Review Article

Multifunctional Nanocellulose for Sustainable Applications: From Preparation to Performance

Nida Arshad, Nichaphat Kitiborwornkul and Malinee Sriariyanun*
Biorefinery and Process Automation Engineering Center, Department of Chemical Engineering and Management, The Sirindhorn International Thai-German Graduate School of Engineering, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand

Prapakorn Tantayotai
Department of Microbiology, Faculty of Science, Srinakharinwirot University, Bangkok, Thailand

Senthil Muthu Kumar Thiagamani
Department of Mechanical Engineering, Kalasalingam Academy of Research and Education, Anand Nagar, Krishnankoil, Tamil Nadu, India

Syahidah
Fakultas Kehutanan, Universitas Hasanuddin Jl. Perintis Kemerdekaan Km. 10 Tamalanrea Makassar, Indonesia

* Corresponding author. E-mail: macintous@gmail.com

DOI: 10.14416/j.asep.2026.05.004
Received: 16 January 2025; Revised: 25 February 2025; Accepted: 11 March 2026; Published online: 12 May 2026

Abstract

Nanocellulose, a renewable material derived from cellulose, has gained significant attention as a sustainable alternative to petroleum-based materials. Owing to its biodegradability, high mechanical strength, large surface area, and tunable surface chemistry, nanocellulose offers great potential for its diverse applications. This review provides a comprehensive analysis of nanocellulose fundamentals, including its structure, sources, and major types, followed by an in-depth evaluation of its diverse application landscape. Particular emphasis is placed on recent technological advancements in biomedical engineering, food packaging, water and wastewater treatment, electronics, energy devices, and emerging multifunctional composites. The review highlights how tailored surface modifications and hybrid material designs significantly enhance nanocellulose's barrier, antimicrobial, mechanical, electrochemical, and adsorptive properties, enabling next-generation materials with improved performance and sustainability. Key challenges, including moisture sensitivity, thermal instability, aggregation behavior, scalability constraints, and characterization inconsistencies, are critically discussed. The study concludes by outlining prospects that include smart and responsive nanocellulose systems, advanced composites, and industrial pathways for integrating nanocellulose into high-value applications. Overall, this work synthesizes recent progress and provides strategic insights for advancing nanocellulose as a versatile material platform for sustainable and high-performance technological solutions.

Keywords: Biorefinery, Extraction, Functional applications, Nanocellulose, Sustainable material

1 Introduction

Petroleum–based materials are widely utilized across multiple industries due to their excellent strength, flexibility, and durability [1]. However, their robust covalent bonds make them resistant to degradation and recycling, resulting in environmental accumulation and long–term ecological challenges [2]. Growing environmental awareness, combined with a global shift toward circular economy models, has intensified the search for renewable and biodegradable alternatives [3]. These concerns have encouraged industries and researchers alike to seek environmentally responsible materials that can replace conventional petroleum–derived plastics [4].

Biopolymers such as cellulose, starch, chitin, alginate, and gelatin have therefore gained significant attention due to their renewability, biocompatibility, and environmentally benign decomposition pathways [5]. Among them, cellulose remains the most abundant natural polymer on Earth, produced at an estimated rate of 1.5×10^{12} tons annually through photosynthesis. Its hierarchical structure, from microfibrils to fibers, offers a robust foundation for producing advanced materials from a diverse range of lignocellulosic biomass sources [6].

Nanocellulose, the nanoscale derivative of cellulose, has emerged as an auspicious next–generation material because it combines the intrinsic advantages of cellulose with unique nanoscale features [7]. These include a large specific surface area, high aspect ratio, tunable surface chemistry, and exceptional mechanical properties, with reported Young's modulus values near 140 GPa and tensile strengths from 1 to 6 GPa [8]. As a result, nanocellulose has generated widespread interest for applications in biomedicine, wastewater treatment, energy devices, food packaging, and flexible electronics [9], [10].

The growing industrial relevance of nanocellulose is also reflected in its accelerating global market expansion. Market analysts estimate the global nanocellulose sector has reached USD 1.12 billion in 2025, with projections exceeding USD 2.97 billion by 2030, driven by expansions in packaging, composites, and filtration technologies [11]. Key industrial players driving global nanocellulose production include CelluForce Inc. and Anomera Inc. (Canada), GranBio (Brazil), and Sappi. Japan hosts several major producers, including Nippon Paper Industries, Oji Holdings Corporation, Chuetsu Pulp and Paper, and NAVITAS. Additional contributors like American Process Inc. and CelluComp Ltd. also support the commercial advancement of nanocellulose for applications in packaging, composites, and advanced materials [12].

Sustainability metrics provide concrete evidence of nanocellulose's environmental potential. A harmonized life–cycle inventory comparing 18 different CNC/CNF production processes reported greenhouse–gas emissions ranging from 1.8 to 1100 kg CO_2-eq per kg nanocellulose; importantly, fully mechanical or enzymatic processes were identified as the lowest–impact routes [13]. Beyond emissions, the choice of cellulose feedstock plays a critical role. Nanocellulose can be produced from abundant agricultural residues, such as straw, bagasse, and other crop by–products, helping to valorize low–value waste streams and reducing reliance on virgin wood pulp. This approach mitigates waste burning, lowers land–use pressure, and aligns with circular bioeconomy strategies. Recent scenario–based LCA modeling shows that CNC produced from agro–industrial by–products can achieve climate-change impacts of 18.9–79.6 kg CO_2-eq/kg, significantly lower than many conventional production pathways [14].

Despite these advantages, several challenges hinder efficient nanocellulose production and large–scale adoption. The crystalline and tightly hydrogen–bonded cellulose structure restricts access to reactive hydroxyl groups, limiting the efficiency of chemical modification and homogeneous functionalization [15]. To address this, diverse pretreatment and modification strategies—such as oxidation, esterification, grafting, and surface–initiated polymerization—have been developed to enhance dispersion, reactivity, and compatibility with hydrophobic matrices [16]. Advances in green processing techniques, including deep eutectic solvents (DES), ionic liquids (ILs), enzymatic pretreatments, and energy–efficient mechanical refining, further contribute to environmentally responsible nanocellulose production [17].

The multifunctionality of nanocellulose enables its integration into a broad spectrum of industrial and environmental technologies. In biomedical fields, nanocellulose supports tissue engineering, wound healing, and drug delivery due to its biocompatibility and structural similarity to extracellular matrices [18]. In environmental applications, nanocellulose–based adsorbents and membranes effectively capture dyes, heavy metals, oils, and pathogens from wastewater owing to their high surface area and tunable surface charge [19]. In food packaging, nanocellulose enhances barrier properties, transparency, and biodegradability while reducing dependence on petroleum–based films [16]. As a reinforcing agent in polymer composites, its high crystallinity and aspect ratio significantly improve tensile strength, modulus, and thermal stability. Ongoing research exploring hybrid nanocellulose materials, stimuli–responsive systems, and multifunctional composites continues to expand its potential across energy storage, electronics, packaging, and sustainability–driven industries [20].

Despite the growing number of reviews on nanocellulose, most existing studies focus primarily on material properties, extraction techniques, or individual application domains, while a systematic integration of sustainable processing strategies with structure–property–application relationships remains limited. Therefore, this review aims to bridge this gap by providing a comprehensive and integrative framework linking nanocellulose structure, processing routes, surface functionalization strategies, and resulting multifunctional properties. Specifically, this review critically examines nanocellulose sources, classifications, and extraction methods, with particular emphasis on emerging green and energy–efficient pretreatment technologies. Furthermore, key functionalization approaches are analyzed to elucidate their effects on mechanical, barrier, electrical, antimicrobial, and adsorption properties, thereby establishing clear structure–processing–property relationships. Finally, multifunctional applications in biomedicine, food packaging, electronics, energy storage, and wastewater treatment are systematically reviewed, followed by a critical discussion of techno–economic challenges and future research directions toward scalable, sustainable nanocellulose production.

2 Fundamentals of Nanocellulose

2.1 *Sources of cellulose*

Cellulose is the most abundant biopolymer on Earth. Plant–derived cellulose is the most used; other organisms, including algae, fungi, and bacteria, can also produce it (Figure 1). The open burning of agricultural residues poses serious environmental and health risks due to the release of harmful pollutants. Instead of being burned, these residues can be valorized as sustainable sources of cellulose for various applications [5], as they contain 18–49% cellulose [17]. In addition, wood–derived materials have attracted significant attention as cellulose feedstocks because of their abundant availability [21], high cellulose content (40–46%), and the advantage of not competing with food resources [17]. Wastepaper accounts for a significant portion of municipal solid waste, and its generation is increasing in tandem with growing paper consumption. Due to its high cellulose content, wastepaper is a valuable raw material for extracting nanocellulose, enabling high–value utilization of this plentiful resource [22]. Microalgae are promising feedstocks for biofuels, chemicals, food, and other products due to their rapid growth, minimal land and freshwater needs, and CO_2 sequestration capacity [23]. In addition to lipids for biofuels, certain microalgae species are rich in cellulose, making them a potential renewable source of this biopolymer [24]. The cellulose content of seaweeds varies significantly among species and is strongly influenced by their classification into green, brown, and red groups [25]. Among 19 species of green seaweeds, the average cellulose content was 9.67 w%, ranging from 1.5 to 34 w% on a dry weight (DW) basis. In 15 species of brown seaweed, cellulose content ranged from 2.2 to 10.2 w% DW, with an average value of 7.88 w%. For 47 species of red seaweeds, the cellulose content varied between 0.85 and 18 w% DW, with a mean of 4.75 w%. Overall, seaweed biomass exhibits a wide cellulose content range of 0.85–34 w% DW [19]. Bacterial cellulose closely resembles plant–derived cellulose in its molecular structure but is naturally free from impurities such as lignin and hemicellulose, resulting in a high purity of 98–99%.[18]. As a sustainable and environmentally friendly alternative, bacteria offer a promising source of cellulose. It exhibits unique properties, including complex nanostructure, high crystallinity, excellent water retention, and remarkable mechanical strength [26]. Tunicates reproduce rapidly, often overgrowing areas and displacing native species, which forces farmers to spend about 15% of their farm gate price annually on cleaning using high–pressure water or lime solutions. Interestingly, these invasive tunicates could be repurposed as a valuable source of cellulose to produce nanocellulose [27]. Generally, dry tunicates contain approximately 60% cellulose and 27% nitrogen–containing components [7]

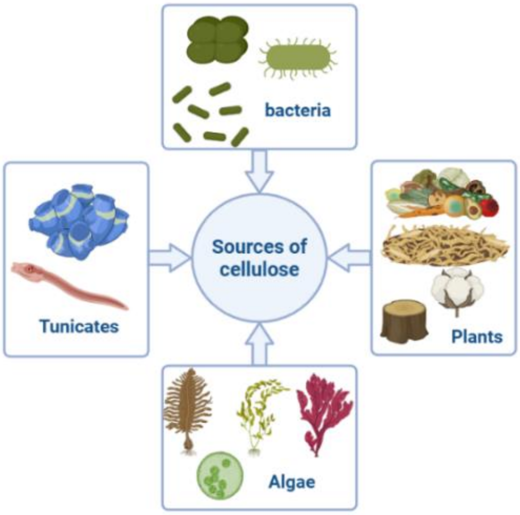

Figure 1: Sources of cellulose for nanocellulose production.

2.2 *Structure of cellulose*

Cellulose is the primary structural component of plant cell walls and constitutes the majority of plant–derived fibers. Lignocellulosic fibers consist of cellulose microfibrils embedded in a matrix of hemicellulose and lignin. Cellulose is a linear homopolysaccharide consisting of repeating anhydro–β–D–glucopyranose units linked by (1,4)–β–glycosidic bonds [4]. The cellulose microfibrils are interconnected through a network of hydrogen bonds between hydroxyl groups (Figure 2), which imparts strong mechanical strength to the lignocellulosic material [2].

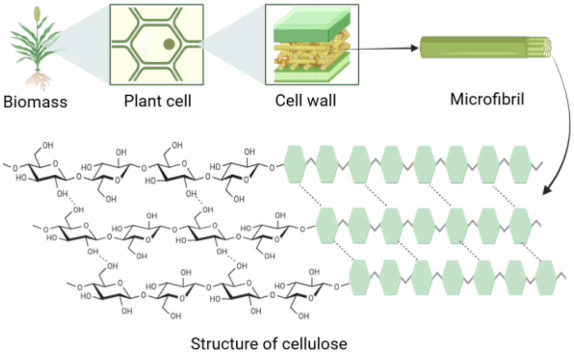

Figure 2: Chemical structure of cellulose.

Its hierarchical structure consists of tightly packed, highly ordered crystalline regions that provide strength and rigidity, interspersed with less ordered amorphous regions that contribute to flexibility and facilitate chemical reactivity [28]. This unique combination of structural features underpins the versatility and a wide range of applications of cellulose in materials, textiles, paper production, and emerging biotechnological processes [29].

2.3 *Types of nanocellulose*

Nanocellulose refers to a group of cellulosic materials characterized by at least one dimension smaller than 100 nm [30]. It is typically derived from plant–based lignocellulosic biomass through top–down processes, resulting in nanocrystals or nanofibrils with widths below 10 nm and lengths ranging from a few microns to several microns [21], [31]. Cellulose can be processed into nanocrystals or nanofibers using various techniques, including mechanical, chemical, and bio-fabrication methods [32]. Compared to natural cellulose fibers, nanocellulose demonstrates enhanced properties such as increased hydrophilicity, a significantly larger specific surface area, and higher tensile strength [33]. These superior features result mainly from strong hydrogen bonding between neighboring hydroxyl groups and van der Waals forces among the nanocellulose molecules [19]. The source of agricultural waste and the conditions of hydrolysis significantly influence the morphology, size, crystallinity, and functional groups of nanocellulose, enabling its synthesis in diverse forms and expanding its range of applications [34]. Table 1 summarizes the properties of various types of nanocellulose derived from different sources.

Table 1: Summary of the properties of nanocellulose from different sources.

