can be customized through diverse production methods. Its versatility and use in composite materials highlight its importance in the progression of material research and engineering.

III. MICROCRYSTALLINE CELLULOSE

Microcrystalline cellulose (MCC) is a distinct variant of cellulose distinguished by its crystalline architecture, demonstrating a high level of crystallinity and remarkable mechanical strength. The standard particle size of MCC varies from 20 to 200 micrometers, and its distinctive structural configuration comprises aggregated crystallites interspersed with small amorphous regions. The amalgamation of rigidity and flexibility renders MCC exceptionally adaptable for diverse applications, including pharmaceuticals, food, and composite materials (Prayoga, 2023; Xiu et al., 2019; Sainorudin et al., 2018). The production of MCC principally entails the regulated hydrolysis of cellulose fibers, which selectively eliminates the amorphous areas while retaining the crystalline portions. Acid hydrolysis, especially with mineral acids like sulfuric or hydrochloric acid, is the predominant technique for generating MCC. This procedure involves exposing cellulose fibers to acidic conditions at regulated temperature and time, resulting in the depolymerization of amorphous regions while preserving the crystalline structure (Prayoga, 2023; Zaki,

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2024; Xiu et al., 2019). The selection of acid, concentration, and reaction conditions markedly affects the ultimate characteristics of MCC, encompassing its crystallinity index, particle shape, and surface chemistry (Кузнецов et al., 2023; Fitriani et al., 2022).

Alternative techniques for generating MCC encompass enzymatic hydrolysis and mechanochemical processes. Enzymatic hydrolysis employs cellulase enzymes to specifically decompose the amorphous areas of cellulose, providing an eco-friendlier alternative to acid hydrolysis. This approach is frequently constrained by enzyme specificity and expense, rendering it less scalable for industrial applications (Diarsa & Gupte, 2021; Suryadi et al., 2017). Mechanochemical procedures, like ball milling and high-pressure homogenization, mechanically fracture cellulose fibers to reveal and separate crystalline domains. Although these methods can attain elevated crystallinity, they are energy-demanding and may produce wider particle size distributions in contrast to acid hydrolysis (Rasheed et al., 2020; Baker & Oguntoye, 2023). The structural characteristics of MCC are inherently connected to its manufacturing process. The crystallinity index, indicating the ratio of crystalline material in the cellulose sample, is a vital characteristic influencing the mechanical and thermal properties of MCC. Increased crystallinity improves tensile strength and deformation resistance, rendering MCC appropriate for reinforcement in composites and medicinal formulations (Prayoga, 2023; Xiu et al., 2019; Sainorudin et al., 2018). Furthermore, particle size and shape influence the flowability, compaction behavior, and surface area of MCC, which are essential for its efficacy in particular applications, including tablet formulation and food additives (Rasheed et al., 2020; Diarsa & Gupte, 2021; Xiu et al., 2019).

Surface chemistry significantly influences MCC production. Acid hydrolysis may transfer leftover sulfate groups onto the surface of MCC particles, resulting in a minor negative charge. This alteration improves the material's dispersibility in aqueous environments and promotes interactions with cationic entities, rendering sulfated MCC especially advantageous for emulsion stabilization and rheological modification (Hindi, 2017; Xiu et al., 2019). In contrast, unsulfated MCC, derived from hydrochloric acid hydrolysis, displays a neutral surface charge and is favored in applications necessitating minimal ionic interactions, such as pharmaceutical excipients (Prayoga, 2023; Xiu et al., 2019; Zaki, 2024). The adaptability of MCC fabrication methods enables the modification of its qualities to satisfy application requirements. MCC is extensively utilized in pharmaceuticals as a binder, disintegrant, and filler owing to its biocompatibility, compressibility, and inert properties. The particle size and crystallinity of MCC can be adjusted to enhance tablet hardness, dissolving rates, and drug release characteristics (Diarsa & Gupte, 2021; Xiu et al., 2019; Ndika et al., 2019). In the food sector, MCC functions as a fat replacer, stabilizer, and texturizing agent, with its rheological properties optimized by modifying particle shape and surface chemistry (Nikolić et al., 2023; Baker & Oguntoye, 2023). In composite materials, MCC's elevated crystallinity and aspect ratio render it a potent reinforcing agent, capable of improving the mechanical and thermal properties of polymer matrices (Rasheed et al., 2020; Li et al., 2020; Baker & Oguntoye, 2023).

