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NANOCELLULOSE: ISOLATION AND EMERGING APPLICATIONS

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ABSTRACT

Nanocellulose has emerged as a multifunctional and sustainable nanomaterial with exceptional mechanical, thermal, and physicochemical properties that support its growing use in environmental, biomedical, packaging, and advanced engineering applications. Derived from abundant lignocellulosic biomass, nanocellulose exists as cellulose nanocrystals, cellulose nanofibrils, and bacterial nanocellulose, each offering distinct advantages for material reinforcement and functionalization. Advances in extraction approaches, particularly deep eutectic solvent pretreatment and optimized mechanical fibrillation, have significantly improved processing efficiency, purity, and scalability while reducing adverse impact on the environmental. The resulting nanocellulose demonstrates high crystallinity, large surface area, tunable surface chemistry, and excellent compatibility with biopolymers, enabling its integration into wastewater treatment membranes, biodegradable packaging films, flexible sensors, antimicrobial surfaces, marine antifouling systems, and energetic composites. Recent studies report remarkable improvements in adsorption capacity, membrane permeability, mechanical strength, and antimicrobial efficacy, underscoring nanocellulose broad technological potential. Despite challenges related to energy consumption, biomass variability, and solvent recovery, ongoing innovations in green pretreatment, functional modification, and composite engineering continue to expand the role of nanocellulose within circular bioeconomy frameworks. Overall, nanocellulose offers transformative opportunities for climate resilient materials and sustainable industrial development.

KEYWORD

Nanocellulose; Cellulose nanocrystals; Cellulose nanofibrils; Bacterial nanocellulose; Sustainable materials; Circular bioeconomy

INTRODUCTION

Nanocellulose, which includes cellulose nanocrystals (CNC), cellulose nanofibrils (CNF), and bacterial nanocellulose (BNC), has rapidly gained prominence as a sustainable, biodegradable, and high-performance nanomaterial. Its exceptional properties, including high crystallinity, low density, tunable surface chemistry, and mechanical strength, position it as a strategic biomaterial for advancing packaging, wastewater treatment, flexible electronics, antimicrobial systems, and structural composites. The growing need to replace petroleum-based materials and to valorize abundant agricultural residues such as oil palm empty fruit bunches (OPEFB), sugar palm fiber, bamboo, kenaf, water hyacinth, white ginger, *Colocasia esculenta* stems, roselle, and sugarcane bagasse has further accelerated interest in nanocellulose based technologies. In addition to being renewable and carbon neutral, nanocellulose enables the conversion of biomass waste into high value functional materials aligned with global sustainability goals. Recent progress in green extraction, particularly deep eutectic solvent (DES) pretreatment, has significantly enhanced delignification efficiency and fibrillation performance, contributing to circular bioeconomy strategies.

STRUCTURE AND CHEMICAL COMPOSITION OF LIGNOCELLULOSIC BIOMASS

Lignocellulosic biomass, the primary source of nanocellulose, exhibits a hierarchical structure composed of cellulose microfibrils embedded within a matrix of hemicellulose and lignin. Figure 1 shows the structural hierarchy of cellulose from plants and bacteria and the corresponding pathways for nanocellulose production.

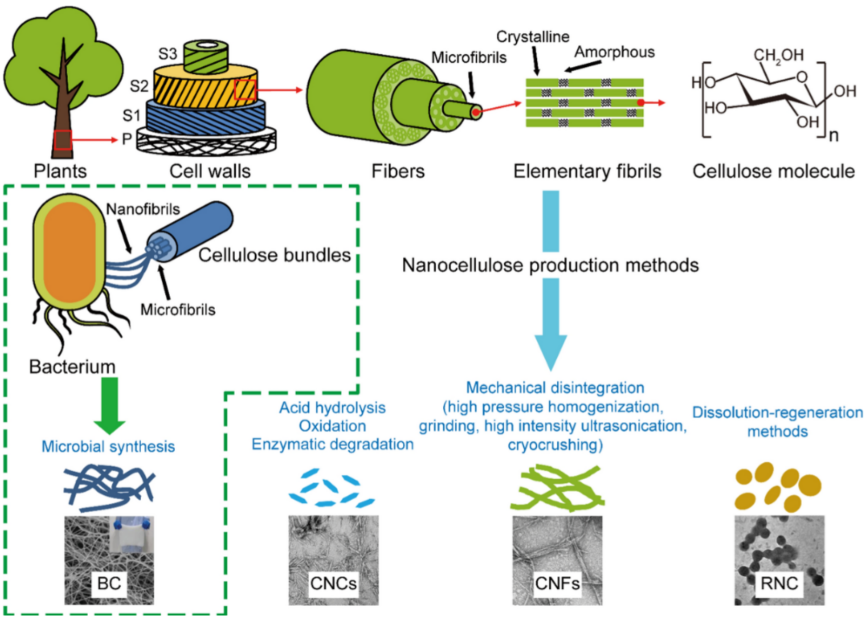

Figure 1: Nanocellulose routes preparation (Qi et al., 2023)