Nanocellulose	Sources	Length	Width	Diameter	Shape	Ref
Cellulose nanocrystal	Peanut shells	50–300 nm		5–40 nm	Rod–like	[35]
	sesame husk			74.30 nm	Oval–shaped	[36]
	mangosteen waste peel	381.2nm		24.5 nm	Rod–like	[37]
	Jackfruit peel	60–150nm		20–30 nm	Rod–like	[38]
	Softwood kraft pulp	23.7 nm	4.7nm	260 nm	Hairy rod–shapes	[39]
	Natural rubber	245.91nm		12.53 nm	Rod–like	[40]
	Office wastepaper	400 nm		15 nm	Rod–like	[22]
	Waste ivory board	350nm		10 nm	Rod–like	
	Waste corrugated paper	200nm		10 nm	Rod–like	
Cellulose nanofiber	Eucalyptus kraft pulp	616.6 µm	18.2 µm		Entangled fibers	[41]
	Eucalyptus kraft	1–5 µm		30–110 nm	Uniform fibers	[42]
	Euterpe oleracea		7.63 nm		Connected fibers	[43]
	Bamboo		2.5–5.0 nm	14.78 nm	Fine fibers	[44]
	Natural rubber	1–2µm		10.84 nm	Entangled fibers	[40]
	Corncob			28.2 nm	Elongated fibers	[45]
	Sawn timber wastes	10–100nm		25–100 nm	Entangled fibers	[24]
	Jackfruit peel	100–500nm		100 nm	Elongated rod	[46]

Table 1: (continued)

Nanocellulose	Sources	Length	Width	Diameter	Shape	Ref
Bacterial nanocellulose	Pear juice wastewater			20–35 nm	Interwined fibers	[47]
	Acid whey	2 µm		20-100 nm	Fibrous network	[48]
	Cantaloupe juice	560–1400 nm		30–40 nm	Needle shape	[49]
	Legume processing wastewater			43 nm	Intertwined fibers	[50]
	Pineapple waste		31–68 nm	47.92–66.32 nm	Fibrous network	[51]
	Heistrin–Schramm medium	14 µm	0.5 µm	30 nm	Long threadlike	[52]
	Bamboo	1–3µm		5–20 nm	Slender fibrous	[8]
	Overripe Banana			64.38 nm	Weblike fibers	[53]

2.3.1. Cellulose nanocrystal (CNC)

Cellulose nanocrystals (CNCs) are commonly derived from lignocellulosic fibers through acid hydrolysis [41]. Their inherent surface charge and high crystallinity promote excellent colloidal stability and uniform dispersion within host polymers, enabling improved material homogeneity. At the same time, their nanoscale architecture supports strong interfacial interactions, allowing CNCs to deliver significant mechanical reinforcement, thermal stability, and structural integrity even at low filler loadings [54]. The CNC membrane provides an efficient barrier to water vapor and oxygen transfer [22]. CNCs typically have diameters of 4–55 nm and lengths of 90–400 nm, and they exhibit distinctive features such as a high density of surface hydroxyl groups, excellent transparency, high purity, and ultrafine structure [55]. The abundant hydroxyl groups can be easily functionalized, enabling hydrogen bonding, electrostatic interactions, or covalent grafting with antimicrobial agents such as chitosan, silver nanoparticles, and essential oils [56].

2.3.2. Cellulose nanofiber (CNF)

Cellulose nanofibers (CNFs) are typically produced from lignocellulosic biomass using methods such as mechanical refining or grinding, chemical or enzymatic treatments, homogenization, microfluidization, or combinations of these techniques [29]. CNFs are produced through a top–down process in which lignocellulosic material is pretreated and then fibrillated, enabling the transition from the microscale to the nanoscale [41]. Beyond their traditional uses, CNFs hold significant potential for diverse applications, including adhesive binders, flexible electronics, automotive components, packaging materials, infrastructure, construction, and separation media. Composites derived from CNF find broad applications when transformed into micro– or nanostructured porous materials [57].

2.3.3. Bacterial nanocellulose (BNC)

Bacterial nanocellulose (BNC) is produced using a bottom–up approach through the bacterial fermentation of sugars [41]. BNC is a nanoscale form of cellulose produced by certain bacteria in the form of a hydrogel membrane [58]. BNC is produced through an oxidative process that metabolizes sugars and organic acids in a medium rich in sugars and nitrogen [48]. In laboratory conditions, BNC is usually synthesized in Hestrin–Schramm (HS) culture medium, which contains glucose and other essential nutrients. However, this method is associated with high production costs [59]. In contrast to plant–derived CNF, BNCs are nearly pure cellulose, lacking additional components such as lignin, hemicellulose, or pectin [60]. Several bacterial strains, including *Acetobacter, Enterobacter, Coronobacter, Rhizobium, Agrobacterium, Aerobacter, Pseudomonas,* and *Alcaligenes*, have been reported to produce BNC. However, strains of *Komagataeibacter* are considered the most efficient for BNC production [61]. Bacterial cellulose production was carried out using pineapple waste as the carbon source by *Komagataeibacter europaeus*, achieving its highest cellulose yield of 5.04 g/L [51].

3 Preparation of Nanocellulose

3.1 *Chemical treatment*

Chemical pretreatment of lignocellulosic biomass constitutes a critical step to systematically overcome biomass recalcitrance and enhance the accessibility of cellulose for subsequent nanocellulose production [62]. These pretreatments can be categorized into several principal types: alkaline treatment, acid hydrolysis, oxidative pretreatment, ionic liquid and deep eutectic solvent treatment, organosolv pretreatment, and dissolution–regeneration methods [63]. The major preparation routes for nanocellulose from biomass are illustrated in Figure 3, highlighting chemical, physical, and biological methods.

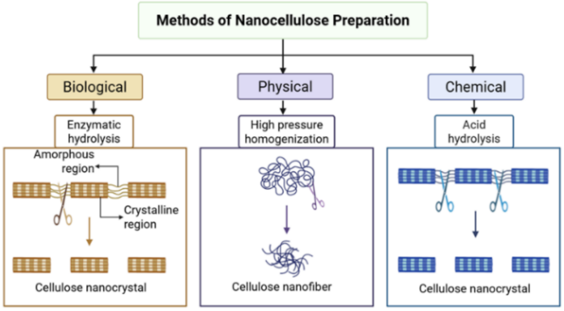

Figure 3: Different methods for the preparation of nanocellulose.

3.1.1. *Alkaline pretreatment*

Alkaline pretreatment utilizes bases such as NaOH, KOH, $Ca(OH)_2$, hydrazine, and ammonium hydroxide to systematically disrupt lignin structures and break ester bonds between lignin and hemicellulose, enhancing porosity and surface area of the biomass. This methodology has been applied to various fibers like banana, jute, and pineapple leaves [64]. Sequential alkaline–acid treatments, combining NaOH and HCl, have further improved cellulose yield, demonstrating a synergistic effect in selectively solubilizing hemicellulose and removing lignin [65].

3.1.2. *Acid hydrolysis pretreatment*

Acid hydrolysis represents another fundamental pretreatment methodology, employing inorganic acids (H_2SO_4, HCl, HNO_3, H_3PO_4) or organic acids (formic and oxalic acids) to hydrolyze amorphous cellulose while preserving crystalline regions selectively. This methodology is extensively utilized to produce CNCs from sources such as cotton, jute, cassava bagasse, and rice husk [64], [66]. Both concentrated and dilute acid systems are employed, with the former maximizing monomer sugar yield, though presenting challenges like corrosion and toxicity, while the latter is safer and cost–effective, particularly enhancing biomass separation to isolate cellulose, hemicellulose, and lignin, which can further be used for nanocellulose synthesis and chemical production [67].

3.1.3. *Green solvent pretreatment*

Ionic liquids (ILs) and deep eutectic solvents (DES) represent emerging "green" solvents due to their low volatility, non–toxicity, and capability to dissolve cellulose, hemicellulose, and lignin without degrading polymer backbones [3]. Delignification or lignin extraction using DES reduces cellulose crystallinity and generates cracks within the pretreated solids, thereby improving subsequent conversion efficiency [66], [67]. ILs such as 1–butyl–3–methylimidazolium chloride ([Bmim]Cl) disrupt hydrogen bonding within cellulose, reducing crystallinity and facilitating further processing [64]. Similarly, DES systems composed of alkali/urea or choline chloride–based mixtures offer cost-effective and sustainable alternatives for biomass pretreatment [68]. Carpentry waste wood flour was pretreated with various acidic and alkaline DESs under microwave irradiation to solubilize lignin and hemicellulose, leaving cellulose as a solid residue. choline chloride/oxalic acid (ChCl/OA) DES achieved the highest extraction yield, up to 60% under mild conditions. Nanocellulose yields were low (1.7–13.7%), likely due to the heterogeneity of the starting material, but all samples exhibited good colloidal stability (ζ–potential 26–37 mV). Hydrodynamic diameter and polydispersity index measurements indicated that the ChCl/OA DES produced the most stable, nanosized, and monodisperse suspensions [69].

Organosolv pretreatment utilizes organic solvents, such as ethanol, methanol, and acetone, often in the presence of acid catalysts, to selectively solubilize lignin and hemicellulose while preserving cellulose integrity. This process is valued for its selectivity and potential for lignin recovery [64]. Among the various chemical pretreatment strategies, dissolution–regeneration techniques also play a significant role. These methodologies utilize solvents such as N–methylmorpholine–N–oxide (NMMO), LiCl/DMAc, and alkali/urea systems to fully dissolve cellulose, which is then reprecipitated to form regenerated nanocellulose (RNC). Recognized for their scalability and environmental compatibility, these approaches are particularly efficient and cost–effective when employing solvent systems like alkali/urea or DES [3]. Collectively, these chemical pretreatment strategies significantly improve cellulose accessibility, reduce energy requirements for mechanical processing, and tailor the structural and chemical properties of nanocellulose products, thereby expanding their applicability in diverse fields [67].

3.2 *Physical treatment*

Physical pretreatment techniques primarily utilize mechanical and surface–modifying forces to facilitate the disintegration of lignocellulosic fibers into nanoscale cellulose structures. These methods are often applied in conjunction with or following chemical pretreatments to enhance efficiency and reduce energy consumption [65]. Among the most prevalent approaches are mechanical shearing methods, including high–pressure homogenization (HPH) and microfluidization, which force cellulose pulp through narrow channels under elevated pressure, generating shear, impact, and cavitation forces that break down fibers. HPH, originally introduced in 1983, is highly effective but can suffer from clogging, which is mitigated by pre–cutting the fibers [66]. Similarly, grinding, using rotating and stationary stones, and ball milling, involving high–energy collisions between milling media within a rotating chamber, are also widely used to disrupt hydrogen bonding and weaken fiber integrity [67]. High–intensity ultrasonication (HIUS) represents another category, where ultrasonic waves generate hydrodynamic shear and cavitation forces. The implosion of microbubbles within fiber cavities assists in fibrillation, with temperature, output power, and fiber size directly affecting efficiency. Combined HIUS and HPH treatments have been shown to improve nanofiber uniformity [66]

3.2.1. Cryogenic method

Cryogenic methods such as cryocrushing involve soaking cellulose in water, freezing it with liquid nitrogen, and then mechanically crushing the frozen material to rupture its structure [65]. Freezing causes the formation of ice crystals within the cell wall, leading to embrittlement and easy crack propagation. As a result, the material requires less milling energy, and the process time is reduced [39]. The high–impact crushing of the brittle, ice–filled fibers effectively breaks down the structure and liberates microfibrils, making cryocrushing a powerful technique for nanocellulose production [66].

3.2.2. Steam and thermal treatment

In the domain of steam and thermal treatment, steam explosion employs high–pressure steam followed by rapid decompression, leading to fiber defibrillation and depolymerization. This method has been particularly effective in treating biomass from sources such as banana, jute, and pineapple leaves, especially when paired with mild chemical treatments [65].

3.2.3. Electrospinning

Electrospinning, though not a mechanical breakdown method *per se*, transforms cellulose into nanofibers using a solvent system (e.g., trifluoroacetic acid) under an electric field, producing fibers with diameters around 270 nm [65]. Lastly, atmospheric plasma treatment constitutes a non–chemical, surface–activation technique. Using high–purity argon plasma under atmospheric pressure, it modifies only the outermost fiber layers, introducing polar functional groups such as hydroxyl and carboxyl groups. This enhances surface energy and adhesion, making the cellulose surface more compatible for further processing with nanocellulose [70]. These diverse physical pretreatment methodologies not only assist in reducing fiber size to the nanoscale but also significantly improve the accessibility, reactivity, and compatibility of cellulose for downstream applications in nanocellulose production.

3.3 ***Biological treatment***

Biological pretreatment methods utilize enzymatic or microbial systems to degrade or modify lignocellulosic biomass in a mild, environmentally sustainable manner. One of the most widely applied approaches is enzymatic hydrolysis, which uses enzymes such as endoglucanase and xylanase to selectively cleave glycosidic bonds in cellulose and hemicellulose. This facilitates the disintegration of fiber structures and enhances nanofibrillation efficiency during subsequent mechanical treatments [66]. Endoglucanase pretreatment, in particular, improves the aspect ratio of nanofibers and increases solids concentration, aiding in downstream high–pressure homogenization. Over 90% of enzyme–treated nanofibers were found to have diameters under 50 nm. Xylanase–aided pretreatment, as described by [64], specifically targets hemicellulose (xylan) and enhances the accessibility of cellulose, resulting in high–quality nanocellulose production.

Despite its advantages, enzymatic pretreatment is limited by high enzyme costs and prolonged processing times [67]. However, these challenges are often outweighed by the ability to preserve cellulose integrity and reduce energy requirements compared to chemical hydrolysis. Furthermore, advances in genetic engineering are enabling improved efficiency in bacterial cellulose production, reinforcing the potential of microbial systems as a sustainable and scalable nanocellulose source. Together, enzymatic and microbial pretreatments offer biologically driven, low–impact alternatives to conventional physical and chemical methods, contributing to the development of eco–friendly nanocellulose production pathways [64]. A comprehensive comparison of nanocellulose production strategies is summarized in Table 2.

Table 2: Comparative overview of different routes for nanocellulose preparation.

Preparation method		Reagent	Properties	Advantages	Limitations	Ref
Chemical	Acid hydrolysis	H_2SO_4	Rod-like (~100 nm) and spherical (~10 nm) particles; size range 304.6–755.6 nm; high yield (82.9–93.6%); high crystallinity (70.92–81.13%)	Low acid consumption with high yield and short processing time	Corrosive chemicals; waste acid generation; process complexity for industrial integration	[71]
	Alkaline treatment	NaOH	diameter 10–20 nm; length 150–350 nm; cellulose I → II transformation; increased crystallinity (+3.5–10.3%)	Tunable properties; reduced mechanical energy demand; scalable;	Reduced yield due to cellulose and hemicellulose solubilization; alkali recovery required	[72]
	Ionic liquid	BMIMCL / EMIMOAC	Fibrous network; diameter 10–25 nm; micrometer-scale length; high yield (93.1%); cellulose I structure preserved; high thermal stability (≈55% residue at 600 °C); IL recyclable (≥4 cycles)	One–step process; very high yield; low temperature; high thermal stability	High cost of ionic liquids; Complex solvent formulation; solvent recovery required	[73]
	Deep eutectic solvent	ChCl: oxalic acid: citric acid	Rod-like individualized fibrils (100–500 nm); thickness 19.5 ± 5.9 nm; CrI = 78%; strong H-bonding ability	reduced cellulose degradation; enhanced H–bond disruption	Energy for solvent formulation; solvent recovery required	[74]
	Organo–solv	Isobutanol	Diameter: 10–40 nm; CrI: 72.5%; Density: 1.3 g cm^{-3}; Young's modulus: 11.45 GPa; Tensile strength: 42.3 MPa	High crystallinity; Excellent mechanical strength; High transparency;	High solvent cost; Technology is still emerging; solvent recovery required	[75]
Physical	Steam explosion		Average diameter: 27.8 nm (Eucalyptus), 28.7 nm (Casuarina); high crystallinity; high thermal stability; high purity	Chemical–free fibrillation step; scalable; high–quality nanofibers;	High energy consumption and also requires high–pressure equipment	[76]
	Electro–spinning	N, N–Dimethyl–formamide	Uniform fiber morphology; enhanced β-phase content; tensile strength~140%; Young's modulus ~110%; elongation ~95% at 1 wt% CNCs; dielectric constant from 5.9 to 9.4	Simple and scalable fabrication; excellent mechanical reinforcement; enhanced	Solvent–based processing; performance sensitive to CNC loading; possible agglomeration at higher filler content	[9]
	Ball milling		Particle size reduced to ~80 nm; increased surface area; reduced aggregation; individualized nanofibrils;	Solvent–free method; environmentally friendly; scalable; effective nanoparticle size reduction	High energy consumption; possible thermal degradation; agglomeration at high loadings	[77]
Biological	Enzymatic		Uniform fibrillar morphology; diameter 20–80 nm; length several micrometers; CrI = 65–75%; high surface area; stable aqueous suspension	Mild processing conditions; high fibrillation efficiency; reduced chemical usage;	Long processing time; high enzyme cost; scale–up challenges	[78]
	Bacterial	Symbiotic culture of bacteria and yeasts	Nanofibril diameter 20–100 nm; crystallinity index 34.3%; fibrous and porous network; yield: 59.58 g/L (wet), 2.75 g/L (dry, 4 days); Young's modulus 4.74 MPa	Green and sustainable process; cost–effective; scalable; high purity product	Relatively low crystallinity and moderate production rate	[48]

4 Functional Modification of Nanocellulose

Nanocellulose functionalization aims to tailor its surface functional groups to improve compatibility with various matrices and enhance its performance in different applications [79]. By introducing specific chemical functionalities, nanocellulose can interact more effectively with polymers, metals, or other composite materials, resulting in enhanced dispersion, improved interfacial bonding, and increased mechanical stability. Through such functional modifications, nanocellulose gains unique physicochemical properties, thereby expanding its versatility and enabling its utilization in diverse fields such as biocomposites, electronics, the food industry, and biomedical engineering [20].