Moreover, the synthesis of MCC from bacterial cellulose presents further benefits compared to conventional plant-based sources. The great purity of bacterial cellulose, along with the lack of lignin and hemicellulose, streamlines the hydrolysis process, minimizing the necessity for expensive pretreatment procedures. The homogeneity of bacterial cellulose fibers guarantees uniform crystallite dimensions and structure, yielding MCC with enhanced performance attributes, rendering it especially appealing for premium applications in biomedicine, electronics, and advanced composites (Rasheed et al., 2020; Xiu et al., 2019; Ndika et al., 2019). Microcrystalline cellulose is distinguished by its well-defined crystalline structure, with features that may be meticulously designed through controlled production methods. The interaction among crystallinity, particle size, and surface chemistry determines the functioning and application potential of MCC, highlighting its significance as a versatile platform material. MCC utilizes advancements in production methods and customizes its structural properties to discover novel applications across many industries (Prayoga, 2023; Rasheed et al., 2020; Xiu et al., 2019; Ndika et al., 2019).

IV. NETWORKED CELLULOSE

Networked cellulose, distinguished by its complex fibrous structure, represents a significant research domain owing to its distinctive morphological and functional attributes. In contrast to micro fibrillated or microcrystalline cellulose, which are composed of distinct fibrils or crystallites, networked cellulose exhibits a continuous, web-like architecture characterized by entangled and cross-linked cellulose chains. This structural configuration yields remarkable porosity, mechanical strength, and surface availability, rendering it appropriate for many applications, such as filtration, tissue engineering, and energy storage (Oliver-Ortega et al., 2021; Khamwongsa et al., 2022). The mechanisms underlying the development of networked cellulose are based on self-assembly and aggregation processes occurring during cellulose synthesis. In bacterial cellulose, glucose monomers are polymerized into β-(1→4)-linked glucan chains by cellulose synthase complexes located within the bacterial membrane. These chains coalesce into fundamental fibrils, which organize into ribbons, finally constructing a three-dimensional network (Huh, 2024, O'Neill et al., 2017). The hierarchical assembly is governed by hydrogen bonding, van der Waals forces, and hydrophobic interactions, enhancing the network's robustness and stability (Guo et al., 2022). The lack of contaminants like lignin and hemicellulose in bacterial cellulose improves the regularity and coherence of its network structure, highlighting its potential for many applications (Khamwongsa et al., 2022).

The morphology of networked cellulose is profoundly affected by production variables such as pH, temperature, nutrient availability, and agitation during fermentation. Static cultivation generally produces thick, flat pellicles with a compact structure, whereas agitated circumstances facilitate the development of more porous, sponge-like networks (Huber et al., 2019). The network's porosity, measured by factors like pore size distribution and specific surface area, is

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essential for its functional characteristics. Highly porous networks have increased permeability and adsorption capacity, rendering them suitable for use in filtration membranes and scaffolds for cellular growth (Wan et al., 2015). Cross-linking is essential to the morphology of networked cellulose. Natural cross-links form by hydrogen bonding between hydroxyl groups on neighbouring cellulose chains, whereas further cross-linking can be achieved through chemical or physical changes to improve mechanical stability and functionality. Chemical cross-linking agents, such epichlorohydrin and glutaraldehyde, interact with hydroxyl groups to establish covalent bonds, hence enhancing the interconnections across cellulose chains (Guo et al., 2022). Physical cross-linking can be accomplished using techniques like as freeze-drying or heat treatment, which promote structural rearrangements and network densification (Wei et al., 2018; Murai et al., 2019). These alterations not only change the mechanical characteristics of networked cellulose but also affect its swelling behaviour, degradation rate, and interaction with external stimuli (Guo et al., 2022).

The structural intricacy of networked cellulose is further emphasized by its anisotropic characteristics. The alignment of cellulose chains during synthesis can result in a network displaying various levels of mechanical anisotropy, characterized by differing tensile strengths and elastic moduli along perpendicular axes (Guo et al., 2022). This anisotropy can be utilized in applications necessitating directional control, such as biomimetic materials or anisotropic composites. The surface topology of networked cellulose, marked by roughness and the distribution of functional groups, substantially affects its interactions with biological entities and chemicals (Guo et al., 2022). Advanced imaging and characterisation techniques, including scanning electron microscopy (SEM) and atomic force microscopy (AFM), have yielded essential insights into the morphology of networked cellulose. These techniques elucidate the complex fibrous structure at micro- and nanoscale levels, whilst X-ray diffraction (XRD) and Fourier-transform infrared spectroscopy (FTIR) assess crystallinity and chemical composition, respectively (Sun, 2023; Guo et al., 2022). These techniques have been crucial in linking morphological characteristics with functional efficacy, facilitating the systematic design of networked cellulose for targeted applications (Sun, 2023).

