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Nanocellulose from Renewable Biomass: Sustainable Production, Characterization, Surface Functionalization, and Emerging Applications in Environmental Biotechnology

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Abstract
Nanocellulose is a sustainable and versatile nanomaterial derived from renewable biomass with significant potential for environmental and biotechnological applications. Owing to its high surface area, tunable surface chemistry, biodegradability, and remarkable mechanical strength, nanocellulose has emerged as a promising alternative to synthetic non-biodegradable polymers in advanced material systems.This review summarizes recent advances in nanocellulose with emphasis on sustainable production strategies, including acid hydrolysis, enzymatic treatment, mechanical fibrillation, and hybrid extraction approaches. The influence of raw material selection, particularly agricultural residues such as sugarcane bagasse, rice husk, wheat straw, forestry by-products, and food-processing wastes, is discussed in relation to extraction efficiency, yield, and physicochemical properties. Structural characteristics, surface functionalization, and major characterization techniques are critically reviewed to explain how physicochemical properties can be tailored for specific environmental and biotechnological applications. Emerging applications in tissue engineering, drug delivery, biosensors, biomedical devices, environmental remediation, and nanocomposites are highlighted, with attention to current trends in multifunctional material design.Nanocellulose demonstrates strong potential as a sustainable functional nanomaterial; however, challenges related to large-scale production, economic feasibility, life-cycle sustainability, and regulatory standardization must be addressed to support broader industrial translation.

Keywords: Nanocellulose; Renewable biomass; Surface functionalization; Sustainable extraction; Environmental biotechnology

I. Introduction

Cellulose, the most abundant natural biopolymer on Earth, has long been recognized as an important renewable and biodegradable raw material for the development of sustainable advanced materials [13, 18, 10]. Nanocellulose, the nanoscale derivative of cellulose, has attracted considerable scientific interest because of its unique physicochemical properties, including high surface area, tunable surface chemistry, excellent mechanical strength, and biodegradability [18, 10]. These characteristics make nanocellulose a promising alternative to synthetic non-biodegradable materials in several technological and biotechnological applications.

Nanocellulose is broadly classified into three major categories: cellulose nanocrystals (CNCs), cellulose nanofibers (CNFs), and bacterial nanocellulose (BNC). CNCs are highly crystalline rod-like structures generally produced by controlled acid hydrolysis and are known for their stiffness and reinforcing capability [17, 21]. CNFs consist of long and flexible fibrils typically obtained through mechanical fibrillation, often assisted by chemical or enzymatic pretreatment, offering excellent network-forming ability. BNC is synthesized by bacterial strains such as *Komagataeibacter xylinus* and exhibits high purity, superior water-holding capacity, and a three-dimensional nanofibrillar network suitable for biomedical use [26, 27].

The growing interest in nanocellulose has been strongly linked to the search for environmentally sustainable and economically viable production methods. Conventional chemical extraction methods such as acid hydrolysis are increasingly being combined with enzymatic and mechanical treatments to improve extraction efficiency, reduce environmental burden, and tailor structural properties such as crystallinity, fiber dimensions, and surface functionality [20, 8]. Raw material selection also plays a critical role in determining yield and final material performance.

Agricultural residues such as sugarcane bagasse, rice husk, and wheat straw, along with forestry by-products and food-processing wastes, are now widely explored as low-cost renewable feedstocks within circular bioeconomy approaches [24, 3].

Nanocellulose has demonstrated remarkable versatility in biotechnology, particularly in tissue engineering, drug delivery, biosensing, wound healing, environmental remediation, nanocomposite packaging, and advanced biomedical devices. Despite significant progress, important challenges remain regarding large-scale production, cost efficiency, reproducibility of material properties, and regulatory standardization for industrial and biomedical translation.

Although several reviews have addressed specific aspects of nanocellulose such as extraction methods, biomedical applications, or composite development, an integrated and updated analysis linking renewable biomass sources, sustainable production pathways, surface functionalization strategies, and emerging environmental-biotechnology applications remains limited. This review provides a consolidated perspective by critically comparing recent advances in feedstock utilization, extraction technologies, characterization approaches, and functional modifications reported between 2020 and 2025, while also highlighting translational challenges related to scalability, cost, and industrial applicability.

Table 1 Comparison of selected recent nanocellulose review articles and the present review

Reference	Main focus of previous review	Limitation identified	Contribution of present review
Abitbol et al. (2016)	General overview of nanocellulose properties and broad applications	Limited emphasis on sustainable biomass sources and environmental production metrics	Includes detailed discussion of agro-industrial residues and sustainable extraction strategies
Rajinipriya et al. (2019)	Nanocellulose in composite materials	Primarily focused on composite reinforcement with limited biotechnology coverage	Expands into biotechnology, biomedical systems, and environmental remediation
Wang et al. (2022)	Source selection and packaging applications	Limited treatment of surface functionalization and regulatory challenges	Integrates functionalization strategies and translational challenges
Ghamari et al. (2025)	Biomass waste extraction for biomedical use	Focused mainly on biomedical direction	Provides broader integration of environmental biotechnology, multifunctional applications, and industrial perspectives
Present review	Sustainable production, characterization, surface functionalization, and environmental biotechnology	—	Integrates agro-waste valorization, functionalization methods, biotechnology applications, and future industrial translation

II. Sources of Nanocellulose

Nanocellulose is an abundant, renewable, and versatile material derived from a wide variety of natural and biological sources. Its availability depends on the origin of cellulose, which can be broadly classified into agricultural residues, forestry resources, bacterial cellulose, and other biomass wastes. The selection of source not only affects extraction yield but also influences the structural, chemical, and functional properties of the resulting nanocellulose.