4.1 *Surface modification techniques*

Physical adsorption is one of the simplest strategies for modifying nanocellulose, mainly used to improve its dispersibility in organic solvents. In this method, molecules such as surfactants attach to the nanocellulose surface through weak, non–covalent interactions [8]. For example, a pH–responsive emulsion system was developed by adsorbing a rosin–based charge–reversible surfactant, maleopimaric acid anhydride (MPAA), onto nanocellulose. At low pH, the positively charged MPAA binds to negatively charged nanocellulose, rendering the surface hydrophobic and enabling stable emulsion formation. When the pH increases, electrostatic repulsion causes desorption, allowing reversible emulsion control and surfactant reuse [80].

Beyond physical adsorption, a range of chemical functionalization techniques has been developed to enhance nanocellulose's dispersibility, reactivity, and compatibility with diverse matrices. Carboxymethylation introduces carboxymethyl groups using monochloroacetic acid, generating a negatively charged surface that promotes fiber swelling and facilitates the breakdown of lignocellulosic fibers into nanocrystals. This modification enables the formation of transparent gels and coatings with excellent oxygen–barrier performance [81]. Higher carboxyl content further reduces self–aggregation and enhances interfacial interactions, improving stability and performance in advanced materials and sensing applications [82].

Esterification is another widely used modification route, involving nucleophilic substitution between cellulose hydroxyl groups and various acids, acyl halides, or anhydrides to form cellulose esters [83]. Acetylation typically occurs at accessible hydroxyl sites on the surface and amorphous regions [81]. Ultrasonication can intensify this process by exposing additional reactive sites and enhancing reagent penetration, enabling direct, one–step synthesis of acetylated CNCs without prior acid hydrolysis. Reaction rates can be further improved using lipase catalysts under supercritical CO_2, offering a greener and more efficient route [83].

Silane coupling modification provides another pathway to hydrophobic nanocellulose. Hydrolyzed silane groups form silanol species that condense into Si–O–Si structures, with some groups reacting directly with cellulose hydroxyls to produce hydrophobic –R–Si–O–R– linkages [84]. Although effective, the method often requires extensive solvent–exchange steps, limiting its environmental compatibility. Alternatively, graft copolymerization attaches hydrophobic polymer chains or functional moieties to the nanocellulose surface, significantly enhancing hydrophobicity and compatibility with polymer matrices [85].

Surface charge modification through sulfonation is also common. Sulfonate groups can be introduced either by converting aldehydes into sulfonates using sulfite/bisulfite reagents [6] or by forming sulfate half–esters during sulfuric acid hydrolysis. However, controlling the degree of sulfation remains challenging. The reaction is sensitive to the conditions and very complicated to control the amount of sulfate half ester on grafted CNCs [81]. Increased sulfonate content greatly boosts water dispersibility and allows the formation of highly viscous, transparent CNF gels [6].

Oxidative methods like TEMPO oxidation and ammonium persulfate (APS) oxidation introduce carboxyl and aldehyde groups that disrupt hydrogen bonding networks and alter crystallinity, thereby improving mechanical nanofibrillation [64]. In particular, TEMPO–mediated oxidation selectively converts C6 hydroxyls into carboxyl groups using NaClO, NaBr, and TEMPO as a catalytic system. The resulting nanocellulose contains both hydroxyl and carboxyl groups, enabling further chemical modification and enhancing electrostatic repulsion between fibrils [86]. Despite these advantages, the high density of polar groups introduced during oxidation leads to strong moisture absorption, which negatively affects the mechanical performance of the material. Therefore, subsequent hydrophobic modification is often essential to enhance stability and broaden the range of applications for functionalized nanocellulose [83]. Figure 4 summarizes these major functionalization strategies—such as sulfonation, phosphorylation, TEMPO-mediated oxidation, and carboxymethylation—which are part of a broader group of oxidative pretreatments.

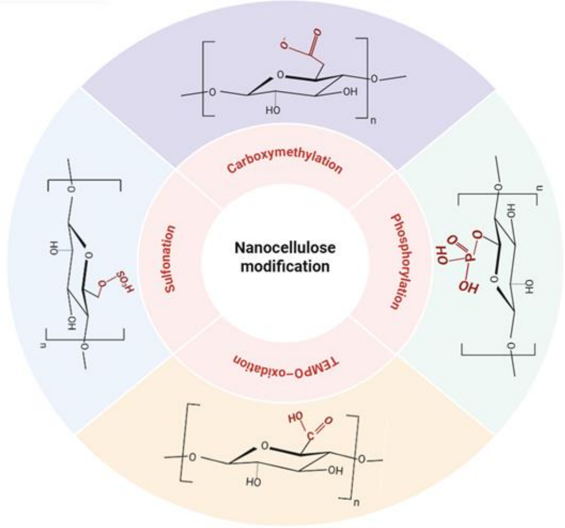

Figure 4: Modification approaches for nanocellulose enabling tailored functionalities.

4.2 *Polymer and nanocomposite modification*

Incorporating nanocellulose into composite materials greatly enhances their mechanical performance, particularly in terms of flexibility, elasticity, and structural reinforcement [87]. Acting as a three–dimensional reinforcing network, nanocellulose improves compressive strength and overall stability of the matrix, reducing the risk of deformation or collapse and extending the functional lifespan of the composite [20]. Surface modification further amplifies these advantages. For example, Poly(lactic acid)–grafted cellulose nanofibers (CNF–g–PLA) exhibit significantly improved dispersibility in organic solvents compared to unmodified CNF, making them more compatible with hydrophobic polymer matrices and better suited for composite fabrication [88].

More advanced functionalization strategies also expand the performance and application potential of nanocellulose–based composites [20]. A two–step modification process involving dicarboxylic acid treatment followed by lysozyme functionalization has been demonstrated to enhance the biocompatibility of polylactide (PLA) biocomposites. The initial dicarboxylic acid modification enables covalent bonding with the PLA matrix, improving nucleation and crystallization without compromising mechanical strength. Subsequent lysozyme grafting imparts antibacterial activity against both Gram–positive and Gram–negative bacteria, enabling the development of multifunctional composites. These combined effects, such as enhanced crystallinity, mechanical stability, and antimicrobial performance, make the resulting materials suitable for sustainable active packaging and biomedical applications [54]. Table 3 summarizes the main methods for nanocellulose functionalization, along with their corresponding functional outcomes and enhanced key properties.

Table 3: Different methods for the functionalization of nanocellulose.

Material	Modification	Objective	Key performance indicators	Ref
BNC/polyvinyl alcohol/silver nanoparticles	*In situ* synthesis of Ag nanoparticles within BNC/PVOH matrix	To impart antimicrobial activity and enhance mechanical and barrier properties	Improved mechanical strength and strong antibacterial activity (17 ± 0.5 mm against *Escherichia coli*, 14 ± 0.0 mm against *Staphylococcus aureus*).	[89]
CMC / Eucalyptus nanocellulose films	Incorporation of nanocellulose (5–30% w/w) via the casting method	Enhance mechanical and thermal properties	Improved Young's modulus (6791.7 MPa at 30% NC) and increased solubility (10–20% NC).	[90]
Acetylated CNF aerogels with solid lipid nanoparticles	Foam template method using biodegradable SLN and BC/acetylated CNF assembly	To enhance hydrophobicity and oil absorption.	Contact angle 138–140°, Oil absorption: 100–140 g/g.	[91]
Carboxylated nanocellulose (c–NC)	Dissolution and carboxylation using a dual polyacid–based ternary deep eutectic solvent	Enhance carboxyl content, yield, and surface functionality	Carboxyl content: 1.25 mmol/g, yield: 40–59%, enhanced H–bond disruption and donor–acceptor interactions.	[74]
TEMS–modified nanocellulose aerogel	Triethoxymethylsilane (TEMS) surface modification	Enhance hydrophobicity, mechanical strength, and oil absorption for environmental applications	Mechanical strength increased from 0.0194 to 0.03614 N/mm², water absorption reduced from 41.7 to 11.3 g/g, oil absorption: 44.3 g/g (cooking oil), 57.6 g/g (motor oil).	[17]

Table 3: (continued)

Material	Modification	Objective	Key performance indicators	Ref
Copper ion–modified nanocellulose film	One–pot reaction: co–soaking CNCs with Cu^{2+} in NaOH solution for 12 h	Improve mechanical strength, hydrophobicity, and impart antibacterial activity	Tensile strength increased from 36.8 to 56.4 MPa, Water contact angle: increased from 46° to 92°, antibacterial activity against *E. coli* and *S. aureus*.	[2]
Nanocellulose reinforced epoxy vinyl resin (EVR)	TEMPO oxidation and silane coupling incorporated into EVR	Improve mechanical strength and hydrophobicity	Tensile (+52.91%), flexural (+45.85%), and fracture toughness (+27.94%) improved.	[8]
Peanut shell nanocellulose	Carboxymethylation with Electron beam irradiation	Improve chemical reactivity and stability	Substitution degree increased from 0.38/0.48 to 0.66/0.69 (120 kGy).	[15]
Nanocellulose–based solid polymer electrolyte (SPE)	Incorporation of plant–derived nano-silica (8–10 nm)	Improve ionic conductivity, cycling stability, and Li^+ deposition uniformity	Ionic conductivity: 2.6×10^{-4} S/cm, Stripping–plating stability: 2000 h at 0.1 mA/cm^2, Stable polarization voltage: 20–70 mV during cycling.	[92]
Jackfruit peel–derived nanocellulose	Ultrasonication, deep–freezing; gelatin as cross–linker	Development of a sustainable, biobased hydrogel with strong texture and stability	Good hardness, adhesiveness, and cohesiveness, Stable at 35 °C for 2 weeks, Viscosity: 15–40 cP.	[46]
Thermally modified TiO_2 nanoparticles	Thermal treatment (e.g., P25/500) + combination with oxidants (H_2O_2, PDS, PMS)	Enhance the photocatalytic degradation of oxytetracycline (OTC)	Achieved >99% OTC degradation in 180 min.	[93]
Guanidine–functionalized sericin	Grafting polyhexamethylene biguanide (PHMB) onto nanocellulose	Hybrid water disinfection and heavy metal removal	Excellent bactericidal activity: 7 log reduction of *E. coli* within 30 min, high Cu(II) adsorption capacity: 571.5 mg/g.	[94]

5 Applications of Nanocellulose

Nanocellulose has emerged as a versatile material with a wide range of functional properties, making it suitable for numerous industrial and environmental applications [40]. Its unique nanostructure, remarkable mechanical robustness, and adaptable surface functionalities support the creation of innovative materials that combine high performance with improved environmental compatibility [20].

5.1 *Biomedical applications*

Nanocellulose has gained significant attention in the biomedical sector due to its outstanding mechanical strength, excellent biocompatibility, and minimal cytotoxicity [95]. Its versatile surface chemistry allows for a wide range of functional modifications, enabling the development of advanced materials tailored for wound healing, tissue engineering, drug delivery, and other medical applications [10]. Figure 5 summarizes the key application areas of nanocellulose, highlighting its potential in biomedical engineering, food packaging, electronics, and water treatment.

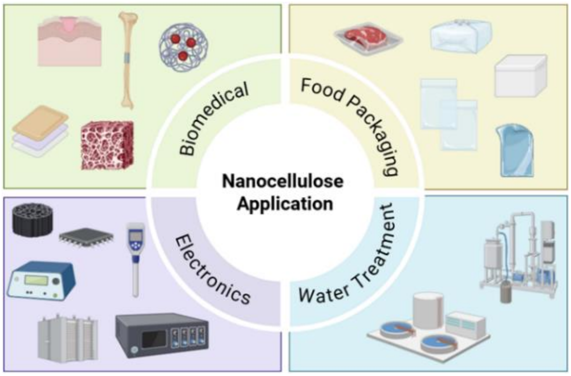

Figure 5: Applications of nanocellulose in different areas.

5.1.1 Tissue engineering scaffolds

Scaffolds fabricated from both natural and synthetic biomaterials have gained significant attention in biomedical applications due to their structural and mechanical resemblance to the native extracellular matrix (ECM). This biomimetic similarity provides an ideal microenvironment that facilitates cell adhesion, proliferation, and differentiation, ultimately promoting tissue regeneration [96]. Among these materials, nanocellulose–based scaffolds have emerged as promising candidates owing to their excellent biocompatibility, tunable porosity, and high surface area. They have been demonstrated to support the growth of various cell types, including fibroblasts, human pluripotent stem cells, HeLa cells, and Jurkat cells, in three–dimensional cultures, maintaining cell viability and proliferation for extended periods ranging from several days to weeks, depending on the cell type [97].

Wound healing and tissue regeneration are complex biological processes that require materials with excellent biocompatibility, antibacterial properties, and the ability to support cell proliferation and tissue remodeling. In this context, nanocellulose–based materials have emerged as promising candidates due to their high porosity, tunable structure, and compatibility with various bioactive agents. Copper nanoparticles not only exhibit strong antimicrobial effects but also promote angiogenesis and stimulate cell proliferation and differentiation, making them highly promising for tissue regeneration and wound healing applications [2]. Highly porous and water–absorbent sponges were developed from brown algae (*Saccharina japonica*) cellulose nanofibers (BACNF). After incorporating antibacterial agents to form BACNF/quaternized chitin/organic rectorite (BACNF/QCR) sponges, the materials exhibited excellent mechanical strength, biocompatibility, and antibacterial activity, effectively promoting neovascularization and collagen regeneration for enhanced skin wound healing [98].

Bone tissue engineering has emerged as a promising approach to overcome the limitations of traditional bone grafts, such as immune rejection and disease transmission. Among the materials explored for scaffold design, nanocellulose has gained significant attention due to its high mechanical strength, biocompatibility, and ability to mimic the extracellular matrix, providing an ideal environment for osteoblast growth and mineralization [99]. Its versatility allows combination with polymers such as polylactic acid (PLA), chitosan, or hydroxyapatite to enhance both mechanical properties and bioactivity, further improving scaffold performance in bone regeneration applications [100]. For instance, using fused deposition modeling, 3D composite scaffolds were fabricated from PLA and cellulose nanocrystals (CNCs) extracted from *Ficus thonningii*, featuring interconnected pores of approximately 400 µm. Incorporation of 3% CNC not only increased PLA's mechanical strength by ~30% in Young's modulus but also improved wettability, reducing the water contact angle by ~17%. Mineralization studies confirmed hydroxyapatite nucleation, while cytocompatibility tests demonstrated that the scaffolds were non–toxic to bone cells. This integrated approach, combining controlled scaffold architecture with enhanced mechanical and biological properties, highlights the potential of nanocellulose–based composites in advancing bone tissue engineering and regenerative medicine [96].