The applications of networked cellulose are as varied as its morphological properties. In biomedical engineering, its significant porosity and biocompatibility render it an exceptional choice for wound dressings, drug delivery systems, and tissue regeneration scaffolds (Oliver-Ortega et al., 2021). The interlinked holes enable the flow of oxygen and nutrients while offering a supporting structure for cellular adhesion and proliferation (Guo et al., 2022). In environmental research, networked cellulose is employed in water purification systems due to its extensive surface area and adjustable porosity, which facilitate the effective adsorption of pollutants and heavy metals liver-Ortega et al., 2021; Khamwongsa et al., 2022). Its mechanical durability and chemical stability make it appropriate for filtration membranes and desalination technologies (Sun, 2023). In energy storage, networked cellulose functions as a lightweight, flexible substrate for electrodes and separators in batteries and supercapacitors. The elevated surface area and conductivity, particularly when integrated with conductive additives such as carbon nanotubes, improve electrochemical performance (Khamwongsa et al., 2022). Additionally, the material's thermal stability and flame retardancy render it a viable element in fire-resistant coatings and insulation materials (Sun, 2023). The adaptability of networked cellulose is demonstrated in its application as a template for the synthesis of metal-organic frameworks (MOFs) and other porous materials, where its structural integrity and surface chemistry offer a stable basis for intricate designs (Oliver-Ortega et al., 2021).

Networked cellulose exemplifies structural sophistication, wherein self-assembly, cross-linking, and morphological variation converge to create a material of exceptional usefulness. Its capacity for customization via regulated synthesis and modification procedures highlights its potential as a foundational material for tackling modern issues in healthcare, environmental sustainability, and sophisticated manufacturing. Further investigation of the complex mechanisms governing its development and shape will provide new opportunities for utilizing the complete potential of networked cellulose in novel applications.

V. NANOCRYSTALLINE CELLULOSE

Nanocrystalline cellulose (NCC), commonly known as cellulose nanocrystals (CNCs), is an exceptional material distinguished by its distinctive crystalline architecture and nanoscale dimensions, generally measuring between 5 to 20 nanometers in diameter and 100 to 500 nanometers in length (Yudhanto et al., 2022; Ren et al., 2019). The dimensions yield an extraordinarily high aspect ratio, which, together with its crystalline structure, imparts NCC remarkable mechanical qualities, including tensile strength and stiffness that can compete with Kevlar (Xu et al., 2015). The crystalline domains of NCC comprise densely packed cellulose chains, reinforced by strong hydrogen bonding, which enhances its exceptional heat stability and degradation resistance (Tazeen et al., 2017). Furthermore, the biodegradability and renewability of NCC render it a viable option for numerous advanced applications, especially in the realm of sustainable materials (Kasa et al., 2016; Rosddi et al., 2020). The synthesis of NCC predominantly entails acid hydrolysis, a method that selectively eliminates the amorphous parts of cellulose while maintaining the crystalline domains. Sulfuric acid is frequently utilized for its efficacy in cleaving glycosidic linkages in amorphous regions, leading to the production of crystalline pieces (Safari & Ven, 2016; Yudhanto et al., 2022). The parameters governing hydrolysis, including acid content, temperature, and reaction duration, are meticulously regulated to attain the targeted particle size and crystallinity. Higher acid concentrations and prolonged reaction periods can produce smaller, more uniform nanocrystals; however, they may also result in significant deterioration and reduced yield (Yudhanto et al., 2022). Following hydrolysis, the resultant suspension undergoes neutralization, dialysis, and sonication to scatter the nanocrystals and inhibit aggregation, producing a stable colloidal suspension appropriate for diverse applications (Usov et al., 2015; Fitriani et al., 2022).