2.1 Agricultural Residues

Agricultural residues represent one of the most sustainable and economical sources of cellulose for nanocellulose production [22, 24, 26]. Large quantities of agricultural by-products such as sugarcane bagasse, rice husk, wheat straw, pineapple leaves, corn stalks, and coconut husks are generated globally each year. These materials are considered suitable raw materials because they typically contain 30–50% cellulose along with hemicellulose and lignin [24, 26].

Sugarcane bagasse, a major by-product of sugar and ethanol industries, contains approximately 40–50% cellulose and has emerged as a promising feedstock because of its abundance, low cost, and high fiber content. Pretreatment methods such as alkaline treatment, bleaching, and acid hydrolysis are commonly applied to remove lignin and hemicellulose before nanocellulose extraction. Hybrid extraction methods combining chemical and mechanical processes have demonstrated the ability to produce high-quality cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs) from bagasse.

Other agricultural residues such as rice husk and wheat straw have also been extensively studied because of their cellulose availability and large-scale generation. Similarly, pineapple leaf fibers, banana pseudostems, and coconut coir have been explored as renewable alternative feedstocks. Valorization of agricultural residues contributes significantly to circular bioeconomy strategies by reducing waste disposal burden and generating value-added biomaterials.

2.2 Forestry-Derived Cellulose

Forestry-derived biomass remains the most traditional and widely used source of cellulose, mainly obtained from wood pulp, cotton, bamboo, and other lignocellulosic materials [14, 18]. Softwood and hardwood pulps are industrially preferred because of their relatively high cellulose content and reliable supply chains.

Depending on extraction conditions, forestry biomass can yield microfibrillated cellulose, cellulose nanofibrils, or cellulose nanocrystals. Forestry-derived feedstocks are particularly important for large-scale industrial nanocellulose production, especially in packaging materials, coatings, and reinforcement applications in polymer composites.

2.3 Bacterial Cellulose

Bacterial cellulose (BC) is biosynthesized by microorganisms such as *Komagataeibacter xylinus* under aerobic fermentation conditions. Unlike plant-derived cellulose, bacterial cellulose is free from lignin and hemicellulose impurities and therefore does not require harsh pretreatment processes. It exhibits high crystallinity, excellent purity, strong tensile properties, and a three-dimensional nanofibrillar network structure [6, 12, 1].

These characteristics make bacterial cellulose highly suitable for biomedical applications including wound healing, drug delivery, and tissue engineering. However, high production cost, expensive culture media, and low scalability remain major limitations for large-scale commercial utilization [1, 26].

2.4 Other Biomass Sources

Alternative non-woody cellulose sources include algae, tunicates, and food-processing by-products such as pomace and fruit peels. These feedstocks can provide unique structural morphologies and functional characteristics, although they remain less extensively studied than agricultural and forestry sources [27, 24].

A comparative overview of different nanocellulose sources is presented in Table 2.

Table 2 Comparative sources of nanocellulose from different feedstocks

Source	Cellulose Content (%)	Advantages	Limitations	Applications
Agricultural residues (sugarcane bagasse, rice husk, wheat straw, pineapple leaves, banana pseudostems, coconut husk)	30–50%	Abundant & low-cost, Valorizes waste (circular bioeconomy), High fiber yield in some residues (bagasse ~40–50%)	Requires extensive pre-treatment (alkali, bleaching), Variable composition due to seasonal/environmental factors	Packaging, nanocomposites, coatings, and paper reinforcement
Forestry-Derived Cellulose (wood pulp, bamboo, cotton)	40–60% (wood pulp), up to 90% (cotton)	Established industrial supply chain, High cellulose yield, Scalable for large-scale production	Deforestation/environmental concerns, pre-treatment required for lignin removal	Reinforcement in polymers, construction materials, coatings, and films

Bacterial Cellulose (*Acetobacter xylinum* and others)	100% (pure cellulose, no lignin/hemicellulose)	High purity & crystallinity, Excellent tensile strength, 3D nanofiber network, Biocompatible	Expensive culture media, Low scalability, Long fermentation time	Biomedical (wound dressings, tissue engineering, drug delivery), electronics, specialty membranes
Other Biomass Sources (algae, tunicates, food industry byproducts)	20–40% (varies by source)	Unique nanostructures, Utilizes underexplored feedstocks, adds value to food/agro-waste streams	Limited research & availability, Lower yields in some cases	Specialty applications, niche biomedical, sensors

III. Types of Nanocellulose

Nanocellulose is generally classified into three major categories based on source, morphology, and synthesis route: cellulose nanocrystals (CNCs), cellulose nanofibers (CNFs), and bacterial nanocellulose (BNC). Each type exhibits distinct structural, mechanical, and functional properties that determine its suitability for industrial, environmental, and biomedical applications.