5.1.2 Drug delivery systems

The incorporation of nanocellulose as a concurrent drug carrier enables targeted and localized drug delivery, minimizing overall drug consumption while providing controlled release of the encapsulated compounds [101]. Owing to its high surface–to–volume ratio, nanocellulose exhibits superior cellular binding and uptake capabilities, thereby improving the efficiency of drug delivery systems. Among its various forms, nanocellulose aerogels stand out as ultra–light, three–dimensional porous materials with large surface areas and remarkable adsorption properties, making them particularly suitable for sustained and controlled drug release [10]. The design and mechanism of such systems depend on the desired release profile and the physicochemical characteristics of the drug. An effective formulation requires careful optimization of the carrier type, drug–loading ratio, and release kinetics to achieve the intended therapeutic performance [102].

The pore structure of nanocellulose composite aerogels can be precisely tuned by adjusting the proportions of nanocellulose, gelatin, and dialdehyde starch, allowing control over their porosity and drug–loading capacity [103]. Stimuli–responsive nanoparticles have gained considerable attention for their ability to modulate drug release under external triggers; however, challenges, such as limited biodegradability and potential toxicity, still restrict their broader biomedical use [104]. To overcome these limitations, a light–activated drug delivery system was developed by integrating CNF hydrogel with thermosensitive liposomes. In this system, the CNF hydrogel served as a biocompatible support matrix in which cationic liposomes were electrostatically bound within the fibrous network, forming a stable depot-like drug reservoir. Upon near–infrared (808 nm) light activation, localized heating induced controlled drug release, achieving 50% release at 20 J/cm² and up to 80% at 80 J/cm², demonstrating the potential of CNF–based systems for precise, on–demand therapeutic delivery [105].

A wide range of pH environments exists within the human body, from highly acidic to basic regions, making pH–responsive hydrogels particularly suitable for drug delivery applications. Anionic hydrogels tend to swell in basic media due to the deprotonation of negatively charged functional groups on the polymer chains, resulting in electrostatic repulsion and expansion of the network, which increases the average pore size. Conversely, cationic hydrogels exhibit the opposite behavior, swelling in acidic conditions. Therefore, the pH of the surrounding environment, along with the intended site of drug delivery, plays a crucial role in controlling the drug release rate [106]. A double–layer, pH–sensitive composite hydrogel system composed of polysaccharides and synthetic polymers was developed for sustained drug release. The inner sodium alginate–carboxymethyl cellulose (SA–CMC) hydrogel core, formed through ionic gelation, exhibits pH sensitivity in the intestinal environment to prevent drug leakage in the stomach, while the outer chemically crosslinked layer enhances structural stability and regulates the release rate [107].

Recent advances in nanocellulose–based materials have focused on combining biocompatible cellulose matrices with functional nanocarriers to achieve precise and sustained drug release [88]. By integrating nanocellulose with lipid– or polymer–based systems, researchers have developed hybrid biomaterials that enhance drug loading efficiency, stability, and therapeutic performance [103]. A hybrid biomaterial combining BNC hydrogel with nanostructured lipid carriers (NLCs) was developed for localized chemotherapy. Using the MDA–MB–231 breast cancer model, the system demonstrated that the neutral NLCs (NLCs–N) achieved higher drug encapsulation (97%) and sustained Doxorubicin release compared to cationic NLCs–H. An optimized 80/20 NLCs–H/NLCs–N formulation provided controlled release, with 50% drug release after 24 hours [108]. Similarly, polyethylene glycol (PEG) and β–cyclodextrin were incorporated into nanocellulose aerogels to enhance their structure, drug–loading capacity, and sustained–release performance. The resulting composite aerogels exhibited high imatinib adsorption (316–365 mg/g) and, when processed through infrared tableting, extended drug release up to 11 hours, thereby improving therapeutic potential [103].

5.1.3 Wound dressings

Wound infections continue to pose a major clinical challenge, leading to delayed healing, higher medical costs, and worsening the global issue of antimicrobial resistance [109]. Conventional wound dressings, such as bandages, cotton, and gauze, often fail to create an optimal healing environment. To address this limitation, biomimetic scaffold–based dressings have been developed to replicate the three–dimensional structure of the skin's extracellular matrix, supporting dermal, epidermal, and angiogenic growth [110]. Among emerging materials, nanocellulose has gained significant attention due to its excellent mechanical strength, flexibility, and biocompatibility, making it a promising candidate for advanced wound care applications [102]. However, the naturally low antibacterial activity of nanocellulose limits its effectiveness in preventing infections. To overcome this, researchers have incorporated metallic nanoparticles such as silver and copper into nanocellulose matrices, enhancing their antimicrobial performance [45]. This synergistic combination of nanocellulose and antimicrobial nanoparticles presents a powerful strategy for developing next–generation wound dressings with enhanced healing efficiency and improved infection control [102].

These nanoparticles exert antibacterial effects primarily by interacting with bacterial cell membranes, adhering to the surface, disrupting membrane integrity, and causing leakage of intracellular components. In some cases, smaller nanoparticles penetrate the cell wall, further damaging internal structures and ultimately leading to bacterial death [109]. A contact–killing material using antimicrobial peptides (AMPs) was developed to prevent wound infections. AMPs disrupt bacterial membranes, causing cell lysis, and are less likely to induce resistance, making them a promising alternative to antibiotics [111]. BNC and TEMPO–oxidized nanocellulose have been developed as advanced wound dressings by functionalizing them with the antimicrobial peptide PLNC8 αβ. The peptide, either physiosorbed onto nanofibrils or encapsulated within mesoporous silica nanoparticles (MSNs), enabled controlled and localized release. These dressings showed strong antimicrobial activity, effectively eradicating infections and enhancing re–epithelialization in a porcine wound model. Their action relies on sustained PLNC8 αβ release that disrupts bacterial membranes while remaining non–toxic to human cells, underscoring nanocellulose's promise for advanced wound healing [112].

5.2 *Food packaging*

Packaging plays a crucial role in the food industry by maintaining freshness, extending shelf life, and protecting products from microbial contamination, oxidation, moisture, and physical damage [113]. However, conventional petroleum–based packaging materials are non–biodegradable and contribute to environmental pollution, while also raising safety concerns due to potential chemical migration [114]. As consumer awareness and food quality demands increase, there is a growing need for packaging materials that are non–toxic, environmentally friendly, mechanically robust, and capable of providing appropriate barrier properties under varying storage conditions [110].

Nanocellulose has emerged as a promising solution due to its biodegradability, high mechanical strength, and excellent gas barrier properties, making it a strong candidate for sustainable food packaging systems. Its surface chemistry also enables functional modifications, allowing incorporation of bioactive or reinforcing agents to enhance performance. For example, tannic acid (TA), a natural polyphenol with antioxidant and antimicrobial properties, can strongly interact with nanocellulose through hydrogen bonding. Integrating TA into nanocellulose–based edible coatings improves protection for post–harvest fruits by reducing microbial spoilage and oxidative deterioration [114]. Similarly, a polyvinyl alcohol–polyethylene oxide (PVA–PEO) nanocomposite was enhanced using a hybrid filler composed of halloysite nanotubes (HNTs) and nanocellulose to improve its suitability for food packaging applications. The addition of nanocellulose significantly enhanced mechanical strength, thermal stability, and oxygen barrier properties while maintaining low water vapor transmission [113].

Beyond improved barrier and mechanical performance, modern food preservation increasingly requires antimicrobial functionality. Antibacterial packaging helps suppress foodborne pathogens and spoilage organisms, thereby enhancing food safety and shelf stability. Recent advances highlight the promise of photothermal antibacterial systems, which can generate localized heat to inactivate bacteria efficiently with low energy input and broad–spectrum effectiveness [115]. Building on this concept, nanocellulose was used as the primary structural matrix to develop multifunctional bioplastic packaging incorporating Ta4C3Tx–immobilized silver nanoparticles and quaternized chitosan. The strong hydrogen–bonded network formed a compact, high–strength composite with ultra-low oxygen permeability. Moreover, the system enabled controlled release of antibacterial agents and exhibited stable photothermal antibacterial performance, providing long–lasting microbial protection [116].

5.3 *Electronics and energy*

In advanced electronics, including flexible sensors, secure data transmission, and triboelectric nanogenerators (TENGs), developing green elastomers with high mechanical strength and stability is crucial. Incorporating nanocellulose into elastomers has been shown to enhance elasticity and toughness [117]. A bio–based electroconductive elastomer was developed by incorporating CNF–polyaniline (CNF–PANI) complexes into natural rubber. CNFs reinforced the elastomer and acted as a template for PANI to form a 3D conductive network. The resulting material has combined flexibility, enhanced mechanical strength, and conductivity, enabling applications in strain sensors and flexible electrodes. This demonstrates how nanocellulose can simultaneously improve elastomer mechanics and support functional conductive networks in sustainable soft electronics [110].

The growing demand for sustainable energy storage has driven interest in eco–friendly supercapacitors that offer high power and fast energy delivery. Among various electrode materials, NC–based materials have gained attention for their renewable origin, unique structure, and excellent electrochemical properties [118]. Since nanocellulose is insulating, it must be made conductive for use as supercapacitor electrodes. This is achieved by coating or incorporating conductive materials through methods like particles, solution, vapor, or sputter deposition. The carboxyl and hydroxyl groups on nanocellulose interact with conductive polymer functional groups, forming strong, high–affinity conductive hybrids [119]. MnO_2 is a promising electrode material for supercapacitors due to its low cost, stability, and eco–friendliness, but its poor hydrophilicity and tendency to agglomerate limit performance. Using nanocellulose as a template improves MnO_2 dispersion, surface area, and ion transport. The resulting 3D flower–like MnO_2/CNC structures enhance electrochemical performance through better electron and ion conductivity [120].

Lithium–ion batteries, widely used in electronics and electric vehicles, face limitations with liquid electrolytes, including electrochemical and thermal instability, leakage, and dendrite formation. Nanocellulose–based solid polymer electrolytes are being developed to improve electrode, electrolyte interface stability, enhance ion transport control, and extend long–term cycling performance [84]. In lithium batteries, separators enable lithium-ion transport while preventing electrode contact. Functionalized separators that anchor anions improve ion selectivity, suppress dendrite growth, and enhance battery safety and efficiency [121]. As anions migrate faster than lithium ions, they lower the lithium-ion transference number and cause concentration polarization, which drives lithium depletion at the anode surface and accelerates dendrite growth, reducing efficiency and safety. To address this, a core–shell structured cationic nanocellulose composite separator immobilizes lithium-salt anions, increasing the transference number to 0.70 and stabilizing the lithium metal anode. Thanks to its high porosity and ionic conductivity, the separator effectively suppresses dendrite formation. When applied in $LiFePO_4$ battery cells, it delivers 141.6 mAh/g after 200 cycles with minimal degradation, demonstrating long-term capacity retention through strong dendrite inhibition [122]. Table 4 summarizes the key applications of nanocellulose across different fields, including biomedical engineering, food packaging, electronics, and water treatment, highlighting its multifunctionality and versatility

Table 4: Applications of nanocellulose in different areas.

Application area	Form	Key properties	Key performance indicators	Ref
Food emulsifiers and encapsulation systems	Zein nanoparticles (ZNPs) complexed with millet bran nanocelluloses (MCNCs, MCNFs, MCNSs)	Improved emulsion stability, encapsulation efficiency, and interfacial adsorption	MCNCs–ZNPs showed the highest surface charge (35.90 mV) and fastest interfacial adsorption and achieved 94.65% encapsulation efficiency.	[123]
Water and wastewater treatment	Nanocellulose/ZnO hybrid ultrafiltration membrane	High water permeance, filtration accuracy, antifouling, and photocatalytic self–cleaning	Water permeance: 5439.7 $L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$, High rejection of nanoparticles >20 nm and macromolecules >100 kDa.	[124]
Biomedical scaffolds	Nanocellulose–collagen hydrogels	Cytocompatibility, tunable 3D structure, support for long–term cell growth	Maintained neuronal viability for over 14 days and promoted neurite outgrowth better than Matrigel and collagen	[97]
Food packaging	Nanocellulose–based edible films from soy hulls (SCT composite films)	Mechanical strength, UV resistance, antibacterial, and antioxidant activity	Elongation 281.03%, tensile strength 114.88 MPa, antibacterial activity 95.55%, and extended grape shelf life from 8 to 18 days at 25 °C.	[114]
Biomedical scaffolds	Self–assembled nanocellulose–based smart scaffold (aldehyde–modified–CNF–silk fibroin–CeO_2)	Antimicrobial activity, cytocompatibility, angiogenesis promotion, tissue regeneration	Effective against *S. aureus* and *E. coli,* and accelerated collagen deposition, and outperformed commercial 3M and PELNAC dressings.	[125]
Food packaging with edible film	Trilaminar edible composite film (kelp nanocellulose, konjac glucomannan, and curcumin)	Antioxidant, antibacterial, and barrier properties	Inhibition zones: increased 1.79× (*E. coli*) and 1.83× (*S. aureus*), hemolysis rate: 0.9%; degradation: 26%, water contact angle: from 42.8° to 72.5°.	[126]
Biomedical	Nanocellulose/ZnO and nanocellulose/CuO	Antibacterial and anti-inflammatory	Nanoparticle size: ZnO ~29 nm, CuO ~42 nm, antibacterial: NC/CuO against Gram-positive & negative, NC/ZnO against Gram-positive strains.	[127]
Flexible energy storage	CNF/carbon nanotube/Co_3O_4 composite electrode films	Specific capacitance, energy density, power density, flexibility, and durability	Specific capacitance: 23.24 F/g at 0.1 A/g, internal resistance: ~20 Ω, energy density 0.517 Wh/kg and power density 21.28 W/kg.	[128]
Flexible electronics and energy harvesting	Amino functionalized nanocellulose and poly(deep eutectic solvent) based conductive elastomer	Mechanical strength, anti–freezing, solvent resistance, flexibility, energy harvesting	Tensile strength: 3.24 MPa; elongation at break: 1698.99%, flexible sensors, cryptographic transmission, triboelectric nanogenerators	[117]
Wastewater treatment	$Co(OH)_2$/stearic acid–based superhydrophobic/superoleophilic nanocellulose membrane	Superhydrophobicity, superoleophilicity, and photocatalytic activity	Water contact angle: 164 ± 2°; oil contact angle: ~0°, Separation efficiency: >94% for four oils, Separation flux: >130 $L \cdot m^{-2} \cdot h^{-1}$.	[129]

5.4 *Wastewater treatment*

The global decline in freshwater availability has intensified the need for advanced technologies capable of treating and reusing wastewater. Contamination from household effluents, industrial discharge, and agricultural runoff introduces organic pollutants, dyes, heavy metals, and pathogens into water systems, necessitating efficient treatment before release into the environment [130]. In response to these challenges, nanocellulose has gained considerable attention as a renewable, bio–based material with tunable surface chemistry and excellent compatibility for environmental applications [32]. Owing to its high aspect ratio, abundant reactive functional groups, and ability to form mechanically robust networks, nanocellulose can be engineered into membranes, adsorbents, catalytic supports, and antimicrobial platforms. These unique features enable the selective capture of pollutants, facilitate molecular sieving, enhance catalytic degradation pathways, and support real-time monitoring through sensing technologies, establishing nanocellulose as a promising building block for advanced wastewater treatment solutions [131].