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Alternative synthesis methods for NCC including enzymatic hydrolysis and mechanochemical treatments. Enzymatic hydrolysis employs cellulase enzymes to selectively decompose the amorphous regions of cellulose, presenting an eco-friendlier alternative to acid hydrolysis; nonetheless, it is frequently constrained by enzyme specificity and cost, which may impede scalability for industrial applications (Carpenter et al., 2015; Singh et al., 2015). Mechanochemical procedures, like ball milling and high-pressure homogenization, entail the mechanical disruption of cellulose fibers to extract crystalline domains. Although these techniques can attain elevated crystallinity, they are energy-demanding and may result in wider particle size distributions relative to acid hydrolysis (Dasan et al., 2016; Trifol et al., 2016). The selection of the synthesis process is contingent upon the desired characteristics of the NCC and the demands of the intended application. The morphological attributes of NCC are intricately connected to its synthesis methodology and the originating material employed. The rod-like morphology of NCC particles results directly from the crystalline architecture of cellulose, with the longitudinal axis oriented parallel to the cellulose chain direction. The aspect ratio, defined as the ratio of length to diameter, is a crucial element that affects the mechanical and rheological properties of NCC. Elevated aspect ratios augment the reinforcing properties of the material, rendering it especially efficacious in composite materials (Liu et al., 2017; Koshani et al., 2021). The hydrolysis process, when utilizing sulfuric acid, introduces sulfate groups onto the surface of NCC particles, resulting in negative charges that improve colloidal stability and promote interactions with other materials, thus allowing NCC to function as a compatibilizer or stabilizer in multiphase systems (Zhou & Hsieh, 2020; Costa et al., 2016). The practical uses of NCC encompass a diverse range of sectors, propelled by its distinctive features. NCC functions as a reinforcing agent in composite materials, markedly improving the mechanical strength, stiffness, and thermal stability of polymer matrix. The elevated aspect ratio and crystallinity facilitate effective stress transfer between the NCC and the matrix, yielding lightweight yet durable materials appropriate for automotive, aerospace, and construction sectors (Zhang et al., 2019; Grząbka-Zasadzińska et al., 2017). Surface modification approaches, including acetylation and silane treatment, can enhance interfacial adhesion and dispersion within the matrix, hence expanding the use of NCC in high-performance composites (Liu, 2024; Fitriani et al., 2021). NCC's biocompatibility and biodegradability render it a compelling option for drug delivery systems, tissue engineering scaffolds, and wound healing applications in the biomedical domain. The elevated surface area and adjustable surface chemistry of NCC enable the regulated release of therapeutic drugs, while its mechanical characteristics offer structural support for tissue regeneration (Kasa et al., 2016; Seljak et al., 2023). NCC-based hydrogels have been engineered for prolonged drug delivery, wherein the nanoparticle network regulates drug diffusion and improves the mechanical integrity of the gel (Ren et al., 2019; Shen et al., 2021). NCC's capacity to create translucent films has been utilized in the advancement of biodegradable packaging materials and optical gadgets (Adnan et al., 2017; Grząbka-Zasadzińska et al., 2017).

The environmental industry has gained advantages from the distinctive characteristics of NCC. Its elevated surface area and porosity render it an efficient adsorbent for contaminants, heavy metals, and organic compounds in water treatment applications. NCC-based membranes and filters exhibit exceptional efficacy in pollutant removal while preserving high permeability and mechanical stability (Carpenter et al., 2015; Nemoto et al., 2015). NCC's renewability and biodegradability correspond with the growing need for sustainable materials, establishing it as a feasible substitute for petroleum-based polymers in packaging, coatings, and textiles (Mahendra et al., 2020; Sun et al., 2016). NCC has emerged as a potential material in electronics and energy storage for flexible electronics, sensors, and energy storage devices. Its elevated dielectric constant and thermal stability render it appropriate for capacitors and insulating layers, while its transparency and mechanical flexibility facilitate applications in flexible displays and photonic devices (Yousefian & Rodrigue, 2016; Gan & Chow, 2018). NCC, when integrated with conductive materials like graphene or carbon nanotubes, creates hybrid materials that exhibit improved electrical and thermal conductivity, facilitating the development of advanced energy storage systems (Rani et al., 2016; Fu et al., 2017). Nanocrystalline cellulose is distinguished by its exceptional structural and functional characteristics, which may be meticulously tailored using regulated synthesis and modification techniques. The nanoscale dimensions, elevated crystallinity, and surface chemistry determine its functioning and application potential, highlighting its significance as a versatile platform material. NCC utilizes advancements in production methods and customizes its structural properties to discover novel applications across several industries, promoting the development of sustainable and high-performance materials.

VI. CELLULOSE-CARBON NANOTUBE COMPOSITES

Cellulose-carbon nanotube (CNT) composites signify a notable progression in materials science, integrating the biocompatibility and renewability of cellulose with the exceptional mechanical, electrical, and thermal characteristics of CNTs. This combination has garnered significant interest owing to its prospective uses in diverse domains, such as electronics, energy storage, biomedical engineering, and environmental sustainability. The distinct attributes of each element are mutually amplified during integration, resulting in composites that demonstrate exceptional performance traits (Xing et al., 2018; Hu et al., 2015; Lee et al., 2016). The structural integration of cellulose and CNTs is mostly determined by the compatibility and interaction of the two materials. Cellulose, distinguished by its many hydroxyl groups, promotes hydrogen bonding and van der Waals interactions, essential for the dispersion and anchoring of CNTs inside the cellulose matrix. The propensity of CNTs to agglomerate, attributable to robust π-π stacking interactions, presents a considerable obstacle to attaining uniform dispersion (Zhang et al., 2020; Hu et al., 2015). Various surface modification strategies have been utilized to resolve this issue. Functionalizing carbon nanotubes with

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carboxyl, hydroxyl, or amine groups improves their dispersibility in aqueous solutions and facilitates covalent interaction with cellulose chains. Furthermore, the incorporation of surfactants or compatibilizers might enhance the stability of CNTs, inhibiting aggregation during the manufacture of composites (Huang et al., 2015; Hu et al., 2015).

