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SUSTAINABLE PATHWAYS IN CELLULOSE AND HEMICELLULOSE NANOMATERIALS FOR THERAPEUTIC APPLICATIONS

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Abstract *The growing attention towards sustainable and environment-friendly resources has spurred research into nanostructured materials derived from plant residues, mainly from cellulose and hemicellulose. These materials provide affordable, biocompatible, and renewable substitutes for various industrial uses. Plant biomass is largely composed of cellulose, which has excellent mechanical properties and wide applications. Cellulose nanocrystals (CNCs), cellulose nanofibrils (CNFs), and bacterial nanocellulose (BNCs) are produced by mechanical, chemical, and enzymatic methods; each has distinct properties that make them useful for a variety of applications. Xylan is the most important hemicellulose nanoparticle, with strong biocompatibility and many biomedical applications. Cellulose and hemicellulose-based nanoparticles have applications in drug delivery, wound healing, tissue engineering, smart packaging, and biosensors. The use of advanced nanomaterials in fields such as electronics, biomedicine, the environment, wastewater treatment, the textile Industry, construction, and cultural heritage conservation is possible through the formation of cellulose- and hemicellulose-based nanomaterials. This review aims to fill gaps in the existing literature and promote new research directions toward green technology. This review also aims to support future collaborative research across interdisciplinary fields and promote the circular economy by converting waste into high-value products.*

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Introduction

Recently, interest in sustainable, green, and environmentally friendly materials has increased greatly (Ciolacu and Darie-Nita, 2016). Plant materials are widely available worldwide, providing a diverse range of nanostructured materials that are renewable, inexpensive, and biocompatible for industrial applications. Plant residues are primarily composed of cellulose (40-50%) and hemicellulose (20-40%). Minor extractable components such as phytochemicals, proteins, lipids, pectin, and sugar minerals play an important role in nanoparticle synthesis and act as stabilizing and reducing agents (Barhoum et al., 2020). The most widely recognized biopolymer is cellulose, a straight-chain polysaccharide with excellent mechanical properties and low production cost. It is highly valuable for advanced materials applications because of its low cost, renewability, biodegradability, and strong mechanical properties. Nowadays, the interest is shifting towards the utilization of cellulose to make high-tech materials that undeniably play a decisive role in the future economy. Cellulosic polymers conserve water molecules through their fibres and are a vital component of plant cell walls, which are made up of hydrogen bonds and van der Waals forces during the process of natural plant growth. Cellulose fibrils are connected by two distinct regions: one is crystalline, and another is amorphous. Researchers can prepare advanced nanocellulose materials from lignocellulosic biomass using mechanical, chemical, and enzymatic methods (Hamawand et al., 2020). These technologies break down the hierarchy of cellulose fibres into nanocellulose forms, including cellulose nanofibrils (CNFs), cellulose nanocrystals (CNCs), and bacterial nanocellulose (BNC), which have exceptional strength, flexibility, and surface properties (Tayeb et al., 2018).

Cellulose nanocrystals (CNC) and cellulose nanofibrils (CNF) are currently in the spotlight for cellulose-based nanomaterial applications in packaging, biomedical devices, electronics, and composite materials because of their high surface area

and tunable surface chemistry (Klemm et al., 2011). Because of their high crystallinity and stiffness, CNCs have a wide range of applications, whereas the flexibility of CNF makes them applicable in many domains. Moreover, functionalizing the surfaces of these nanocellulose materials can improve properties such as hydrophobicity, thermal stability, and polymer compatibility, thereby opening avenues for wider application in sustainable materials (Habibi et al., 2010). On Earth, the second most abundant biopolymer is hemicellulose, found in plant cell walls where it provides structural strength by crosslinking lignin and cellulose. Hemicellulose is amorphous in structure and soluble in water due to the variety of glycosidic linkages it possesses in a single molecule, unlike cellulose. The distinct molecular makeup of various plant species and the sections from which they are harvested vary. Hemicellulose-based biomaterials are generally effective oxygen barriers and are non-toxic, biocompatible, and bioactive. Hemicelluloses can be further hydrolyzed into hexose and pentose sugars as a main component for ethanol and other biobased products, or transformed into a variety of biopolymers. In the biorefinery industry, it can be utilized to produce value-added products such as biofuels, bioplastics, and food additives (Avanthi et al., 2017)