Nanocellulose can be derived from plant-based as well as bacterial sources through chemical, mechanical, enzymatic, or combined treatment methods. Depending on the processing route, different forms such as microfibrillated cellulose (MFC), nanofibrillated cellulose (NFC), and nanocrystalline cellulose (CNC/NCC) can be obtained. A comparative summary of the structural characteristics, production methods, and application potential of cellulose nanocrystals (CNCs), cellulose nanofibers (CNFs), and bacterial nanocellulose (BNCs) is presented in Table 3.

Table 3 Comparison of Different Types of Nanocellulose

Feature	CNCs	CNFs	BNCs
Source	Derived from plant biomass (wood, cotton, sugarcane bagasse, etc.)	Plant biomass (wood pulp, agricultural residues)	Produced extracellularly by bacteria (e.g., *Komagataeibacter xylinus*)
Structure	Highly crystalline, rod-like nanoparticles	Long, flexible, entangled fibrils with both crystalline and amorphous regions	3D network of pure cellulose nanofibers
Size Range	Diameter: 5–20 nm; Length: 100–500 nm	Diameter: 5–50 nm; Length: up to several micrometers	Diameter: 20–100 nm; Length: micrometers (forms hydrogel-like network)
Crystallinity	High (~54–88%)	Moderate (depends on mechanical treatment)	High (>80%)
Production Methods	Acid hydrolysis (H_2SO4, HCl), enzymatic treatment	Mechanical fibrillation (homogenization, grinding), sometimes enzymatic or chemical pretreatment	Microbial fermentation under static or agitated conditions
Key Properties	High stiffness, optical transparency, good reinforcing ability	High aspect ratio, flexibility, high water-holding capacity	High purity, excellent biocompatibility, high water retention

3.1 Cellulose Nanocrystals (CNCs)

Cellulose nanocrystals, also known as nanocrystalline cellulose, are rod-shaped nanoparticles produced by acid hydrolysis of natural cellulose fibers. This process selectively removes the amorphous regions of cellulose, leaving behind highly ordered crystalline domains.

CNCs generally possess lengths of 100–500 nm and diameters of 5–20 nm, resulting in a high aspect ratio. They exhibit exceptional mechanical stiffness, with a Young's modulus of approximately 100–150 GPa, high crystallinity, and excellent reinforcing capability. Their high surface area also enables surface modification for specific functional applications [27].

CNCs are widely applied in nanocomposites, drug delivery carriers, packaging films, and rheology modifiers for food and cosmetic formulations [1, 9].

The molecular arrangement of cellulose chains, characterized by extensive intermolecular and intramolecular hydrogen bonding between hydroxyl (–OH) groups, is illustrated in Fig. 1.

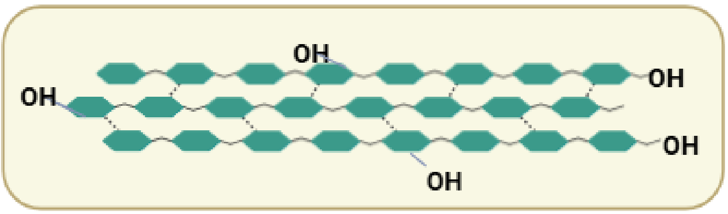

Fig. 1 CelluloseNanocrystals

3.2 Cellulose Nanofibers (CNFs)

Cellulose nanofibers, also referred to as nanofibrillated cellulose (NFC), consist of long, flexible, and entangled fibrils mainly obtained through mechanical fibrillation processes such as grinding, homogenization, or enzymatic pretreatment. Unlike CNCs, CNFs retain both crystalline and amorphous regions of cellulose.

Their diameters typically range from 5–60 nm, while lengths may extend to several micrometers, resulting in a three-dimensional web-like network structure.

CNFs possess high tensile strength, transparency, lightweight characteristics, and strong hydrogen-bonding ability. Their high water-holding capacity allows stable hydrogel formation. CNFs are therefore widely used in biodegradable films, coatings, aerogels, supercapacitors, wastewater treatment systems, and wound-healing materials [1].

Cellulose nanofibers consist of aligned cellulose chains stabilized through extensive hydrogen bonding. The repeating glucose units form linear β-1,4-linked chains, which assemble into nanoscale fibrils through intermolecular interactions, as illustrated in Fig. 2.