The shape of cellulose-CNT composites is significantly influenced by the fabrication technique and the relative ratios of the two constituents. Standard methods for fabricating these composites encompass solution casting, electrospinning, layer-by-layer assembly, and in situ polymerization. Solution casting entails the dispersion of CNTs in a cellulose solution, succeeded by the evaporation of the solvent to yield a solid film. This process is simple and economical; nevertheless, it may result in uneven CNT distribution if appropriate dispersion procedures are not utilized (Promsung, 2024; Bae et al., 2018). Conversely, electrospinning generates fibrous composites characterized by significant alignment and porosity, rendering them appropriate for use in filtration, sensors, and tissue engineering scaffolds. Layer-by-layer assembly facilitates meticulous regulation of the composite's thickness and composition, permitting the fabrication of multilayered structures with customized qualities. In situ polymerization guarantees thorough mixing and robust interfacial interactions by concurrently manufacturing cellulose and integrating CNTs (Feng & Jiang, 2015; Ye et al., 2022). The resultant composites display a hierarchical architecture, wherein the nanoscale dimensions of CNTs and cellulose fibrils form a highly interconnected network. This network markedly improves the mechanical characteristics of the composite, as CNTs serve as reinforcing agents, dispersing stress and inhibiting crack formation. The mechanical properties of cellulose-CNT composites are remarkable, as research indicates that incorporating merely 1–2 wt% CNTs can substantially improve the tensile strength of cellulose films while preserving their lightweight and flexible characteristics (Kobashi et al., 2020; Lee et al., 2016). This mechanical reinforcement is particularly beneficial in applications necessitating elevated strength-to-weight ratios, such as aerospace components and flexible electronics (Han et al., 2019; Park, 2024).

Besides mechanical advantages, cellulose-CNT composites demonstrate enhanced electrical and thermal conductivity. Carbon nanotubes (CNTs) exhibit inherent electrical conductivities between 10^4 and 10^6 S/m, and their integration into cellulose matrices creates percolation networks that enhance charge transport, converting the typically insulating cellulose into a conductive substance (Kobashi et al., 2017; Shashkeev et al., 2018). The electrical conductivity of the composite is significantly influenced by CNT loading, with a critical percolation threshold being observed at 0.5–2 wt%. Past this barrier, conductivity escalates dramatically as the CNT network achieves complete connectivity (Lin et al., 2016; Wright et al., 2017). This improved conductivity has been utilized in numerous applications, such as flexible electrodes, sensors, and electromagnetic interference (EMI) shielding materials (Cho et al., 2019; Li et al., 2023). The inclusion of CNTs enhances thermal conductivity due to their remarkably high thermal conductivities (~3000 W/m·K). This attribute is especially significant in applications necessitating effective heat dissipation, including thermal interface materials and heat sinks (Kim & Kim, 2017; Zhu et al., 2021). The amalgamation of elevated thermal conductivity and mechanical pliability renders cellulose-CNT composites exemplary prospects for application in flexible electronics and energy-efficient systems.

The biocompatibility of cellulose, along with the multifunctional characteristics of CNTs, renders these composites advantageous for biomedical applications. They have been investigated for applications in drug delivery systems, tissue engineering scaffolds, and biosensors. The porous architecture of cellulose serves as a reservoir for therapeutic medicines, whilst the conductive network of carbon nanotubes facilitates controlled release via electrical stimulation (Li et al., 2022; Li, 2023). Cellulose-CNT composites provide mechanical support, electrical conductivity, and biocompatibility in tissue engineering, rendering them appropriate scaffolds for the regeneration of electrically active tissues (Aigbodion et al., 2022; Bechteler et al., 2021). Furthermore, cellulose-CNT composites possess considerable ramifications in the environmental and energy industries. In water treatment, these composites function as effective adsorbents and membranes for the elimination of contaminants, heavy metals, and organic pollutants owing to their elevated surface area and porosity (Billah et al., 2021; Lee et al., 2016). Carbon nanotubes (CNTs) have been thoroughly investigated for their uses in supercapacitors, batteries, and fuel cells, as their conductive network improves the electrochemical performance of the composite (Park et al., 2022; Estrada et al., 2015).