5.4.1 Heavy metal removal

Wastewater contamination by heavy metal ions poses a major global threat to ecosystems and human health. Rapid industrialization and urbanization have resulted in the continuous discharge of toxic metals from industries such as electroplating, mining, textiles, and battery manufacturing. These non–biodegradable metals persist and accumulate in the environment, causing long–term ecological and biological harm. Therefore, efficient water resource management, wastewater recycling, and the removal of hazardous metal ions have become urgent environmental priorities [32]. Metals such as copper, zinc, chromium, lead, nickel, arsenic, mercury, and cadmium are particularly hazardous, as even trace concentrations can cause severe physiological and neurological disorders in humans, as well as detrimental effects on plants and aquatic organisms [5].

In recent years, nanocellulose has emerged as a promising and eco–friendly adsorbent for heavy metal removal due to its abundant hydroxyl groups, large specific surface area, and high mechanical stability. Electrostatic attraction, a dominant mechanism of physical adsorption, typically occurs between the charged functional groups on the nanocellulose surface and the oppositely charged metal ions [131]. However, the native form of nanocellulose has a limited adsorption capacity because its surface chemistry lacks sufficient active sites to strongly bind metal ions. To overcome this limitation, various surface modification techniques have been developed to enhance its adsorption performance [94].

Chemical modification through the introduction of functional groups such as carboxyl, phosphate, sulfhydryl, or ester groups significantly increases the negative surface charge of nanocellulose, thereby enhancing its affinity toward metal cations [131]. Among these, carboxylation pretreatment is one of the most extensively studied and effective approaches for improving metal ion adsorption, particularly for Pb^{2+}, Ni^{2+}, and Cd^{2+} removal. Such modifications are often achieved by grafting nanocellulose with methacrylic acid, maleic acid, or by employing TEMPO–mediated oxidation to produce carboxylated nanocellulose adsorbents. The modification process generally involves free–radical copolymerization, enabling the covalent attachment of functional polymers to nanocellulose via grafting copolymerization [10].

To further enhance adsorption efficiency and pH responsiveness, researchers have explored the integration of nanocellulose with cationic polymers such as branched polyethyleneimine (PEI), which is rich in amino groups. For instance, PEI has been crosslinked with nanocellulose using glutaraldehyde (GA) to form pH–sensitive nanoparticles (NC–PEI/GA) for effective removal of As(V) from acidic wastewater. However, the electrostatic interactions between PEI and TEMPO–oxidized nanocellulose alone are relatively weak and unstable. Therefore, GA serves as a crucial crosslinking agent, strengthening the structural stability of the nanocomposite and improving its adsorption capacity under acidic conditions [32].

5.4.2 Dye removal

In addition to heavy metals, organic dyes are a major class of pollutants that pose serious threats to human health and the environment due to their toxicity, resistance to degradation, and tendency to bioaccumulate. These dyes are typically classified based on their charge into anionic and cationic dyes [132]. Anionic dyes, such as direct and acid dyes, can be effectively removed through electrostatic interactions with cationic NC, highlighting the potential of nanocellulose as an efficient adsorbent in wastewater treatment [6].

Adsorption is widely employed for dye removal because it is cost–effective, operationally simple, and highly efficient. Ideal adsorbents are characterized by high surface area, suitable porosity, and strong mechanical and chemical stability, which allows for multiple cycles of reuse. However, conventional powdered adsorbents face challenges such as requiring large quantities for effective removal and difficulties in post–treatment separation. To address these limitations, composite bead systems have been developed using materials such as polyvinyl alcohol (PVA), alginate, and inorganic fillers. Among these, nanocellulose–based hydrogels have emerged as a promising alternative. Nanocellulose hydrogels are non–toxic, highly porous, and mechanically robust, providing enhanced adsorption capacity and easier recovery. These properties make them highly suitable for efficient and reusable dye removal applications [37].

Beyond its use as a dye adsorbent, nanocellulose also serves as an excellent support material for enzyme immobilization, enhancing catalytic activity, stereoselectivity, stability, and reusability. NC–based immobilized enzymes have thus gained increasing attention for water treatment applications [133]. For instance, nanocellulose was used to immobilize the laccase enzyme PersiLac1, producing a green and efficient nano–biocatalyst for dye degradation. The immobilization significantly improved the removal efficiency of malachite green (MG) and congo red (CR) at 150 mg/L, increasing from 54% to 98% for MG and from 12% to 60% for CR. This demonstrates the remarkable enhancement in catalytic performance and reusability achieved through NC–based enzyme immobilization compared to using pristine nanocellulose alone [34].

5.4.3 Antibacterial application

Cellulose, in its native form, lacks inherent antimicrobial properties, necessitating chemical modification or functionalization with agents such as metal nanoparticles (e.g., gold, silver, copper, zinc) or antibiotics to confer antibacterial activity [134]. Nanocellulose fibers can be assembled into mechanically robust, interconnected structures, which serve as versatile platforms for multifunctional applications. For example, grafting polyhexamethylene biguanide (PHMB) onto nanocellulose aerogels not only imparted strong antibacterial activity, achieving a 7–log reduction of *E. coli* within 30 minutes, but also enhanced heavy metal adsorption due to abundant functional groups from sericin and CNC–PHMB, allowing a high adsorption capacity of 571.5 mg/g for Cu^{2+}. This dual functionality enables the aerogel to act as a multifunctional membrane filter capable of both water disinfection and heavy metal removal [94]. Another strategy for antibacterial activity is photocatalysis, in which photocatalysts generate reactive oxygen species (ROS) upon light exposure. Nanoparticle–enabled photocatalytic oxidation provides an alternative approach for designing antibacterial membranes. Common photocatalysts include semiconductors such as TiO_2 and ZnO, which absorb light through their band gaps and produce ROS that inactivate microbes [109].

Despite these advancements, conventional antibacterial agents face challenges such as rising antibiotic resistance, cytotoxicity of certain metal nanoparticles toward mammalian cells, and the gradual leaching of grafted biocides, which diminishes long–term effectiveness [135]. To overcome these limitations, non–leaching, contact–active strategies have been developed. For instance, gentamicin was covalently attached to a nanocellulose–based sponge via multi–crosslinking of CNF, cellulose acetoacetate, and APTES, followed by enamine bond formation. The resulting gentamicin–functionalized sponge exhibited exceptional antibacterial performance, achieving over 99.9% bactericidal activity against *E. coli* and *S. aureus* [57].

6 Key Challenges and Sustainability Aspects of Nanocellulose

Nanocellulose production continues to face significant technical and economic barriers, particularly during the isolation stage. Current methods, such as acid hydrolysis, enzymatic treatment, cryogenic crushing, and mechanical fibrillation, are highly energy–intensive and contribute substantially to production cost. Mechanical refining is among the most widely used techniques, yet achieving high fibrillation requires large electrical inputs, limiting its feasibility for industrial–scale operation [136]. Other mechanical strategies show similar constraints: high–pressure homogenizers yield uniform CNFs but require 1.1–8.8 kWh/kg and frequent maintenance, microfluidizers provide precise size control but consume around 2.55 kWh/kg with slow throughput and clogging issues, and ultrafine grinders offer lower energy demand (1.3–3.1 kWh/kg) but produce slightly less uniform fibers [137]. Acid hydrolysis, though capable of producing high–quality CNCs, involves costly steps such as acid recovery, neutralization, and extensive washing. Techno–economic analysis indicates that incorporating acid recovery slightly reduces CNC selling price ($4.69/kg vs. $4.89/kg) but increases capital investment and environmental impacts, making the process more expensive and less sustainable overall [138]. Thus, despite improvements in quality, current isolation methods remain limited by high operational and energy costs.

Beyond production challenges, several material–related limitations hinder the broader adoption of nanocellulose. One major issue is the reduced thermal stability of sulfuric–acid–derived CNCs due to the presence of sulfate ester groups. Studies using 40% and 60% H_2SO_4 on sugarcane bagasse show that higher acid levels increase sulfate substitution and dispersion but significantly lower thermal stability. CNCs produced with 40% acid exhibit higher crystallinity and a more favorable balance between structure and performance, emphasizing the need to tune acid concentration for high–performance applications [139].

Aggregation also remains a persistent obstacle. Critical agglomeration and peptization concentration studies demonstrate that cation interactions with sulfate half–esters can trigger clustering even in well–dispersed CNC suspensions. This sensitivity to salts and neutralization steps makes long–term colloidal stability difficult to maintain, posing challenges for consistent processing and product reliability [140].

The hydrophilicity of nanocellulose represents a major challenge for its compatibility with hydrophobic polymer matrices [141]. The abundance of surface hydroxyl groups promotes strong hydrogen bonding between nanocellulose fibrils, leading to agglomeration, poor dispersion, and weak interfacial adhesion when incorporated into nonpolar polymers such as polyethylene (PE), polypropylene (PP), polylactic acid (PLA), and polyvinylidene fluoride (PVDF) [142]. These interfacial incompatibilities significantly limit stress transfer efficiency and reduce the mechanical and barrier performance of nanocellulose–reinforced composites [141].

While nanocellulose exhibits excellent oxygen barrier properties valuable for packaging, moisture sensitivity greatly reduces performance under humid conditions. High water uptake leads to swelling and loss of barrier efficiency, with behavior strongly influenced by surface charge and counterions [143]. For instance, sulfated CNCs absorb more moisture in the presence of H^+ or Na^+ than Ca^{2+}. Although factors such as crystallinity, surface chemistry, and temperature affect moisture response, their combined influence is still poorly understood, highlighting the need for improved strategies to enhance moisture resistance and polymer compatibility without relying on costly chemical modifications [144].

Characterization difficulties further complicate progress. The absence of standardized methods for CNF particle size measurement remains a critical gap. The highly branched and irregular fibrillar structure of CNFs makes defining measurable features difficult, while sample preparation can cause fibrils to separate or entangle unpredictably [40]. Although transmission electron microscopy (TEM) and atomic force microscopy (AFM) can accurately measure diameters, fibril length cannot be reliably determined because the start and end points are not clearly identifiable. These inconsistencies hinder comparison across studies and slow progress toward industrial standardization [145].

Sustainability concerns, particularly regarding raw materials, have driven interest in alternative feedstocks. Agricultural residues represent a promising opportunity for more sustainable nanocellulose production. These residues are frequently burned, composted, or discarded, yet they can be converted into high–value nanomaterials instead of becoming waste [45]. Replacing wood pulp, which is expensive and associated with deforestation and ecological pressures, with agricultural byproducts offers a circular and environmentally responsible production pathway [51]. This approach helps conserve forests, reduces environmental pressure from wood–based pulp sourcing, and minimizes pollution from crop–waste burning. Utilizing these abundant residues can lower production costs while supporting cleaner manufacturing and strengthening the bio–based economy [35].

Techno–economic assessment (TEA) plays an increasingly important role in shaping sustainable nanocellulose development. Although many studies address production pathways, energy requirements, surface modification, and application performance, comprehensive energy and cost analyses remain limited [137]. Detailed TEA comparisons between bench-scale and pilot–scale operations are scarce, leaving uncertainty around scale–up challenges and cost–saving opportunities. Expanding TEA research is essential to improve process design, enhance economic viability, and support the transition toward industrial–scale nanocellulose manufacturing [138].

Different cellulose processing routes yield distinct forms of nanocellulose, resulting in substantial variation in their functional performance and environmental footprint. Factors including raw material source, production pathways, chemical consumption, water and energy usage, and waste generation collectively govern the overall sustainability of nanocellulose materials [146]. These multidimensional impacts can be systematically evaluated through Life Cycle Assessment (LCA), which quantifies environmental burdens across the entire product life cycle, from biomass cultivation and raw material extraction to manufacturing, use, and end–of–life management. Key impact categories typically include global warming potential, abiotic resource depletion, ecotoxicity, water depletion, and land use change [147].

Recent cradle–to–gate LCA studies indicate that current CNC production technologies remain both energy– and chemical–intensive, with reported global warming potentials of approximately 28.6 kg CO_2–eq per kg of dry CNC, primarily driven by alkaline and acidic chemical inputs (NaOH, H_2SO_4, $NaClO_2$) and steam consumption. Comparative scenario analyses further reveal that feedstock purity, acid recovery integration, and decarbonization of process heat represent dominant levers for environmental performance improvement [148]. In particular, CNC production from high–purity dissolving pulp combined with efficient acid recovery significantly reduces energy demand and greenhouse gas emissions, while substituting fossil–derived steam with renewable natural gas can lower climate change impacts by more than 60%, albeit with certain trade–offs in ecotoxicity and ozone depletion [149]. These findings emphasize that nanocellulose cannot be universally regarded as inherently sustainable, as its environmental benefits are highly dependent on processing strategies, energy integration, and system–level optimization [150].

Beyond current–state assessments, prospective life cycle assessment (pLCA) frameworks provide valuable insight into the long–term sustainability trajectories of nanocellulose technologies. Screening–based modeling of early–stage sugar beet pulp biorefineries has demonstrated an economic learning rate of approximately 9%, translating into environmental learning rates of 3.1–6.6% through enhanced energy efficiency, chemical minimization, and process intensification. When integrated with Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs), these learning–driven improvements are projected to yield up to 24.5% reduction in climate change impacts by 2075, achieving a final footprint of ~78 kg CO_2–eq kg^{-1} CNM under optimistic sustainability scenarios [149]. These results highlight the crucial role of learning–by–doing, capacity scaling, and dynamic technological evolution in driving long–term environmental performance improvements.

In parallel, efforts to reduce environmental burdens have stimulated increasing interest in greener pretreatment and extraction technologies. Conventional cellulose isolation relies heavily on strong acids and alkalis, resulting in high chemical consumption, intensive water usage, and complex wastewater treatment requirements. To overcome these limitations, alternative environmentally benign pretreatments, including hot water extraction, supercritical fluid processing, ionic liquids (ILs), deep eutectic solvents (DESs), and their hybrid systems, have been extensively explored [151]. While hot water and supercritical fluid methods operate under elevated temperature and pressure, they eliminate the need for toxic reagents. Among these, supercritical CO_2 stands out due to its tunable solvating power, non–toxicity, low viscosity, and facile recovery, making it an attractive green processing medium [152]. Similarly, IL– and DES–based systems offer high delignification efficiency, solvent recyclability, and favorable biodegradability profiles, reinforcing their potential as sustainable alternatives for next–generation nanocellulose biorefineries [3].

Collectively, these insights underscore the complex interplay between process efficiency, environmental performance, and economic viability in nanocellulose production. Addressing energy intensity, chemical consumption, technological scalability, and environmental trade–offs, while advancing sustainable feedstocks, renewable energy integration, and green processing technologies, will be essential for enabling large–scale, cost–effective, and environmentally responsible nanocellulose manufacturing.

7 Conclusion

Nanocellulose has emerged as a highly versatile and sustainable nanomaterial that aligns with the growing demand for environmentally responsible and high–performance alternatives to conventional polymers. Its nanoscale dimensions, remarkable mechanical strength, and reactive surface functionalities enable a wide range of structural and functional modifications. Through various preparation and modification methods, nanocellulose properties can be precisely tuned to meet the requirements of diverse applications. As demonstrated in biomedical, environmental, packaging, and electronic sectors, nanocellulose–based materials combine biodegradability, renewability, and mechanical robustness with enhanced functionality, making them highly promising for next–generation technologies. Despite this progress, several critical barriers continue to limit widespread industrial implementation. Moisture sensitivity, thermal instability of sulfuric–acid–derived CNCs, particle aggregation, and batch–to–batch variability present persistent material–level challenges. These technical issues are compounded by practical constraints, including high energy consumption during fibrillation, costly purification processes, and ongoing difficulties in scaling production while maintaining uniform quality. Moreover, the lack of standardized characterization and quality–control protocols leads to inconsistent reporting and limits direct comparison across studies. Addressing these technical, economic, and standardization challenges will be essential to unlock nanocellulose's full potential and enable its integration into high–value, industrially relevant applications.