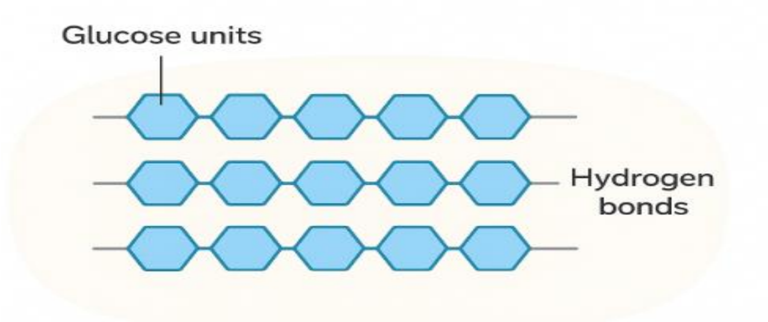

Fig.2CelluloseNanofibers

3.3 Bacterial Nanocellulose (BNC)

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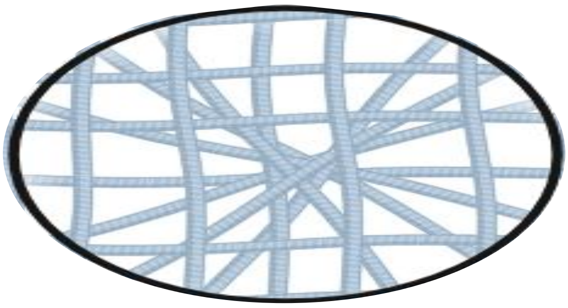

Fig. 3 Bacterial Nanocellulose

The classification and production pathways of nanocellulose are schematically illustrated in Fig. 4.

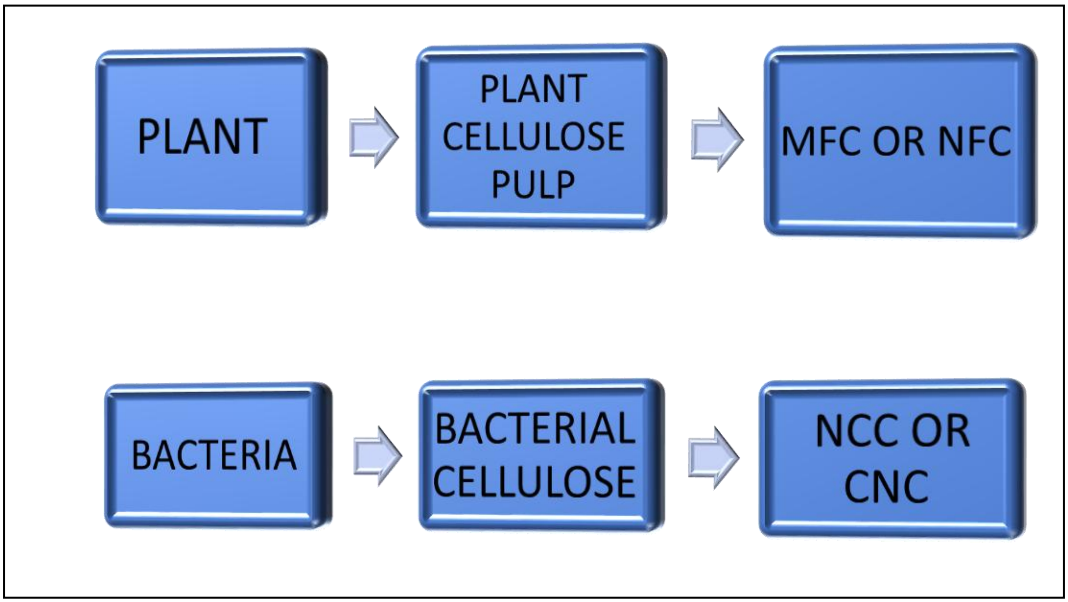

Fig. 4Schematic Representation of Nanocellulose Classification and Production

IV. Production Strategies of Nanocellulose

Nanocellulose production relies on a wide variety of methods, all of which have been designed to efficiently disintegrate lignocellulosic biomass into nanoscale components while preserving or even enhancing cellulose intrinsic properties. In this respect, recent reviews have extensively discussed major production routes and process optimization [1,27]. The production route has a great impact on yield, morphology, crystallinity, and final application possibilities of nanocellulose. Major strategies include acid hydrolysis, mechanical disintegration, enzymatic treatments, and combined approaches [13,17,24,27]. In addition, valorization through agro-industrial residues such as Sugarcane bagasse represents a promising sustainable pathway.

4.1 Pre-treatment approaches

Pre-treatment is a critical step for improving cellulose accessibility and reducing the energy demand of subsequent nanocellulose production processes. Various pre-treatment strategies modify the physicochemical structure of cellulose before nanofibrillation, influencing fiber swelling, surface chemistry, defibrillation efficiency, and overall process performance. The main advantages of pre-treatment include improved nanocellulose yield and quality, lower overall production cost, reduced energy consumption, and enhanced compatibility with mechanical, chemical, and biological processing routes [1]. A summary of commonly used pre-treatment techniques and their corresponding structural transformations is presented in Table 4.