Cellulose-carbon nanotube composites illustrate the novel integration of natural and synthetic elements to produce multifunctional systems with exceptional features. Their superior mechanical, electrical, and thermal properties, along with biocompatibility and renewability, establish them as revolutionary materials for diverse applications. Ongoing improvements in fabrication methods and structural customization will enhance the capabilities of cellulose-CNT composites to tackle global issues in healthcare, energy, and environmental sustainability.

VII. CELLULOSE-CLAY COMPOSITES

Cellulose-clay composites signify a notable progression in material research, merging the distinct characteristics of cellulose and diverse clay minerals to produce hybrid materials with improved mechanical, thermal, and barrier properties. The hierarchical structure of these composites, marked by the incorporation of clay platelets into the cellulose matrix, enhances the intrinsic properties of each component and introduces functions that cannot be achieved by each material independently. This structural configuration is crucial in assessing the applicability of cellulose-clay composites in several domains, such as packaging, building, biomedical engineering, and environmental remediation (Qin et al., 2018; Jali, 2023). The morphological properties of cellulose-clay composites are chiefly determined by the intercalation and exfoliation of clay particles inside the cellulose matrix. Clay minerals, including montmorillonite, kaolinite, and halloysite, are layered silicates characterized by

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a high aspect ratio and surface area, which enhance their interaction with cellulose (Baruah, 2022). The incorporation of clay can transpire by intercalation, wherein cellulose chains infiltrate the interlayer spaces of the clay, or through exfoliation, where the clay layers are entirely distributed throughout the cellulose matrix. The extent of intercalation or exfoliation depends on elements including the kind of clay, the source of cellulose, and the processing conditions used during manufacture (Karan et al., 2018; Manna, 2022). Methods include solution blending, melt compounding, and in situ polymerization are frequently employed to fabricate these composites, each influencing the ultimate morphology and characteristics of the material (Mekdad, 2016).

The mechanical and barrier characteristics of cellulose-clay composites are very significant. The integration of clay platelets markedly improves the tensile strength, modulus, and toughness of the composite, while their lamellar architecture creates a convoluted pathway that obstructs the transport of gases and liquids, thus enhancing barrier efficacy (Qin et al., 2018, Jali, 2023). This is particularly advantageous in packaging applications, where inhibiting oxygen and moisture infiltration is essential for prolonging the shelf life of perishable products. The barrier characteristics of these composites can significantly surpass those of pure cellulose, rendering them exceptionally appealing for sustainable packaging solutions (Jali, 2023). Furthermore, the biodegradability and renewability of cellulose correspond with the rising need for environmentally sustainable materials, establishing cellulose-clay composites as a feasible substitute for traditional plastics (Tetyana, 2022). Besides mechanical and barrier improvements, cellulose-clay composites demonstrate enhanced heat stability and flame retardancy. The inorganic composition of clay enhances the thermal resistance of the composite, effectively protecting the cellulose matrix from heat and oxidative degradation (El-Feky, 2024). The addition of clay increases the thermal decomposition initiation temperature and diminishes the emission of flammable volatiles during burning, rendering these composites appropriate for construction and protective coating applications (Karan et al., 2018). Moreover, the flame-retardant characteristics can be augmented by integrating supplementary flame retardants that synergistically interact with clay to create a protective char layer during burning (Qin et al., 2018).

The biocompatibility of cellulose, along with the distinctive characteristics of clay, renders cellulose-clay composites as viable options for biomedical applications. These materials have been investigated for applications in drug delivery systems, tissue engineering scaffolds, and wound healing materials. The porous architecture of cellulose facilitates the encapsulation of medicinal substances, whereas the stratified structure of clay for regulated release mechanisms (Halib et al., 2017). The antibacterial qualities of specific clays can be utilized to avert infections in biomedical applications, hence augmenting the efficacy of cellulose-clay composites in healthcare (Lahiri et al., 2021; Nomicisio et al., 2023). Cellulose-clay composites have demonstrated efficacy in the removal of contaminants from water and soil within the environmental sector. The elevated surface area and cation exchange capacity of clay, along with the structural characteristics of cellulose, enable the selective adsorption of heavy metals and organic contaminants (El-Feky, 2024; Manna, 2022). These composites have been efficiently employed as membranes and filters for water treatment, exhibiting great selectivity and flux while obstructing the transmission of pollutants (Vallejo et al., 2021, Manna, 2022). Cellulose-clay composites demonstrate the synergistic advantages of integrating natural and inorganic components to produce multifunctional systems with exceptional features. Their hierarchical structure improved mechanical and barrier properties, thermal stability, and biocompatibility render them revolutionary materials for various applications. Ongoing research and development in fabrication methods and material enhancements will enhance the capabilities of cellulose-clay composites in tackling global issues in healthcare, energy, and environmental sustainability (Qin et al., 2018; Jali, 2023).