Cellulose originates from plant cell walls and bacterial synthesis, progressing from fibers to elementary fibrils and individual cellulose molecules. Various production approaches yield distinct nanocellulose types, for examples bacterial cellulose (BC) via microbial synthesis, cellulose nanocrystal (CNC) through acid hydrolysis, oxidation, or enzymatic degradation, cellulose nanofibril (CNF) via mechanical disintegration methods such as high-pressure homogenization and ultrasonication, and regenerated nanocellulose (RNC) through dissolution–regeneration processes. The overall chemical composition typically ranges between 30 to 60 wt% cellulose, 10 to 30 wt% hemicellulose, and 5 to 25 wt% lignin, depending on species and growth conditions. Removal of hemicellulose and lignin increases the accessibility of cellulose microfibrils and enables the production of high purity cellulose suitable for CNC or CNF extraction (Ilyas et al., 2017). The crystalline and amorphous arrangement of cellulose determines the mechanical and optical properties of nanocellulose, with CNC benefiting from higher crystallinity gained through selective acidic hydrolysis, while CNF retains longer fibrils with strong network forming ability. Clear understanding of biomass composition plays a significant role on optimization of extraction routes and achieving consistent nanocellulose quality.

EXTRACTION AND PRETREATMENT TECHNOLOGIES

Nanocellulose extraction relies on a combination of chemical, mechanical, and emerging green pretreatment strategies that enhance cellulose purity, accessibility, and fibrillation efficiency. Conventional processing combined chemical delignification and alkaline mercerization with acid hydrolysis to isolate high-purity CNC, while mechanical methods such as microfluidization and high-pressure homogenization generate long, high-aspect-ratio CNF despite their high energy demand (Ilyas et al., 2018). Green pretreatment technologies, including deep eutectic solvents like choline chloride–lactic acid mixtures, improve biomass swelling, lignin removal, and fibrillation efficiency while reducing waste and energy consumption, enabling uniform CNC and CNF production from agricultural residues. Ionic liquids further advance sustainable cellulose extraction by disrupting cellulose hydrogen bonding networks to achieve dissolution efficiencies above 25 %, yielding regenerated cellulose with lower crystallinity, higher porosity, and enhanced enzymatic digestibility across diverse biomass sources (Norfarhana et al., 2024). Although IL systems face cost, viscosity, and recovery challenges, their selectivity, recyclability, and compatibility with milder processing conditions highlight their strong potential for next-generation biorefinery applications.

APPLICATIONS

Nanocellulose is applied across diverse sectors due to its exceptional reinforcing ability, tunable surface chemistry, and sustainability, offering major advantages in wastewater treatment, packaging, paper strengthening, marine coatings, energetic materials, and biomedical technologies. In water purification, CNC- and CNF-based adsorbents and membranes achieve over 95 % removal of heavy metals and dyes while enhancing hydrophilicity, porosity, fouling resistance, and flux, as demonstrated by nanocellulose-filled ENR/PVC membranes that significantly improve TSS, COD, and ammonia removal in palm oil mill effluent (Norfarhana et al., 2025) . In biodegradable packaging, CNC and CNF markedly strengthen biopolymer films and reduce water vapor permeability, supporting food-safe, eco-friendly materials. Their integration into pulp and paper enhances tensile, burst, and tear strength through improved fiber bonding, with reinforcement effectiveness strongly influenced by morphology and surface chemistry (Kasmani & Samariha, 2022). Functionalized nanocellulose also delivers non-toxic marine antifouling performance through quaternary ammonium modification, offering durable protection against biofouling. In energetic and propellant systems, nitro-functionalized nanocellulose provides higher energy density, safer handling, and more controlled combustion than traditional nitrocellulose Norrrahim et al. (2021). Biomedical applications leverage its biocompatibility and antimicrobial potential, with modified nanocellulose enabling wound healing, drug delivery, antimicrobial membranes, and tissue engineering scaffolds, underscoring its versatility as a next-generation advanced material.

CHALLENGES AND FUTURE PROSPECTS

Although nanocellulose offers numerous advantages, it is a known fact that challenges remain in production scalability, mechanical energy demands, biomass variability, and aggregation during drying. Additional concerns include cost and recyclability for DES and ionic liquid systems, as well as regulatory constraints for food and biomedical applications. Future work should emphasize energy efficient fibrillation, solvent recovery, functional nanocomposite development, and industry scale processing. As global industries pursue sustainability, nanocellulose is positioned to contribute significantly to climate resilient packaging, clean water technologies, biomedical systems, and next generation composite materials.

CONCLUSIONS

Nanocellulose represents a central platform material for sustainable technology due to its exceptional mechanical properties, functional versatility, and renewable origin. Advances in DES and ionic liquid pretreatment, combined with optimized mechanical extraction methods, continue to improve environmental compatibility and processing efficiency. Its proven performance in wastewater treatment, packaging, sensors, coatings, and biomedicine demonstrates broad applicability. With ongoing innovation and expansion of the circular bioeconomy, nanocellulose is expected to play a vital role in addressing global sustainability and material challenges.

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