Table 4 Pre-treatment Methods and Physicochemical Alterations

S.No	Pre-treatment Methods	Process-Driven Transformations
1.	Mechanical Refining	Swells and peels fiber cell walls in an aqueous medium, therefore increasing the surface area for fibrillation.
2	Chemical Soaking	Dilute acids, bases, or organic acids, including formic acid and oxalic acid, can be used in partial hemicellulose/lignin removal, thus reducing equipment corrosion.
3	Steam Explosion	Exposes fibers to pressurized steam followed by rapid depressurization that breaks down lignocellulosic structures and enhances defibrillation efficiency.
4	Enzymatic Hydrolysis	Enzymes cleave amorphous cellulose regions selectively under mild, environmentally friendly conditions, reducing energy consumption.
5	TEMPO oxidation	Introduces carboxyl groups into the cellulose, enabling its fibrillation into fine nanofibers.
6	Twin-Screw Extrusion	Produces high-solid CNF suspensions with up to 60% less energy consumption compared with conventional techniques.

4.2 Acid Hydrolysis

Acid hydrolysis is one of the most widely used methods for producing cellulose nanocrystals (CNCs). Strong mineral acids such as sulfuric acid and hydrochloric acid selectively hydrolyze the amorphous regions of cellulose, leaving behind highly crystalline rod-like domains.

This method offers advantages such as high crystallinity, narrow particle size distribution, and stable aqueous suspensions, particularly when sulfuric acid is used because sulfate groups introduced onto the surface improve colloidal stability.

However, conventional acid hydrolysis is constrained by the use of strong acidic reagents, which may lead to partial cellulose degradation, reduced product yield, and significant wastewater generation. Although it remains the standard method for CNC production, further optimization is required to improve environmental sustainability.

4.3 Mechanical Treatments

Mechanical methods are primarily used for the production of cellulose nanofibers (CNFs) by separating fibrils from bulk cellulose fibers through high-energy disintegration forces. These techniques rely mainly on shear, impact, and cavitation forces to disrupt hydrogen bonding and liberate nanoscale fibrils.

The commonly used mechanical approaches and their corresponding structural modifications are summarized in Table 5.

Table 5 Common Mechanical methods and their Induced modification

S.No	Mechanical Methods	Induced Modifications
1	High-pressure homogenization	Cellulose slurry is forced through narrow channels to induce shear and impact forces.
2	Grinding & refining	High shear mixing disrupts hydrogen bonds, liberating nanoscale fibrils.
3	Ultrasonication	In this process acoustic cavitation creates sites of local high pressure that will act to fragment the fibers.

Mechanical treatments are advantageous because they are solvent-free, scalable, and capable of producing long entangled nanofibers with high aspect ratios. However, they are energy-intensive and often require chemical or enzymatic pre-treatment to reduce energy demand.

4.4 Enzymatic Treatments

Enzymatic treatment has gained increasing attention because of its green and selective nature in nanocellulose production. Enzymes such as endoglucanases selectively hydrolyze amorphous cellulose regions, weakening fiber structure and lowering energy consumption during subsequent mechanical disintegration.

The major advantages include mild operating conditions, reduced chemical waste generation, and improved environmental compatibility. Limitations include relatively long processing times, high enzyme cost, and incomplete hydrolysis when reaction conditions are not optimized.

This strategy is particularly effective when integrated with mechanical treatments, balancing sustainability and production efficiency.

4.5 Hybrid Methods

Hybrid production methods combine chemical, mechanical, and enzymatic treatments to overcome the limitations of single-process approaches.

In acid–mechanical hybrid systems, acid hydrolysis first reduces cellulose crystallinity, followed by homogenization or grinding to achieve further fibrillation.

In enzymatic–mechanical systems, enzymatic pretreatment lowers the energy required during grinding, homogenization, or ultrasonication.

Hybrid methods often produce nanocellulose with tailored dimensions, surface functionality, and structural properties, making them highly adaptable for applications ranging from nanocomposites to biomedical scaffolds [24,27,26].

4.6 Case Study: Sugarcane Bagasse as a Raw Material

The bagasse, a type of lignocellulosic residue produced during sugar production, has gained increasing attention due to its low cost and ready availability as a feedstock for the production of nanocellulose. Rich in cellulose at 40-50%, hemicellulose, and lignin, bagasse requires the use of pre-treatment methods such as alkali pulping, bleaching, or acid delignification. The acid hydrolysis of pre-treated bagasse results in rod-like CNCs with high crystallinity. The mechanical fibrillation of cellulose derived from bagasse yields CNFs with excellent reinforcing capabilities for biocomposites and the Hybrid methods offer better yields and tunable dimensions of nanocellulose from bagasse. The valorization of waste and alignment with the circular bioeconomy is appropriately achieved by this approach through the transformation of agro-residues and this results in the conversion of sugarcane bagasse into high-value nanomaterials.

V. Characterization of Nanocellulose

Advanced characterization techniques are essential for comprehensively understanding nanocellulose in terms of morphology, structure, thermal stability, and surface chemistry. These analyses are critical for correlating physicochemical properties with performance in different applications.