VIII. COMPARATIVE ANALYSIS OF MODIFIED CELLULOSE FORMS

The various types of modified cellulose, such as micro fibrillated cellulose (MFC), microcrystalline cellulose (MCC), nanocrystalline cellulose (NCC), cellulose-carbon nanotube (CNT) composites, and cellulose-clay composites, display unique morphological characteristics and functional properties essential for their use in multiple domains. An examination of these materials demonstrates a complicated relationship among their structural properties, manufacturing techniques, and performance indicators, highlighting their distinct advantages and limits. The fundamental distinctions among these cellulose derivatives lie in their morphology, shaped by the characteristics of the initial material and the employed processing procedures. MFC is defined by a convoluted network of nanoscale fibrils, offering a high aspect ratio and extensive surface area, rendering it appropriate for reinforcing and rheology modification applications (Sawant & Salam, 2022; Murphy & Collins, 2016). MCC comprises aggregated crystallites that provide enhanced mechanical strength and thermal stability, yet have restricted flexibility, rendering it suitable as a binder and stabilizer in medicines and food products (Ribeiro et al., 2020; Chabros et al., 2019). Networked cellulose, characterized by its fibrous structure, is distinguished by its porosity and mechanical strength, facilitating its use in filtration, tissue engineering, and energy storage (Степина et al., 2023). NCC epitomizes the highest level of crystallinity and nanoscale dimensions, distinguished by rod-like particles that offer remarkable mechanical reinforcement and optical clarity (Pan et al., 2019). The elevated crystallinity and surface charge impart distinctive characteristics, including colloidal stability and adjustable surface chemistry, beneficial for advanced composites and biological applications (Gong et al., 2022). Cellulose-CNT composites utilize the biocompatibility of cellulose alongside the electrical and thermal conductivity of carbon nanotubes, producing materials with multifunctional properties appropriate for flexible electronics and energy storage (Abraham et al., 2016). Cellulose-clay composites integrate the fibrous characteristics of cellulose with the stratified architecture of clay minerals, so improving barrier qualities, mechanical

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strength, and thermal stability, rendering them appropriate for use in packaging and construction (Степина, 2018).

The functional properties of each modified cellulose variant are intricately connected to their morphological traits. The vast surface area and entangled network of MFC promote robust interactions with adjacent matrices, rendering it suitable for composite materials and hydrogels (Sawant & Salam, 2022; Murphy & Collins, 2016). Nonetheless, its propensity for aggregation and restricted processability in dry states provide obstacles for industrial applications (Ribeiro et al., 2020). MCC's elevated crystallinity and compressibility render it extensively utilized in the pharmaceutical and food sectors; yet, its comparatively modest surface area and restricted dispersibility in aqueous environments limit its applicability in scenarios necessitating significant reactivity (Chabros et al., 2019). The porosity of networked cellulose facilitates effective mass movement; nevertheless, heterogeneity in pore size may restrict consistency and scalability (Степина et al., 2023). NCC's remarkable mechanical and optical characteristics are mitigated by issues concerning agglomeration and scalability of production (Pan et al., 2019). Cellulose-CNT composites necessitate improvements in dispersion methods to enhance interfacial interactions, whereas cellulose-clay composites encounter difficulties in attaining adequate clay exfoliation and compatibility with cellulose (Abraham et al., 2016; Степина, 2018). Overcoming these limits requires collaborative efforts across materials science, chemical engineering, and biotechnology. Advancements in fabrication methods, including green chemistry strategies and mechanochemical processes, offer potential solutions to existing difficulties (Mahmoudi, 2018). Surface modification techniques, such as polymer or surfactant functionalization, can improve compatibility and functionality (Abraham et al., 2016). The creation of hybrid materials that integrate several cellulose derivatives, such as MFC-NCC or cellulose-CNT-clay composites, offers promising prospects for engineering materials with customized features (Abraham et al., 2016).

The development of wearable electronics, smart packaging, and regenerative medicine underscores the necessity for ongoing innovation in modified cellulose materials. Researchers can utilize their distinctive morphological and functional characteristics to develop advanced materials that tackle urgent global issues in healthcare, energy, and environmental sustainability (Mahmoudi, 2018). As the discipline advances, a comprehensive understanding of structure-property correlations and the development of standardized methodologies for characterisation and testing will be crucial for converting laboratory findings into practical applications (Mahmoudi, 2018). The comparative analysis of modified cellulose variants highlights the diversity and adaptability of these materials, each possessing distinct advantages and drawbacks. By tackling the problems related to its manufacturing and application, researchers can unveil new opportunities for utilizing the complete potential of modified cellulose in creative and sustainable technologies.