Depending on chemical composition, the main types of hemicellulose nanoparticles are xylan, xyloglucan, and mannan. After hydrolysis, hemicellulose can be converted into biochemicals such as xylitol, furfural, levulinic acid, or biofuel (Chandel et al., 2018). Xylan nanoparticles and other hemicellulose nanostructures have potential applications in drug delivery, packaging, and material development (Huang et al., 2021). Combining hemicellulose with cellulose and lignin during the production of bio-composites not only enhances thermo-mechanical properties but also supports the development of bio-based, biodegradable alternatives to petroleum-derived plastics (Schwarzhans et al., 2017). Nano biotechnology is a promising field worldwide for producing sustainable and harmless nanomaterials. Nanoparticles synthesized from plant extracts provide non-toxic materials with high bioactivity, bioavailability, and biocompatibility (Barhoum et al., 2020). The development of new cellulose- and hemicellulose-based nanocomposite systems is possible by manipulating material properties at the nanoscale, resulting in novel and promising qualities, including low density and high mechanical properties. The applications of these nanocomposites include self-cleaning nanocoatings, nanoscale freshness indicators, nanosensors, electronic or energy-storing devices, construction or cultural heritage preservation materials, smart packaging, environmental remediation, and coating or restoring agents in the textile industry, reaching advanced functionalities driven by novel cellulose and hemicellulose-based nanomaterials (Mishra et al., 2024; Upadhyay et al., 2024). Because of the unique properties of biopolymeric nanocomposites, they can also be used in tissue engineering scaffolds, gene or drug delivery, regenerative or wound dressing materials, antibacterial agents, bone or cartilage restoration, and cancer treatments (Selvaraj et al., 2024). Overall, this review highlights the production and characterization of cellulose- and hemicellulose-based nanomaterials and emphasizes their sustainable potential applications across various health and industrial domains (Ciolacu and Darie, 2016)

Types of Cellulosic Nanoparticles

The two primary structural domains of cellulose fibrils are their highly organized (crystalline) and less organized (amorphous) structures. Numerous methods can isolate cellulose nanocrystals (CNC) and cellulose nanofibrils (CNF), the two most commonly used forms of nanocellulose, from the cellulose source. Some Gram-negative bacteria produce bacterial cellulose (BC), the third form and distinct from the other two. It forms spontaneously through a bottom-up process, while top-down techniques are used to produce CNC and CNF. Based on size, purpose, and production method, nanocelluloses can be divided into three primary groups. These factors largely depend on the cellulose source and processing parameters, as shown in Table 1 (Fornari et al., 2022).

Table 1. Types of Nanocellulose, their Features and Application

Types of Nanocellulose	Source Materials	Production Methods	Typical Dimensions	Advantages	Disadvantages	References
Cellulose Nanocrystals (CNCs)	Cotton, wood pulp and plant residue	Acid hydrolysis (sulfuric acid most common)	Diameter: 3-5 nm, Length is 100-300 nm (plants); Diameter is 10-20 nm, Length: 500-2000 nm (tunicates)	High stability, wide surface area, high strength, good optical properties	Dimensions vary depending on processing conditions	(Kumar et al., 2021)
Cellulose Nanofibrils (CNFs)	Wood (primarily), sugar beets, potato tubers, hemp and flax	Mechanical treatment (often combined with enzymatic or chemical)	Width: 20-100 nm, Length: >10,000 nm	High mechanical strength, rigidity, low thermal expansion, and good barrier properties	High energy consumption during processing	(Kumar et al., 2021)

Bacterial Nanocellulose (BNC)	Cultured by bacteria	Bottom-up assembly of sugars	Single fiber thickness up to a few nanometers	High crystallinity, purity, flexibility, water content, and biocompatibility	Low production scalability, expensive culture media	(Abdullah et al., 2021; Khalid et al., 2021)

Nanofibrillar Cellulose

Nanofibrillar cellulose consists of both amorphous and crystalline domains and can be created through strong mechanical fibrillation that releases fibrils from integrated microfiber bundles. High aspect ratio nanoscale fibrils, or CNFs, are created when hydrogen bond-induced cellulose chain stacking occurs. Width ranges from 2-60 nm, or some micrometers, in length (Hoeng et al., 2016). Numerous studies have documented its remarkable qualities, including its enormous surface area, biodegradability, lightweight, and outstanding mechanical capabilities (Tayeb et al., 2018). In fundamental fibres, hydrogen bonds between OH radical groups give cellulose chains a highly organized structure, making them easier to bind to other polymer components like lignin or proteins and form networks in aqueous environments (Zhu et al., 2016).