Acknowledgments

The authors would like to thank the National Science, Research, and Innovation Fund (NSRF), King Mongkut's University of Technology North Bangkok (Project No. KMUTNB-FF-69-B-03), and Srinakharinwirot University (Contract No. 645/2568) for financial support of this work.

Authors Contributions

N. Arshad: Conceptualization, Investigation, Writing-Original draft, N. Kitiborwornkul: Review & Editing P. Tantayotai: Review & Editing, S. M. K. Thiagamani: Review & Editing, Syahidah: Review & Editing, M. Sriariyanun: Conceptualization, Data curation, Reviewing, Editing, and Funding acquisition.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors utilized the ChatGPT tool to enhance the language and readability of the manuscript.

References

[1] I. Raheem et al., "A comprehensive review of approaches in carbon capture and utilization to reduce greenhouse gases," *Applied Science and Engineering Progress*, vol. 18, no. 2, Art. no. 7629, 2025, doi: 10.14416/j.asep.2024.11.004.

[2] J. Song, et al., "Copper-coordinated nanocellulose for multifunction composite film preparation," *Industrial Crops and Products* 229, 2025, Art. no. 121036, doi: 10.1016/j.indcrop.2025.121036.

[3] N. Arshad et al., "Deep eutectic solvents (DESs) in lignocellulosic biomass pretreatment: Mechanisms and process optimization," *Bioresource Technology Reports*, vol. 31, 2025, Art. no. 102190, doi: 10.1016/j.biteb.2025.102190.

[4] Z. Hoseinpour, R. Niazmand, and M. Heydari-Majd, "Extraction and characterization of nanocellulose from *Cuminum cyminum* L. husk by ball-milling-assisted ultrasound," *Carbohydrate Polymer Technologies and Applications*, vol. 11, 2025, Art. no. 100934, doi: 10.1016/j.carpta.2025.100934.

[5] M. Kaur and J. Pal, "Evaluation of efficiency of wheat straw nanocellulose as nanoadsorbent for the removal of divalent copper, lead and zinc from aqueous solution," *Carbohydrate Polymer Technologies and Applications*, vol. 6, 2023, Art. no. 100350, doi: 10.1016/j.carpta.2023.100350.

[6] X. Sun and F. Jiang, "Periodate oxidation-mediated nanocelluloses: Preparation, functionalization, structural design, and applications," *Carbohydrate Polymers*, vol. 341, 2024, Art. no. 122305, doi: 10.1016/j.carbpol.2024.122305.

[7] H. Seddiqi et al., "Cellulose and its derivatives: towards biomedical applications," *Cellulose*, vol. 28, pp. 1893–1931, 2021, doi: 10.1007/s10570-020-03674-w.

[8] W. Ma et al., "Preparation and durability of hydrophobically modified nanocellulose/epoxy vinyl resin composites: Multi-scale analysis in simulated pore solution of seawater sand concrete," *Construction and Building Materials*,

vol. 498, 2025, Art. no. 143997, doi: 10.1016/j.conbuildmat.2025.143997.

[9] P. Velayudhan, A. G. Pillai, M. S. Kala, N. Kalarikkal, B. Raneesh, and S. Thomas, "Boosting dielectric and mechanical functionality in electrospun PVDF through cellulose nanocrystal-mediated β-phase formation," *Polymer*, vol. 337, 2025, Art. no. 128999, doi: 10.1016/j.polymer.2025.128999.

[10] Y. Wang et al., "Nanocellulose from agro-industrial wastes: A review on sources, production, applications, and current challenges," *Food Research International*, vol. 192, 2024, Art. no. 114741, doi: 10.1016/j.foodres.2024.114741.

[11] Mordor Intelligence, "Nanocellulose Market Size & Share Analysis – Growth Trends & Forecasts (2025–2030)," Mordor Intelligence, Telangana, India

[12] Nanocellulose Market, "Nanocellulose Market Report – Demand, Growth & Industry Outlook 2025 to 2035," Nanocellulose Market, UK, 2025.

[13] S. Kane et al., "Harmonized life-cycle inventories of nanocellulose and its application in composites," *Environmental Science & Technology*, vol. 57, no. 48, pp. 19137–19147, 2023, doi: 10.1021/acs.est.3c04814.

[14] J. Müller-Carneiro et al., "Scenario-based life cycle assessment of cellulose nanocrystals production from agro-industrial by-products in 2040," *Journal of Cleaner Production*, vol. 522, 2025, Art. no. 146238, doi: 10.1016/j.jclepro.2025.146238.

[15] X. Zhang et al., "Electron beam pre-irradiation enhances substitution degree, and physicochemical and functional properties of carboxymethyl peanut shell nanocellulose," *Industrial Crops and Products*, vol. 209, 2024, Art. no. 118035, doi: 10.1016/j.indcrop.2024.118035.

[16] D. Jose et al., "Influence of acetic acid pretreatment and its residue on bioethanol and biogas production from water hyacinth," *Applied Science and Engineering Progress*, vol. 17, no. 3, 2024, Art. no. 7326, doi: 10.14416/j.asep.2024.02.001.

[17] M. B. Agustin et al., "Enzymatic crosslinking of lignin nanoparticles and nanocellulose in cryogels improves adsorption of pharmaceutical pollutants," *International Journal of Biological Macromolecules*, vol. 266, 2024, Art. no. 131168, doi: 10.1016/j.ijbiomac.2024.131168.

[18] L. T. K. Vu, A. T. K. Nguyen, and N. L. Le, "Activity and stability of lipases immobilized onto acetylated bacterial cellulose," *Applied Science and Engineering Progress*, vol. 16, no. 4, 2023, Art. no. 6812, doi: 10.14416/j.asep.2023.04.002.

[19] B. Machado, S. M. Costa, I. Costa, R. Fangueiro, and D. P. Ferreira, "The potential of algae as a source of cellulose and its derivatives for biomedical applications," *Cellulose*, vol. 31, pp. 3353–3376, 2024, doi: 10.1007/s10570-024-05816-w.

[20] Q. Ji, Z. Li, L. Su, I. D. Boateng, C. Zhou, and X. Liu, "Preparation, functional modification and industrial application of nanocellulose aerogels – A comprehensive review," *Biomass and Bioenergy*, vol. 193, 2025, Art. no. 107591, doi: 10.1016/j.biombioe.2025.107591.

[21] M. B. Agustin et al., "Enzymatic crosslinking of lignin nanoparticles and nanocellulose in cryogels improves adsorption of pharmaceutical pollutants," *International Journal of Biological Macromolecules*, vol. 266, 2024, Art. no. 131168, doi: 10.1016/j.ijbiomac.2024.131168.

[22] W. Lei et al., "A study on preparation of low-cost environment-friendly self-assembled nanocellulose membrane from waste paper," *Industrial Crops and Products*, vol. 221, 2024, Art. no. 119453, doi: 10.1016/j.indcrop.2024.119453.

[23] S. Qiu et al., "Effects of crystalline nanocellulose on wastewater-cultivated microalgal separation and biomass composition," *Applied Energy*, vol. 239, pp. 207–217, 2019, doi: 10.1016/j.apenergy.2019.01.212.

[24] M. Zaki et al., "Microbial enhancement of nanocellulose isolation from sawn timber industrial wastes and fabrication of biocomposite membranes," *Bioresource Technology Reports*, vol. 20, 2022, Art. no. 101242, doi: 10.1016/j.biteb.2022.101242.

[25] M. Zaki et al., "Microbial treatment for nanocellulose extraction from marine algae and its applications as sustainable functional material," *Bioresource Technology Reports*, vol. 16, 2021, Art. no. 100811, doi: 10.1016/j.biteb.2021.100811.

[26] K. Przygrodzka et al., "Bacterial cellulose production by *Komagataeibacter xylinus* with the use of enzyme-degraded oligo- and polysaccharides as the substrates," *Applied*

Sciences, vol. 12, no. 24, 2022, Art. no. 12673, doi: 10.3390/app122412673.

[27] M. J. Dunlop, B. Acharya, and R. Bissessur, "Isolation of nanocrystalline cellulose from tunicates," *Journal of Environmental Chemical Engineering*, vol. 6, no. 4, pp. 4408–4412, 2018, doi: 10.1016/j.jece.2018.06.056.

[28] R. Peretz, E. Sterenzon, Y. Gerchman, V. Kumar Vadivel, T. Luxbacher, and H. Mamane, "Nanocellulose production from recycled paper mill sludge using ozonation pretreatment followed by recyclable maleic acid hydrolysis," *Carbohydrate Polymers*, vol. 216, pp. 343–351, 2019, doi: 10.1016/j.carbpol.2019.04.003.

[29] X. Zhao et al., "Bioinspired design toward nanocellulose-based materials," *Materials Today*, vol. 66, pp. 409–430, 2023, doi: 10.1016/j.mattod.2023.04.010.

[30] S. Beluns et al., "From wood and hemp biomass wastes to sustainable nanocellulose foams," *Industrial Crops and Products*, vol. 170, 2021, Art. no. 113780, doi: 10.1016/j.indcrop.2021.113780.

[31] N. Wahlström et al., "Cellulose from the green macroalgae *Ulva lactuca*: Isolation, characterization, optotracing, and production of cellulose nanofibrils," *Cellulose*, vol. 27, no. 7, pp. 3707–3725, 2020, doi: 10.1007/s10570-020-03029-5.

[32] F. Chai, R. Wang, L. Yan, G. Li, Y. Cai, and C. Xi, "Facile fabrication of pH-sensitive nanoparticles based on nanocellulose for fast and efficient As(V) removal," *Carbohydrate Polymers*, vol. 245, 2020, Art. no. 116511, doi: 10.1016/j.carbpol.2020.116511.

[33] H. Kamada, Y. Hata, K. Sugiura, T. Sawada, and T. Serizawa, "Interfacial jamming of surface-alkylated synthetic nanocelluloses for structuring liquids," *Carbohydrate Polymers*, vol. 331, 2024, Art. no. 121896, doi: 10.1016/j.carbpol.2024.121896.

[34] S. Ariaeenejad, E. Motamedi, and G. H. Salekdeh, "Highly efficient removal of dyes from wastewater using nanocellulose from quinoa husk as a carrier for immobilization of laccase," *Bioresource Technology*, vol. 349, 2022, Art. no. 126833, doi: 10.1016/j.biortech.2022.126833.

[35] X. Zhang et al., "Electron beam pre-irradiation enhances substitution degree, and physicochemical and functional properties of carboxymethyl peanut shell nanocellulose," *Industrial Crops and Products*, vol. 209, 2024, Art. no. 118035, doi: 10.1016/j.indcrop.2024.118035.

[36] M. Al-haql, H. Habbal, B. Al Oklah, and N. Qurabi, "Extraction and characterization of spherical nanocellulose from sesame husks," *Heliyon*, vol. 11, no. 1, 2025, Art. no. e41269, doi: 10.1016/j.heliyon.2024.e41269.

[37] Holilah et al., "Fabrication a sustainable adsorbent nanocellulose–mesoporous hectorite bead for methylene blue adsorption," *Case Studies in Chemical and Environmental Engineering*, vol. 10, 2024, Art. no. 100850, doi: 10.1016/j.cscee.2024.100850.

[38] S. Padhi, A. Singh, V. Orsat, and W. Routray, "Isolation and characterization of nanocellulose from jackfruit peel: A comparative analysis of organic and inorganic acid hydrolysis on structural, thermal, and rheological properties," *Biomass and Bioenergy*, vol. 196, 2025, Art. no. 107716, doi: 10.1016/j.biombioe.2025.107716.

[39] F. Mahrous, R. Koshani, M. Tavakolian, K. Conley, and T. G. M. van de Ven, "Formation of hairy cellulose nanocrystals by cryogrinding," *Cellulose*, vol. 28, no. 13, pp. 8387–8403, 2021, doi: 10.1007/s10570-021-04092-2.

[40] W. Somphol et al., "Extraction of cellulose nanocrystals and nanofibers from rubber leaves and their impacts on natural rubber properties," *Applied Science and Engineering Progress*, vol. 17, 2024, Art. no. 7281, doi: 10.14416/j.asep.2023.11.010.

[41] G. Signori-Iamin, R. J. Aguado, J.-L. Putaux, A. F. Santos, W. Thielemans, and M. Delgado-Aguilar, "Energy and property trade-offs in nanocellulose production: High-pressure homogenization at different processing consistencies," *Chemical Engineering Journal*, vol. 509, 2025, Art. no. 161257, doi: 10.1016/j.cej.2025.161257.

[42] P. Vijay, W. Batchelor, and K. Saito, "One-pot treatment of cellulose using iron oxide catalysts to produce nanocellulose and water-soluble oxidised cellulose," *Carbohydrate Polymers*, vol. 282, 2022, Art. no. 119060, doi: 10.1016/j.carbpol.2021.119060.

[43] D. T. de Farias et al., "Cellulose nanofibrils from *Euterpe oleracea* residue extracted by acid hydrolysis and ultrasonic processing," *Industrial Crops and Products*, vol. 234, 2025, Art. no. 121502, doi: 10.1016/j.indcrop.2025.121502.

[44] G. Mu, et al., “Highly-efficient defibrillation of bamboo-based lignin-coated cellulose nanofibrils via facile hydrothermal and ethanol solvothermal pretreatments,” *Industrial Crops and Products*, vol. 234, 2025, Art. no. 121554, doi: 10.1016/j.indcrop.2025.121554.

[45] G. C. R. Bahadur et al., “Nanocellulose from Mankamana-3 corncob biomass: Synthesis, characterization, surface modification and potential applications,” *Bioresource Technology Reports*, vol. 28, 2024, Art. no. 101971, doi: 10.1016/j.biteb.2024.101971.

[46] R. Brahma and S. Ray, “Valorization of jackfruit peel as nanocellulose hydrogels: Synthesis and characterization,” *Food and Humanity*, vol. 5, 2025, Art. no. 100662, doi: 10.1016/j.foohum.2025.100662.

[47] Y. Yan et al., “*In situ* production of bacterial nanocellulose–activated carbon composites from pear juice industry wastewater by two new *Komagataeibacter intermedius* and *Komagataeibacter xylinus* isolates for heavy metal removal,” *Environmental Technology & Innovation*, vol. 33, 2024, Art. no. 103497, doi: 10.1016/j.eti.2023.103497.

[48] D. Liu et al., “Bacterial nanocellulose production using cost-effective, environmentally friendly, acid whey based approach,” *Bioresource Technology Reports*, vol. 24, 2023, Art. no. 101629, doi: 10.1016/j.biteb.2023.101629.

[49] N. E. A. El-Naggar, A. B. A. Mohammed, and S. E. El-Malkey, “Bacterial nanocellulose production using cantaloupe juice, statistical optimization and characterization,” *Scientific Reports*, vol. 13, no. 1, 2023, Art. no. 51, doi: 10.1038/s41598-022-26642-9.

[50] Y. Yan et al., “Enhanced preservation of cut rose flowers through bacterial nanocellulose produced from legume wastewater and fortified with *Auricularia auricula* polysaccharide,” *Postharvest Biology and Technology*, vol. 219, 2025, Art. no. 113277, doi: 10.1016/j.postharvbio.2024.113277.