IX. BACTERIAL CELLULOSE MODIFICATIONS AND THEIR IMPLICATIONS

Bacterial cellulose (BC) is a very promising biomaterial owing to its remarkable purity, crystallinity, and nanostructured shape, rendering it appropriate for many applications in advanced biomaterials and sustainable technologies. The adaptability of BC has been markedly improved through several changes, including micro fibrillated cellulose (MFC), microcrystalline cellulose (MCC), nanocrystalline cellulose (NCC), and composites incorporating carbon nanotubes (CNT) and clay. Every alteration confers distinct structural and functional characteristics, allowing BC to address various difficulties in sectors such as healthcare, energy, and environmental sustainability. Microfibrillated cellulose (MFC) is defined by its intricate network of nanoscale fibrils, which enhances its surface area and mechanical strength. These characteristics render MFC especially advantageous in applications necessitating reinforcement and rheological modification, such as in packaging and biomedical scaffolds (Srivastava, 2024; Courtenay et al., 2018). The lightweight and durable characteristics of MFC facilitate the creation of composites that are simultaneously strong and flexible, essential in industries such as coatings and tissue engineering (Pircher et al., 2015). In contrast, microcrystalline cellulose (MCC) is recognized for its elevated crystallinity and compressibility, rendering it a vital ingredient in pharmaceuticals and food additives. Its small structure guarantees reliable performance in applications requiring mechanical strength and thermal stability, while it may encounter constraints in flexibility and dispersibility (Oprea & Voicu, 2020).

Networked cellulose, characterized by its fibrous structure, provides exceptional porosity and mechanical strength, rendering it appropriate for applications in filtration, tissue engineering, and energy storage systems (Taokaew et al., 2015). The capability to customize pore size and surface chemistry facilitates the modification of materials to fulfill certain requirements, such as improving pollutant adsorption or fostering cell proliferation (Emre & KIVILCIM, 2023). Nanocrystalline cellulose (NCC), characterized by its rod-like nanoparticles, improves optical transparency and mechanical strength, hence broadening its applications in advanced composites and optoelectronics (Stricher et al., 2021). The incorporation of CNTs into cellulose matrices produces cellulose-CNT composites, merging the biocompatibility of cellulose with the enhanced electrical and thermal conductivity of CNTs, facilitating advancements in flexible electronics and energy storage (Palantöken et al., 2019). Cellulose-clay composites utilize the lamellar structure of clay to enhance barrier characteristics and thermal stability, underscoring their promise in sustainable packaging and environmental remediation (Guo et al., 2022). Notwithstanding the exceptional characteristics of these altered variants of bacterial cellulose, they encounter particular problems that necessitate additional investigation and innovation. MFC and NCC present challenges concerning aggregation and scalability, whilst MCC's restricted surface area may limit its efficacy in specific applications (Camarero-Espinosa et al., 2016). The heterogeneity in pore size and mechanical properties of networked cellulose hinders standardization attempts, and attaining uniform dispersion of CNTs in cellulose-CNT composites presents a considerable difficulty (Feng et al., 2017). The intricacies of clay

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exfoliation and compatibility in cellulose-clay composites require continuous research (Doench et al., 2019).

Overcoming these restrictions necessitates interdisciplinary strategies encompassing materials science, chemical engineering, and biotechnology. Innovations in fabrication methods, including green chemistry and mechanochemical treatments, offer potential solutions to existing difficulties (Yin et al., 2015). Surface modification techniques, such as functionalization with polymers or bioactive compounds, can improve the compatibility and functionality of modified cellulose variants (Phan et al., 2020). The creation of hybrid materials integrating various cellulose derivatives, such as MFC-NCC or cellulose-CNT-clay composites, offers promising prospects for engineering materials with customized properties for applications (Pajorová et al., 2020). Emerging advancements in artificial intelligence (AI) and bioinspired designs are advancing the field of bacterial cellulose. AI-driven algorithms can enhance production processes and expedite the identification of novel material formulations, while bioinspired designs reveal unparalleled functionality in bio-composite materials (García et al., 2016). Sustainable production techniques, such as the use of waste substrates and circular economy strategies, guarantee that BC adheres to international sustainability objectives (Courtenay et al., 2016).

X. CONCLUSION

The comprehensive examination of bacterial cellulose alterations underscores its significant potential as a fundamental material. By utilizing its distinctive characteristics and tackling current problems, researchers can further innovate and broaden the application range of BC-based materials. These advancements not only tackle significant global issues in healthcare, energy, and environmental sustainability but also facilitate a future in which bacterial cellulose is integral to the development of sustainable, high-performance, and multifunctional materials that serve societal and planetary interests.

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