5.1 Morphological Characterization

The nanoscale dimensions and morphology of cellulose nanocrystals (CNCs), cellulose nanofibers (CNFs), and bacterial nanocellulose (BNC) are commonly analyzed using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). SEM provides information on surface topography and fiber network morphology, whereas TEM enables direct observation of rod-like CNCs and fibrillar CNFs, often revealing entangled nanoscale web structures.

Atomic force microscopy (AFM) further enables three-dimensional surface profiling and height measurement, allowing confirmation of nanometric diameters as well as statistical analysis of fiber length and width distributions [16,23].

5.2 Structural Characterization (XRD, FT-IR, Raman)

X-ray diffraction (XRD) is widely used to determine the crystallinity index of nanocellulose, which significantly influences mechanical strength and thermal stability. Acid-hydrolyzed cellulose nanocrystals generally exhibit higher crystallinity compared with cellulose nanofibers because amorphous regions are selectively removed during hydrolysis [26,27].

Fourier transform infrared spectroscopy (FTIR) is employed to identify characteristic cellulose functional groups, including hydroxyl (–OH), C–O–C, and C–H stretching vibrations, thereby confirming the chemical integrity of nanocellulose after processing.

Raman spectroscopy complements FTIR by providing a molecular fingerprint of cellulose and enabling detection of subtle changes in molecular vibrations associated with chemical modification of the cellulose backbone [1].

5.3 Thermal Characterization

The thermal stability of nanocellulose is commonly evaluated using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC).

TGA provides weight-loss profiles associated with moisture evaporation, decomposition of residual hemicellulose or lignin, and cellulose degradation. Cellulose nanocrystals often exhibit higher onset degradation temperatures because of their greater crystallinity.

DSC provides information regarding thermal transitions such as glass transition behavior, crystallization, and heat flow, which is particularly useful when designing nanocellulose-based composites for temperature-sensitive applications [7,15].

5.4 Surface Chemistry Studies

Surface chemistry strongly influences the colloidal stability, reactivity, and functional performance of nanocellulose. Zeta potential measurement is widely used to determine surface charge and electrostatic repulsion between suspended particles, thereby indicating dispersion stability in aqueous systems.

Common surface functionalization strategies include carboxylation, sulfonation, and polymer grafting, which are typically evaluated using elemental analysis and FTIR spectral shifts.

Such modifications significantly expand the applicability of nanocellulose in drug delivery systems, biosensing platforms, and nanocomposite materials [9,28].

5.5 Surface Functionalization of Nanocellulose

Surface functionalization plays a crucial role in expanding the applicability of nanocellulose by modifying its surface hydroxyl groups to improve compatibility, dispersibility, reactivity, and biological performance. The abundant hydroxyl groups present on cellulose nanocrystals (CNCs), cellulose nanofibrils (CNFs), and bacterial nanocellulose (BNC) provide active sites for chemical modification, enabling the introduction of new functional groups without significantly altering the crystalline core structure.

Among the most widely used modification approaches, **TEMPO-mediated oxidation** has received considerable attention because it selectively converts primary hydroxyl groups into carboxyl groups under mild reaction conditions. This modification improves aqueous dispersibility, increases negative surface charge, and enhances interactions with metal ions, polymers, and biological molecules. TEMPO-oxidized nanocellulose has been extensively investigated for hydrogel preparation, drug delivery systems, and biosensor fabrication due to its improved colloidal stability and functional responsiveness.

Esterification is another important surface modification strategy in which hydroxyl groups react with organic acids or acid derivatives to introduce hydrophobic or reactive functional groups. Acetylation and succinylation are commonly employed to improve compatibility with non-polar polymer matrices, particularly in nanocomposite preparation. Such modifications contribute to better interfacial adhesion and improved mechanical performance in biodegradable composite materials.

Carboxylation and sulfonation further enhance the functional properties of nanocellulose by increasing electrostatic interactions and enabling selective adsorption processes. Carboxylated nanocellulose has shown strong potential in wastewater treatment, heavy metal adsorption, and enzyme immobilization because of its high density of active binding sites.

In addition to conventional chemical methods, **polymer grafting** has emerged as an effective route to produce multifunctional nanocellulose systems. In grafting approaches, polymer chains are covalently attached to the nanocellulose surface to tailor thermal stability, pH sensitivity, and biological compatibility. Grafted nanocellulose materials have demonstrated promising applications in controlled drug release, tissue engineering scaffolds, and smart biomedical coatings.

Recent developments also include **dual functionalization**, where more than one functional group is introduced onto the nanocellulose surface to achieve combined properties such as simultaneous drug loading and imaging capability. Such multifunctional systems are gaining importance in advanced biotechnology applications, particularly in responsive biomaterials and diagnostic platforms.

Overall, surface functionalization significantly enhances the versatility of nanocellulose and allows precise tailoring of its physicochemical properties for targeted environmental and biotechnological applications.