[51] Y. S. Tseng et al., “Removal of heavy metal vanadium from aqueous solution by nanocellulose produced from *Komagataeibacter europaeus* employing pineapple waste as carbon source,” *Bioresource Technology*, vol. 369, 2023, Art. no. 128411, doi: 10.1016/j.biortech.2022.128411.

[52] A. Muñoz-Juan et al., “*Caenorhabditis elegans endorse* bacterial nanocellulose fibers as functional dietary fiber reducing lipid markers,” *Carbohydrate Polymers*, vol. 331, 2024, Art. no. 121815, doi: 10.1016/j.carbpol.2024.121815.

[53] C. Molina-Ramírez, A. Cañas-Gutiérrez, C. Castro, R. Zuluaga, and P. Gañán, “Effect of production process scale-up on the characteristics and properties of bacterial nanocellulose obtained from overripe banana culture medium,” *Carbohydrate Polymers*, vol. 240, Art. no. 116341, 2020, doi: 10.1016/j.carbpol.2020.116341.

[54] A. Grząbka-Zasadzińska, W. Smułek, N. Kuleta, R. Gąsiorowski, and S. Borysiak, “Lysozyme-modified nanocellulose for enhanced nucleation and antibacterial properties in advanced polylactide composites,” *International Journal of Biological Macromolecules*, vol. 321, 2025, Art. no. 146299, doi: 10.1016/j.ijbiomac.2025.146299.

[55] M. Raza, M. Jawaid, and B. Abu-Jdayil, “Nanocellulose extraction from date palm waste using 1-butyl-3-methylimidazolium hydrogen sulphate,” *International Journal of Biological Macromolecules,* vol. 294, 2025, Art. no. 139539, doi: 10.1016/j.ijbiomac.2025.139539.

[56] M. Babicka et al., “Miscanthus and sorghum as sustainable biomass sources for nanocellulose production,” *Industrial Crops and Products*, vol. 186, 2022, Art. no. 115177, doi: 10.1016/j.indcrop.2022.115177.

[57] Y. Xiao et al., “A light-weight and high-efficacy antibacterial nanocellulose-based sponge via covalent immobilization of gentamicin,” *Carbohydrate Polymers*, vol. 200, pp. 595–601, 2018, doi: 10.1016/j.carbpol.2018.07.091.

[58] D. M. Rodrigues et al., “A green approach to biomass residue valorization: Bacterial nanocellulose production from agro-industrial waste,” *Biocatalysis and Agricultural Biotechnology*, vol. 56, Art. no. 103036, 2024, doi: 10.1016/j.bcab.2024.103036.

[59] M. Fiallos-Cardenas, C. Gavin, K. Huilcarema-Enríquez, A. Cumbicus-Bravo, and F. Pozo, “Innovation in obtaining bacterial nanocellulose from banana rachis: Effects of ozone treatment,” *Case Studies in Chemical and Environmental Engineering*, vol. 11, 2025, Art. no. 101044, doi: 10.1016/j.cscee.2024.101044.

[60] A. Mautner and A. Bismarck, “Bacterial nanocellulose papers with high porosity for optimized permeance and rejection of nm-sized pollutants,” *Carbohydrate Polymers*, vol. 251,

2021, Art. no. 117130, doi: 10.1016/j.carbpol.2020.117130.

[61] A. Maged, O. E. A. Al-Hagar, S. Ahmed Abu El-Magd, S. Kharbish, A. Bhatnagar, and D. Abol-Fotouh, “Bacterial nanocellulose–clay film as an eco-friendly sorbent for superior pollutants removal from aqueous solutions,” *Environmental Research*, vol. 257, 2024, Art. no. 119231, doi: 10.1016/j.envres.2024.119231.

[62] M.A.A. Abakar et al., “Valorization of Coffee By-Products through Biorefinery Approaches for a Sustainable Bioeconomy,” *Applied Science and Engineering Progress*, vol. 20, no. 2, 2027, Art. no. 8046, doi: 10.14416/j.asep.2026.01.006.

[63] B. Saha, N. Arshad, M. Sriariyanun, W. Rodiahwati, and M. P. Gundupalli, “Anaerobic digestion: Technology for biogas as a source of renewable energy from biomass—A review,” *Applied Science and Engineering Progress*, vol. 18, no. 4, 2025, Art. no. 7895, doi: 10.14416/j.asep.2025.07.008.

[64] Y. Qi et al., “Nanocellulose: A review on preparation routes and applications in functional materials,” *Cellulose*, vol. 30, pp. 4115–4147, 2023, doi: 10.1007/s10570-023-05169-w.

[65] M. N. Khan et al., “Production of nanocellulose from lignocellulosic biomass and its potential applications: A review,” *Global NEST Journal*, vol. 26, no. 4, pp. 1–17, 2024, doi: 10.30955/gnj.005604.

[66] M. Nasir, R. Hashim, O. Sulaiman, and M. Asim, “Nanocellulose: Preparation methods and applications,” in *Cellulose-Reinforced Nanofibre Composites*, Cambridge, UK: Woodhead Publishing, 2017, doi: 10.1016/B978-0-08-100957-4.00011-5.

[67] S. P. Thomas, “A brief review on extraction and characterization of nanocellulose from date palm biomass,” *Cellulose*, vol. 37, 2025, Art. no. 18, doi: 10.1007/s44444-025-00005-x.

[68] N. Arshad et al., “Emerging technologies in pretreatment and hydrolysis for high-solid-loading bioethanol production from lignocellulosic biomass,” *Fermentation*, vol. 11, no. 11, 2025, Art. no. 613, doi: 10.3390/fermentation11110613.

[69] G. Cisternino, F. Baldassarre, G. Ciccarella, P. Mastrorilli, and M. M. Dell’Anna, “Microwave assisted treatment of carpentry waste wood flour with natural deep eutectic solvents for nanocellulose production and removal of organic pollutants,” *Carbohydrate Polymer Technologies and Applications*, vol. 8, 2024, Art. no. 100572, doi: 10.1016/j.carpta.2024.100572.

[70] A. Demir, F. G. Balpetek, E. Yiğit, E. Özdoğan, and F. Ayhan, “From waste cotton to functional textiles: Nanocellulose reinforcement and effect of plasma treatment,” *Fibers and Polymers*, vol. 26, no. 1, pp. 247–259, 2025, doi: 10.1007/s12221-024-00808-w.

[71] L. Zhou et al., Efficient preparation of cellulose nanocrystals with a with a high yield through simultaneous acidolysis with a heat–moisture treatment,” *Food Chemistry*, vol. 391, 2022, Art. no. 133285, doi: 10.1016/j.foodchem.2022.133285.

[72] G. Banvillet, G. Depres, N. Belgacem, and J. Bras, “Alkaline treatment combined with enzymatic hydrolysis for efficient cellulose nanofibrils production,” *Carbohydrate Polymers*, vol. 255, 2021, Art. no. 117383, doi: 10.1016/j.carbpol.2020.117383.

[73] P. Phanthong, S. Karnjanakom, P. Reubrovcharoen, X. Hao, A. Abudula, and G. Guan “A facile one-step way for extraction of nanocellulose with high yield by ball milling with ionic liquid,” *Cellulose*, vol. 24, pp. 2083–2093, 2017, doi: 10.1007/s10570-017-1238-5.

[74] D. Y. Hoo, et al., “Advancing sustainable high degree carboxylation of nanocellulose using dual polyacid ternary deep eutectic solvent,” *Bioresource Technology*, vol. 437, 2025, Art. no. 133112, doi: 10.1016/j.biortech.2025.133112.

[75] V. A. Barbash, O. V. Yashchenko, A. N. Zakharchenko, and E. A. Shniruk, “Preparation and properties of nanocellulose from organosolv straw pulp,” *Nanoscale Research Letters*, vol. 12, 2017, Art. no. 241, doi: 10.1186/s11671-017-2001-4.

[76] V. Raju et al., “Isolation and characterization of nanocellulose from selected hardwoods, viz., *Eucalyptus tereticornis* Sm. and *Casuarina equisetifolia* L., by steam explosion method,” *Scientific Reports*, vol. 13, 2023, Art. no. 1199, doi: 10.1038/s41598-022-26600-5.

[77] Y. K. Verma, A. K. Singh, M. K. Paswan, and P. K. Gurmaita, “Preparation and characterization of bamboo based nanocellulose by ball milling and used as a filler for preparation of nanocomposite,” *Polymer*, vol. 308, 2024, Art. no. 127396, doi: 10.1016/j.polymer.2024.127396.

[78] W. Chumchoochart and J. Tinoi, “Nanocellulose production from rice straw derived-cellulose by

enzymatic hydrolysis and its effect on lipase activity," *Applied Science and Technology Progress*, vol. 27, no. 2, 2022, doi: 10.14456/apst.2022.39.

[79] J. Kawalerczyk et al., "The effect of urea–formaldehyde adhesive modification with diisocyanate-functionalized nanocellulose on the properties of particleboard," *International Journal of Adhesion and Adhesives*, vol. 135, 2024, Art. no. 103850, doi: 10.1016/j.ijadhadh.2024.103850.

[80] W. Zhang et al., "A novel pH-responsive emulsion system stabilized by nanocelluloses modified with a rosin-based charge-reversible surfactant," *International Journal of Biological Macromolecules*, vol. 304, 2025, Art. no. 140938, doi: 10.1016/j.ijbiomac.2025.140938.

[81] F. Kareem, R. Chandrawati, and M. U. Ahmed, "Tailoring nanocellulose: A comprehensive exploration of functionalisation with small, macro, and inorganic molecules for enhanced sensing and dual-mode biosensing," *Measurement*, vol. 239, 2025, Art. no. 115499, doi: 10.1016/j.measurement.2024.115499.

[82] S. Jirathampinyo, W. Chumchoochart, and J. Tinoi, "Integrated biobased processes for nanocellulose preparation from rice straw cellulose," Processes, vol. 11, no. 4, 2023, Art. no. 1006, doi: 10.3390/pr11041006.

[83] L. Wang, L. Hui, and W. Su, "Superhydrophobic modification of nanocellulose based on an octadecylamine/dopamine system," *Carbohydrate Polymers*, vol. 275, 2022, Art. no. 118710, doi: 10.1016/j.carbpol.2021.118710.

[84] B. E. Channab, A. El Idrissi, Y. Essamlali, and M. Zahouily, "Nanocellulose: Structure, modification, biodegradation and applications in agriculture as slow/controlled release fertilizer, superabsorbent, and crop protection—A review," *Journal of Environmental Management*, vol. 352, 2024, Art. no. 119928, doi: 10.1016/j.jenvman.2023.119928.

[85] B. Sun, C. Zhang, X. Li, L. Zhong, Z. Zhang, and D. Zhou, "Nanocellulose-based hydrogels for smart sensors," *Carbohydrate Polymers*, vol. 368, no. 2, 2025, Art. no. 124152, doi: 10.1016/j.carbpol.2025.124152.

[86] J. M. Loaiza, E. A. Gutiérrez, J. C. García, and F. López, "Cascade biorefinery approach to obtain hemicelluloses, lignin, cellulose and nanocelluloses from high-yield forest crops (*Ulmus minor*) for different industrial applications," *Industrial Crops and Products*, vol. 236, 2025, Art. no. 122031, doi: 10.1016/j.indcrop.2025.122031.

[87] N. T. Van Anh et al., "Utilization of rice husk and alum sludge to produce an efficient adsorbent composite for recovery of nutrients from wastewater," *Applied Science and Engineering Progress*, vol. 17, no. 1, 2024, Art. no. 6898, doi: 10.14416/j.asep.2023.08.002.

[88] R. Ma et al., "One-pot cellulose nanofibrillation, surface-modification and grafting by deep eutectic solvent towards high-performance 3D printing nanocellulose-enriched bionanocomposites," *Industrial Crops and Products*, vol. 210, 2024, Art. no. 118134, doi: 10.1016/j.indcrop.2024.118134.

[89] H. Khan et al., "Biotransformation of banana peel waste into bacterial nanocellulose and its modification for active antimicrobial packaging using poly(vinyl alcohol) with in situ generated silver nanoparticles," *Food Packaging and Shelf Life*, vol. 38, 2023, Art. no. 101115, doi: 10.1016/j.fpsl.2023.101115.

[90] J. B. S. Ferraz, J. S. de Oliveira, E. L. Oliveira, and C. P. de Oliveira, "Development and characterization of biodegradable films based on carboxymethylcellulose with incorporated eucalyptus (*Eucalyptus grandis*) nanocellulose," *Food Chemistry*, vol. 495, 2025, Art. no. 146532, doi: 10.1016/j.foodchem.2025.146532.

[91] D. Chen, Y. Y. Lee, C. P. Tan, Y. Wang, and C. Qiu, "Robust porous aerogel frameworks with high oil absorption derived from hierarchical nanocellulose/lipid nanoparticle composites," *Carbohydrate Polymers*, vol. 370, 2025, Art. no. 124442, doi: 10.1016/j.carbpol.2025.124442.

[92] R. T. Yulianti et al., "Surface-modified nano-silica on nanocellulose-based solid polymer electrolytes for safe lithium metal batteries," *Journal of Energy Storage*, vol. 132, 2025, Art. no. 117860, doi: 10.1016/j.est.2025.117860.

[93] T. Q. Thao, N. T. T. Hien, P. T. Lam, and N. N. Huy, "Exploring the mechanism for the photocatalytic degradation of oxytetracycline in water using TiO_2 and supplementary oxidants," *Applied Science and Engineering Progress*, vol. 18, no. 3, 2025, Art. no. 7651, doi: 10.14416/j.asep.2024.11.007.

[94] J. Yin et al., "Bioinspired and dual-functional nanocellulose aerogels for water disinfection and heavy metal removal, *Nano Today*, vol. 51, 2023,

Art. no. 101918, doi: 10.1016/j.nantod.2023.101918.

[95] N. A. Azra et al., "Oil-palm-based nanocellulose reinforced thermoplastic polyurethane for plastic encapsulation of biomedical sensor devices: Water absorption, thickness swelling and density properties," *Applied Science and Engineering Progress*, vol. 16, no. 1, 2023, Art. no. 5696, doi: 10.14416/j.asep.2022.02.001.

[96] K. M. N'Gatta et al., "3D printing of cellulose nanocrystals based composites to build robust biomimetic scaffolds for bone tissue engineering," *Scientific Reports*, vol. 12, no. 1, 2022, Art. no. 21244, doi: 10.1038/s41598-022-25652-x.

[97] V. Torresan et al., "Nanocellulose–collagen composites as advanced biomaterials for 3D in vitro neuronal model systems," *Carbohydrate Polymers*, vol. 348, 2025, Art. no. 122901, doi: 10.1016/j.carbpol.2024.122901.

[98] H. Gao et al., "Construction of cellulose nanofibers/quaternized chitin/organic rectorite composites and their application as wound dressing materials," *Biomaterials Science*, vol. 7, no. 6, pp. 2571–2581, 2019, doi: 10.1039/C9BM00288J.

[99] P. N. Christy, S. K. Basha, and V. S. Kumari, "Multifunctional organic and inorganic hybrid bionanocomposite of chitosan/poly(vinyl alcohol)/nanobioactive glass/nanocellulose for bone tissue engineering," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 135, 2022, Art. no. 105427, doi: 10.1016/j.jmbbm.2022.105427.