Cellulose Nanocrystals (CNCs)

The term "nanocrystalline cellulose" refers to cellulose nanocrystals. When cellulose nano-whiskers are produced by biosynthesis, they resemble primary cellular nanofibrils in terms of their crystalline regions. They are extracted from wood, plant fibre, and microfibrillar and nanofibrillar amorphous cellulose domains (Dagnino et al., 2025). Through transverse hydrolysis, this approach isolates fibrils by attacking disordered areas with acid, leaving the highly crystalline domains resistant to acid hydrolysis. The cellulose polymer maintains its linearity and strong intermolecular forces between neighbouring chain regions. Smaller aspect ratios (length 100 up to 500 nm and breadth 10 up to 50 nm) and a high degree of crystallinity (up to 50–90% depending on process parameters) characterize cellulose nanocrystals in comparison to CNFs (Shahmiri et al., 2021). Researchers have investigated numerous cellulose sources to improve CNC separation for higher productivity and quality. The linearity of cellulose and its strong intermolecular interactions between adjacent chains produce the ordered regions shown in Figure 1. The end products that contain crystalline particles have a rod-like or whisker-like appearance because of tapering ends that occur through the cleavage process (Quiroz Castañeda and Folch-Mallol, 2013; Tayeb et al., 2018)

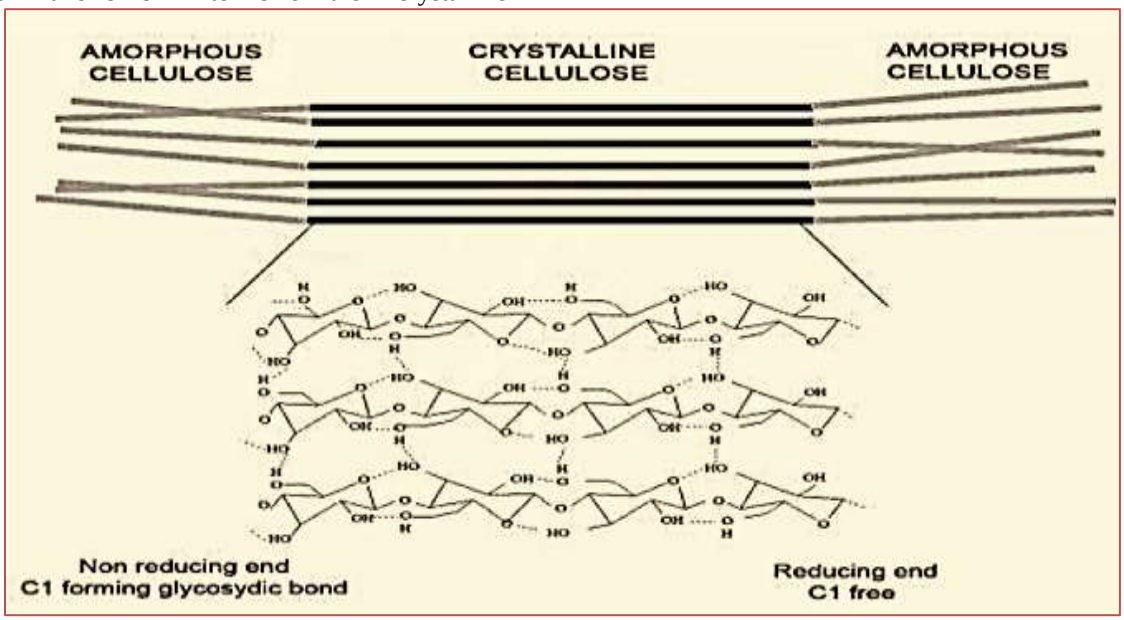


Figure 1. Speculative arrangement of amorphous and crystalline regions inside cellulose nanofibrils) and Illustration of the repeating unit in cellulose, including the β-(1, 4)-glycosidic linkage; dotted lines denote intramolecular hydrogen bonds; (source (Quiroz Castañeda and Folch-Mallol, 2013).