Table6 Common surface functionalization methods of nanocellulose and their major applications

Functionalization method	Functional group introduced	Main advantage	Major applications
TEMPO-mediated oxidation	Carboxyl (-COOH)	Improves aqueous dispersibility, increases surface charge, enhances colloidal stability	Hydrogels, drug delivery, biosensors, wound dressing materials
Esterification	Ester groups (-COOR)	Enhances hydrophobicity and compatibility with polymer matrices	Biodegradable nanocomposites, packaging materials
Acetylation	Acetyl (-$COCH_3$)	Reduces moisture sensitivity and improves thermal stability	Polymer reinforcement, barrier films
Carboxylation	Carboxyl (-COOH)	Provides active binding sites for adsorption and immobilization	Heavy metal removal, enzyme immobilization, wastewater treatment
Sulfonation	Sulfonate (-SO_3H)	Improves ionic interaction and dispersion behavior	Conductive composites, membrane applications
Polymer grafting	Covalently attached polymer chains	Tailors pH sensitivity, thermal behavior, and biological response	Controlled drug release, tissue engineering scaffolds
Dual functionalization	Multiple functional groups	Combines two or more targeted properties in one material	Bio-imaging, multifunctional biomedical systems

VI. Applications of Nanocellulose

Because of its biodegradability, biocompatibility, high surface area, and tunable surface chemistry, nanocellulose has attracted significant attention across multiple industrial and biotechnological sectors. Surface functionalization further expands its application potential by enabling specific interactions with biological, chemical, and environmental systems.

6.1 Biomedical Applications

Nanocellulose derived from plant biomass through chemical or biological processing exhibits diverse functional properties that support advanced biomedical applications. These include drug delivery, tissue engineering, and wound healing. The broad application spectrum of nanocellulose is illustrated in Fig. 5.

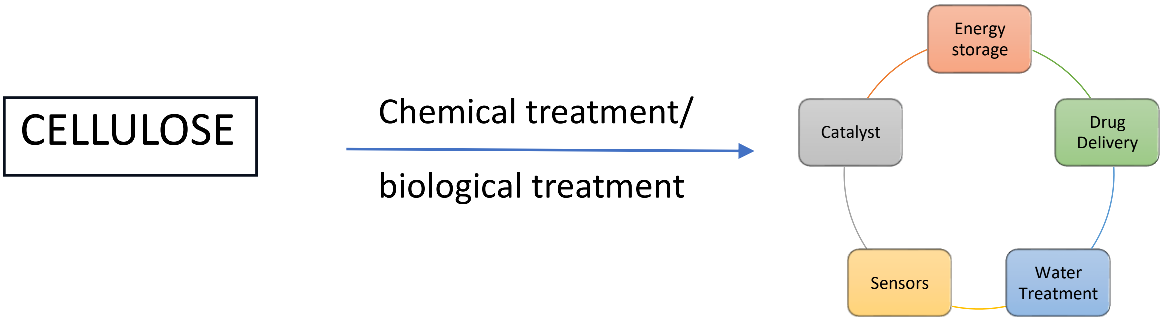

Fig. 5 Applications of Nanocellulose

6.1.1Drug Delivery

Functionalized cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs) are used as drug carriers for both hydrophobic and hydrophilic therapeutic agents, enabling controlled and sustained drug release. Their high specific surface area improves drug loading efficiency, while abundant surface hydroxyl groups allow chemical modification for targeted delivery and responsive release systems [24,26].

6.1.2 Tissue Engineering:

Nanocellulose-based scaffolds closely mimic the extracellular matrix (ECM), thereby promoting cell attachment, proliferation, and differentiation.

Bacterial nanocellulose (BNC) exhibits high purity, excellent water retention capacity, and strong mechanical integrity, making it particularly suitable for bone, cartilage, and skin tissue regeneration applications [6,12].

6.1.3Wound Healing

Bacterial nanocellulose-based wound dressings provide a moist healing environment, excellent oxygen permeability, and protection against microbial contamination.

Because of its safety, biocompatibility, and favorable clinical performance, nanocellulose has already been incorporated into several commercial wound-care materials.

6.2 Food Packaging and Biodegradable Films

Nanocellulose has emerged as a promising alternative to petroleum-based plastics in sustainable food packaging applications.

The incorporation of cellulose nanocrystals and cellulose nanofibers into biopolymer films improves mechanical strength, barrier performance, and thermal stability. In particular, reduced permeability to oxygen, oil, and moisture contributes to extended shelf life of perishable products [9].

Because nanocellulose-based films are renewable and compostable, they support reduction of plastic waste and align with circular economy goals [27].

6.3 Environmental Applications

The high adsorption capacity and surface functionality of nanocellulose make it highly effective for environmental remediation.

Functionalized cellulose nanocrystals and cellulose nanofibers can adsorb heavy metals, dyes, and organic pollutants from wastewater.

In addition, nanocellulose serves as an efficient filtration material because of its nanoscale porosity, hydrophilicity, and resistance to fouling [26].

Hybrid nanocellulose composites have demonstrated efficient removal of arsenic, lead, and emerging contaminants, supporting sustainable water purification technologies [9, 28].

6.4 Nanocomposites and Coatings

Nanocellulose is widely used as a reinforcing agent in polymer matrices because of its high mechanical strength and low density.