[100] S. Iswarya, T. Theivasanthi, and S. C. B. Gopinath, "Sodium alginate/ hydroxyapatite/ nanocellulose composites: Synthesis and potentials for bone tissue engineering," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 148, 2023, Art. no. 106189, doi: 10.1016/j.jmbbm.2023.106189.

[101] S. Das, B. Ghosh, and K. Sarkar, "Nanocellulose as sustainable biomaterials for drug delivery," *Sensors International*, vol. 3, 2022, Art. no. 100135, doi: 10.1016/j.sintl.2021.100135.

[102] S. M. I. A. Rafee, M. S. U. Alim, S. Alam, and K. S. Salem, "Nanocellulose polymorphs for biomedical applications: Recent advances, prospects and challenges—A review," *Carbohydrate Polymer Technologies and Applications*, vol. 11, 2025, Art. no. 100916, doi: 10.1016/j.carpta.2025.100916.

[103] Y. Li, X. Liu, Z. Liu, S. Wang, and F. Kong, "Fabrication of controllable structure of nanocellulose composite aerogel for targeted drug delivery," *Carbohydrate Polymers*, vol. 358, 2025, Art. no. 123518, doi: 10.1016/j.carbpol.2025.123518.

[104] Y. Yang et al., "Light-activatable liposomes for repetitive on-demand drug release and immunopotentiation in hypoxic tumor therapy," Biomaterials, vol. 265, 2021, Art. no. 120456, doi: 10.1016/j.biomaterials.2020.120456.

[105] P. Gangurde et al., "Harnessing liposomal nanocellulose hydrogel for NIR-light driven on-demand drug delivery," *Carbohydrate Polymer Technologies and Applications*, vol. 10, 2025, Art. no. 100787, doi: 10.1016/j.carpta.2025.100787.

[106] T. Kopač, M. Krajnc, and A. Ručigaj, "A mathematical model for pH-responsive ionically crosslinked TEMPO nanocellulose hydrogel design in drug delivery systems," *International Journal of Biological Macromolecules*, vol. 168, pp. 695–707, 2021, doi: 10.1016/j.ijbiomac.2020.11.126.

[107] Y. Hu et al., "A double-layer hydrogel based on alginate–carboxymethyl cellulose and synthetic polymer as sustained drug delivery system," *Scientific Reports*, vol. 11, no. 1, 2021, Art. no. 9142, doi: 10.1038/s41598-021-88503-1.

[108] L. Melro et al., "Bacterial nanocellulose as a versatile scaffold for biomedical applications: Synthesis, functionalization, and future prospects," *Applied Materials Today*, vol. 46, 2025, Art. no. 102858, doi: 10.1016/j.apmt.2025.102858.

[109] F. Seyedpour et al., "Advances and challenges in tailoring antibacterial polyamide thin film composite membranes for water treatment and desalination: A critical review," *Desalination*, vol. 581, 2024, Art. no. 117614, doi: 10.1016/j.desal.2024.117614.

[110] C. Yang et al., "Preparation and applications of magnetic nanocellulose composites: A review," *Carbohydrate Polymers*, vol. 354, 2025, Art. no. 123317, doi: 10.1016/j.carbpol.2025.123317.

[111] S. Atefyekta et al., "Antimicrobial peptide-functionalized mesoporous hydrogels," *ACS*

Biomaterials Science & Engineering, vol. 7, no. 4, pp. 1693–1702, 2021, doi: 10.1021/acsbiomaterials.1c00029.

[112] E. Zattarin et al., "Controlled release of antimicrobial peptides from nanocellulose wound dressings for treatment of wound infections," *Materials Today Bio*, vol. 32, 2025, Art. no. 101756, doi: 10.1016/j.mtbio.2025.101756.

[113] J. Thomas, P. S. Thomas, and R. Stephen, "Improved mechanical, thermal, and barrier properties of halloysite nanotubes and nanocellulose incorporated PVA–PEO films for food packaging applications," *Food Packaging and Shelf Life*, vol. 46, 2024, Art. no. 101373, doi: 10.1016/j.fpsl.2024.101373.

[114] K. Yu et al., "Tough, antibacterial, antioxidant, antifogging and washable chitosan/nanocellulose-based edible coatings for grape preservation," *Food Chemistry*, vol. 468, 2025, Art. no. 142513, doi: 10.1016/j.foodchem.2024.142513.

[115] F. Sun, J. Zhao, P. Shan, K. Wang, H. Li, and L. Peng, "Gelatin-based composite film integrated with nanocellulose and extract–metal complex derived from coffee leaf for sustainable and active food packaging," *Food Hydrocolloids*, vol. 159, 2025, Art. no. 110610, doi: 10.1016/j.foodhyd.2024.110610.

[116] X. Wang, S. Xuan, K. Ding, P. Jin, Y. Zheng, and Z. Wu, "Photothermal controlled antibacterial $Ta_4C_3T_x$–AgNPs/nanocellulose bioplastic food packaging," *Food Chemistry*, vol. 448, 2024, Art. no. 139126, doi: 10.1016/j.foodchem.2024.139126.

[117] H. Chen et al., "Amino-functionalized nanocellulose-derived flexible elastomer for cryptographic information transmission and triboelectric nanogenerators," *Industrial Crops and Products*, vol. 227, 2025, Art. no. 120855, doi: 10.1016/j.indcrop.2025.120855.

[118] J. Han et al., "Nanocellulose-templated assembly of polyaniline in natural rubber-based hybrid elastomers toward flexible electronic conductors," *Industrial Crops and Products*, vol. 128, pp. 94–107, 2019, doi: 10.1016/j.indcrop.2018.11.004.

[119] N. Choudhary et al., "Recent advancements in nanocellulose-based supercapacitors for energy storage devices: A review," *Carbohydrate Polymer Technologies and Applications*, vol. 7, 2024, Art. no. 100416, doi: 10.1016/j.carpta.2023.100416.

[120] N. P. D. Ngidi, B. S. Martincigh, and V. O. Nyamori, "Recent progress on nanocellulose-based nanocomposites for application in photovoltaic solar cells and supercapacitors," *Journal of Materials Research and Technology*, vol. 37, pp. 1682–1704, 2025, doi: 10.1016/j.jmrt.2025.05.013.

[121] H. B. Youcef et al., "Functionalized cellulose as quasi single-ion conductors in polymer electrolyte for all-solid-state Li/Na and Li–S batteries,"*Solid State Ionics*, vol. 345, 2020, Art. no. 115168, doi: 10.1016/j.ssi.2019.115168.

[122] Z. Ma, R. Zeng, S. Zou, B. Na, S. Lin, and H. Liu, "Nanocellulose-confined phase inversion towards cationic composite separators for stable lithium metal batteries," *Journal of Energy Storage*, vol. 135, 2025, Art. no. 118371, doi: 10.1016/j.est.2025.118371.

[123] Y. Zhu et al., Morphology-regulated stabilization mechanisms of complexes involving nanocellulose and zein nanoparticles in O/W and $W_1/O/W_2$ emulsions: Interfacial property and network formation," *Food Chemistry*, vol. 493, 2025, Art. no. 145966, doi: 10.1016/j.foodchem.2025.145966.

[124] Y. Lou et al., "High-permeance nanocellulose/ZnO hybrid membranes with photo-induced antifouling performance for wastewater purification," *Carbohydrate Polymers*, vol. 348, 2025, Art. no. 122807, doi: 10.1016/j.carbpol.2024.122807.

[125] G. Ma et al., "A novel multifunctional self-assembled nanocellulose-based scaffold for the healing of diabetic wounds," *Carbohydrate Polymers*, vol. 361, 2025, Art. no. 123643, doi: 10.1016/j.carbpol.2025.123643.

[126] X. Wang et al., "A trilaminar edible film of nanocellulose, konjac glucomannan, and curcumin with pH-responsive and amphiphilic properties: Preparation, characterization, and application," *Food Chemistry*, vol. 488, 2025, Art. no. 144913, doi: 10.1016/j.foodchem.2025.144913.

[127] J. L. López-Miranda et al., "A green approach for biomedical and photocatalytic applications using sargassum-derived nanocellulose foams decorated with MO nanoparticles (M = Zn, Cu)," *International Journal of Biological*

Macromolecules, vol. 315, 2025, Art. no. 144439, doi: 10.1016/j.ijbiomac.2025.144439.

[128] W. K. Cheng et al., "Nanocellulose paper electrodes: Flexible, free-standing platforms for wearable electronic devices," *International Journal of Biological Macromolecules*, vol. 320, 2025, Art. no. 145991, doi: 10.1016/j.ijbiomac.2025.145991.

[129] K. Liu et al., "Durable $Co(OH)_2$/stearic acid-based superhydrophobic/superoleophilic nanocellulose membrane for highly efficient oil/water separation and simultaneous removal of soluble dye," *Industrial Crops and Products*, vol. 203, 2023, Art. no. 117190, doi: 10.1016/j.indcrop.2023.117190.

[130] S. Yadav and S. Kamsonlian, "Progress on the development of techniques to remove contaminants from wastewater: A review," *Applied Science and Engineering Progress*, vol. 16, no. 3, 2023, Art. no. 6729, doi: 10.14416/j.asep.2023.02.001.

[131] X. Jiao et al., "Nanocellulose-based functional materials towards water treatment," *Carbohydrate Polymers*, vol. 350, 2025, Art. no. 122977, doi: 10.1016/j.carbpol.2024.122977.

[132] W. W. Leow et al., "Facile synthesis of hybrid-polyoxometalates nanocomposite for degradation of cationic and anionic dyes in water treatment," *Applied Science and Engineering Progress*, vol. 18, no. 1, 2025, Art. no. 7485, doi: 10.14416/j.asep.2024.07.014.

[133] S. Ariaeenejad, E. Motamedi, and G. Hosseini Salekdeh, "Application of the immobilized enzyme on magnetic graphene oxide nano-carrier as a versatile bi-functional tool for efficient removal of dye from water," *Bioresource Technology*, vol. 319, 2021, Art. no. 124228, doi: 10.1016/j.biortech.2020.124228.

[134] M. Zubair et al., "Recent advances in nanocellulose-based two-dimensional nanostructured membranes for sustainable water purification: A review," *Carbohydrate Polymers*, vol. 329, 2024, Art. no. 121775, doi: 10.1016/j.carbpol.2024.121775.

[135] M. K. J. Nidhi, H. Nagaraja, H. Gouda, M. G. Kotresh, and B. Uma Reddy, "Bactericidal and antivirulence potential of sulphate-functionalized nanocellulose extracted from *Nelumbo nucifera* Gaertn," *Chemical Physics Impact*, vol. 11, 2025, Art. no. 100921, doi: 10.1016/j.chphi.2025.100921.

[136] W. Kargupta, T. Stevenson, S. Sharman, J. Tanner, and W. Batchelor, "Sustainable production of nanocellulose: Technoeconomic assessment, energy savings and scalability," *Journal of Cleaner Production*, vol. 425, 2023, Art. no. 138748, doi: 10.1016/j.jclepro.2023.138748.

[137] J. Yang et al., "Effect of alkali concentration on the nanofibrillation efficiency of cellulose by mechanical grinding," *BioResources*, vol. 21, no. 1, pp. 288–304, 2026, doi: 10.15376/biores.21.1.288-304.

[138] N. Rajendran, T. Runge, R. D. Bergman, P. Nepal, and C. Houtman, "Techno-economic analysis and life cycle assessment of cellulose nanocrystals production from wood pulp," *Bioresource Technology*, vol. 377, 2023, Art. no. 128955, doi: 10.1016/j.biortech.2023.128955.

[139] N. L. Khumalo et al., "Effect of acid concentration on structural, thermal, and morphological properties of cellulose nanocrystals from sugarcane bagasse and their reinforcement in poly(furfuryl alcohol) composites," *Crystals*, vol. 15, no. 5, 2025, Art. no. 403, doi: 10.3390/cryst15050403.

[140] C. Metzger, D. Auber, S. Dähnhardt-Pfeiffer, and H. Briesen, "Agglomeration of cellulose nanocrystals: The effect of secondary sulfates and their use in product separation," *Cellulose*, vol. 27, no. 17, pp. 9839–9851, 2020, doi: 10.1007/s10570-020-03476-0.

[141] A. Ramos, J. M. Rodilla, R. Ferreira, and Â. Luís, "Enhancing hydrophobicity of nanocellulose-based films by coating with natural wax from *Halimium viscosum*," *Applied Sciences*, vol. 15, 2025, Art. no. 7576, doi: 10.3390/app15137576.

[142] E. Aigaje, A. Riofrio, and H. Baykara, "Processing, properties, modifications, and environmental impact of nanocellulose/biopolymer composites: A review," *Polymers*, vol. 15, 2023, Art. no. 1219, doi: 10.3390/polym15051219.

[143] M. Garg et al., "Moisture uptake in nanocellulose: The effects of relative humidity, temperature and degree of crystallinity," *Cellulose*, vol. 28, no. 14, pp. 9007–9021, 2021, doi: 10.1007/s10570-021-04099-9.

[144] J. Zhang and J. P. Youngblood, "Cellulose nanofibril-based hybrid coatings with enhanced moisture barrier properties," *Materials Advances*, vol. 6, no. 9, pp. 2833–2844, 2025, doi: 10.1039/d4ma01276c.

[145] R. Moon, L. Johnston, C. Land-Hensdal, and W. Batchelor, "Perspectives on cellulose nanofibril size measurement using scanning electron microscopy," *Cellulose*, vol. 32, no. 5, pp. 2793–2810, 2025, doi: 10.1007/s10570-025-06458-2.

[146] F. Foroughi et al., "A review on the life cycle assessment of cellulose: From properties to the potential of making it a low carbon material," Materials, vol. 14, 2021, Art. no. 714, doi: 10.3390/ma14040714.

[147] F. A. G. S. Silva, S. Branco, F. Dourado, B. Neto, and M. Gama, "Life cycle assessment of bacterial cellulose and comparison to other cellulosic sources," *Journal of Cleaner Production*, vol. 493, 2025, Art. no. 144876, doi: 10.1016/j.jclepro.2025.144876.

[148] R. P. B. Ashok, D. Kumar, P. Nepal, R. Bergman, and T. Runge, "Cellulose nanocrystals from forest residues: An integrated techno-economic analysis and life cycle assessment," *Resources, Conservation & Recycling*, 2026, Art. no. 108778, doi: 10.1016/j.resconrec.2026.108778.

[149] K. M. Rebec, J. Turk, and M. Kunaver, "Quantifying the environmental implication of cotton-fiber-based nanocrystalline cellulose: A life-cycle assessment," *Sustainable Production and Consumption*, vol. 45, pp. 192–202, 2024, doi: 10.1016/j.spc.2023.12.026.

[150] C. Santulli, "Life cycle, cost assessment, and commercialization of nanocellulose and its composites," in *Applications of Nanocellulose and Nanocellulose-Based Composites*. Amsterdam, Netherland: Elsevier, 2026, doi: 10.1016/B978-0-443-31622-7.00023-8.

[151] X. Q. Wu et al., "Production of cellulose nanofibrils and films from elephant grass using deep eutectic solvents and a solid acid catalyst," *RSC Advances*, vol. 11, no. 23, pp. 14071–14078, 2021, doi: 10.1039/d1ra02259h.

[152] R. Roy, M. S. Rahman, and D. E. Raynie, "Recent advances of greener pretreatment technologies of lignocellulose," *Current Research in Green and Sustainable Chemistry*, vol. 3, 2020, Art. no. 100035, doi: 10.1016/j.crgsc.2020.100035.