It has been incorporated into automotive, aerospace, and construction materials to reduce overall weight while maintaining structural performance [27, 1].

Nanocellulose-based coatings also provide excellent transparency, barrier properties, and durability for applications in paints, packaging films, and anticorrosive surfaces [24].

6.5 Electronics and Sensors

Recent advances have positioned nanocellulose as an important material in flexible and wearable electronics because of its lightweight nature, transparency, and biodegradability.

It serves as an effective substrate for flexible displays, printed electronics, and conductive films.

Functionalized nanocellulose has also been applied in biosensors for detection of glucose, toxins, and pathogens [9, 27].

Bacterial nanocellulose-based conductive composites are being explored for energy storage devices such as supercapacitors and batteries, offering new opportunities for sustainable electronic materials [1].

VII. Challenges and Future Directions

Despite the significant scientific progress and broad application potential of nanocellulose, several technical, economic, and regulatory challenges continue to limit its large-scale industrial adoption and commercial translation [1, 27]. Addressing these limitations is essential for enabling sustainable commercialization and broader technological integration.

7.1 Cost-effectiveness and Scalability

Although laboratory-scale production of nanocellulose is well established, large-scale manufacturing remains challenging because of the high energy demand associated with mechanical disintegration and the extensive use of strong chemical reagents. Conventional extraction processes often require intensive mechanical treatment, acid hydrolysis, or multiple purification steps, which increase production cost and environmental burden. The development of low-cost, energy-efficient, and environmentally sustainable production routes is therefore critical for commercialization. Hybrid production strategies combining chemical, mechanical, and enzymatic treatments have shown strong potential to reduce energy consumption while improving yield and process efficiency [24, 26].

7.2 Standardization of Production Protocols

The absence of universally standardized production protocols leads to considerable variation in particle size, crystallinity, surface chemistry, and functional performance of nanocellulose. This variability complicates comparison between studies and limits reproducibility across industrial applications. Standardized methods for production, characterization, quality control, and reporting are therefore necessary to ensure batch-to-batch consistency and reliable material performance. In addition, feedstock variability among agricultural residues further influences nanocellulose yield and material properties, necessitating biomass-specific process optimization.

7.3 Regulatory and Safety Considerations

Although nanocellulose is generally considered biocompatible and environmentally favorable, concerns remain regarding long-term biological interactions, nanoscale toxicity, biodegradation behavior, and environmental fate. Comprehensive toxicological evaluation and clear regulatory frameworks are required before wider implementation in biomedical, food, and environmental sectors. Such regulatory development will be particularly important for clinical applications, implantable biomaterials, and food-contact systems.

7.4 Integration with Emerging Technologies

Future development of nanocellulose is strongly linked to its integration with emerging advanced technologies. In 3D printing, nanocellulose-based bioinks have enabled precise biofabrication of tissues and implants with tunable mechanical strength, structural fidelity, and improved biocompatibility [26]. In nanomedicine, functionalized nanocellulose is being explored for targeted drug delivery, gene delivery systems, and personalized therapeutic platforms [1]. In bioelectronics, bacterial nanocellulose combined with conductive nanomaterials shows strong potential for neural interfaces, implantable devices, and sustainable wearable electronics.

7.5 Future Research Outlook

Future research should prioritize low-energy extraction systems, recyclable chemical processes, multifunctional nanocellulose hybrid materials, and integrated life-cycle sustainability assessment to support industrial scalability. Expanding nanocellulose applications in smart packaging, bioelectronics, environmental sensing, and precision biomedical systems may further accelerate its transition from laboratory-scale innovation to commercially viable sustainable material platforms.

VIII. Conclusion

Nanocellulose has emerged as a highly promising sustainable nanomaterial owing to its unique structural diversity, tunable surface chemistry, and broad functional applicability. The three major forms—cellulose nanocrystals, cellulose nanofibers, and bacterial nanocellulose—collectively provide versatile material platforms for applications in environmental biotechnology, biomedicine, packaging, and advanced composites. Recent advances in sustainable extraction, surface functionalization, and biomass valorization have significantly expanded its technological potential. Continued interdisciplinary research focused on process optimization, industrial scalability, and regulatory harmonization will be essential for enabling the large-scale adoption of nanocellulose in next-generation sustainable material systems.

9.List of abbreviations

CNF – Cellulose nanofibers
CNC – Cellulose nanocrystals
BNC – Bacterial nanocellulose
SEM – Scanning electron microscopy
TEM – Transmission electron microscopy
AFM – Atomic force microscopy
XRD – X-ray diffraction
FTIR – Fourier transform infrared spectroscopy
TGA – Thermogravimetric analysis
DSC – Differential scanning calorimetry
ECM – Extracellular matrix

10. Declarations

Competing interests

The authors declare no competing interests.

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Authors contributions

Srimathi P and Swetha S contributed to literature collection, manuscript drafting, and content organization. Chamundeeswari M supervised the work, reviewed the manuscript, and approved the final version. All authors read and approved the final manuscript.

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