Bacterial Nanocellulose (BNC)

Microbial cellulose, also known as bacterial nanocellulose (BNC), is a type of nanocellulose produced by microbes and is purer than other types of nanocellulose (Abdullah et al., 2021; Thomas et al., 2020). This bottom-up nanostructured cellulose is made by using microorganisms to assemble low-molecular-weight sugars; the resulting individual fibres are a few nanometers thick. The two most popular approaches for generating BNC are static and mixed procedures, which allow manipulation of several parameters, including morphology and

physical and mechanical properties (Kumar and Han, 2021). Key characteristics of BNC include high crystallinity, high purity, high flexibility, high thermal and mechanical resistance, and high water content, almost 99% in the hydrogel nanocellulose network. BNC is an efficient material for medical implants, biotechnology, tissue reconstruction engineering, or regenerative medicine applications due to its biocompatibility, biological functions, and non-toxicity. However, the biggest challenge is scaling up industrial Bacterial nanocellulose synthesis, which is currently difficult due to low productivity, high culture costs, and complex fermentation processes (El-Gendi et al., 2022). Using industrial waste as a source for extraction could help address these issues. It is inexpensive, readily accessible, and can be processed using clean technology, which lowers waste disposal costs for businesses that supply raw materials and protects the environment(El-Gendi et al., 2022).

Types of Hemicellulose Nanoparticles

Hemicellulose refers to polysaccharides that form cell walls and bond strongly with cellulose microfibrils through hydrogen bonds and Van der Waals forces. Hemicellulose typically contains a diverse range of plant polysaccharides, such as D-xylose, D–mannose, D-galactose, and L-arabinose, along with 4-O-methyld-glucuronic acid. This is a heterogeneous group of polymers(Wijaya et al., 2021b).

Xylan Nanoparticles (XNPs)

Xylan nanoparticles (XNPs) are an essential type of hemicellulose that can be used for drug delivery. XNPs are strong nanomaterials with shatter resistance. Compared with other naturally derived nanoparticles, XNPs have unique properties, including biodegradability, biocompatibility, nontoxicity, immunogenicity, and antitumor activity (Cartaxo da Costa Urtiga et al., 2020; Lima et al., 2021). XNPs can be used as an adhesive, emulsifier, and thickener in manufacturing, as well as as additives for plastic making, paper making, textile production, prodrugs, drug carriers, magnetite particle carriers, wound dressings, and hydrogels. Most XNPs are synthesized through precipitation and dialysis (Wijaya et al., 2021a). In recent decades, XNP manufacturing in various fields has been less developed than that of other nanomaterials from nature. This is because XNP formation is complex. Purifying xylan from other hemicellulose monomers is also required to produce high-quality XNPs. Moreover, the functionalization of drugs with XNPs in a drug delivery system requires additional steps to enable the formation of specific bonds. Previous research has carried out XNP or drug functionalization using various compounds such as acetic acid, succinic anhydride, formic acid, stearic acid, and others (Garcia et al., 2001).

Methods for Preparation of Nanocelluloses

Mechanical, chemical, and enzymatic treatments of lignocellulose can prepare nanocellulose. Various techniques are used to prepare different nanoparticles, with their pros and cons shown in **Table 2**.

Table 2. Nanoparticle Preparation Techniques with their Pros and Cons

Nanoparticles Preparation Techniques	Pros and Cons	References
High Pressure Homogenization (HPH)	NPs with diameters: 20-100 nm. High energy, often clogging the homogenizer, and damage to the crystalline structure can occur.	(Lunardi et al., 2021)
Microfluidization	Nanoparticles are mostly less than 100 nm in diameter.	(Gimondi et al., 2023)
Grinding	Particle size ranges in micrometers rather than nanometers. Damages the fiber.	(Camargo et al., 2021)
Cryocrushing	Produces particles with diameters of 30-80 nm	(Mali and Sherje, 2022)
High-intensity ultrasonication	No use of any chemical treatment	(Singh and Nanda, 2015)
Steam Explosion	Minimize environmental impact	(Serrano-Martínez et al., 2024)
Acid Hydrolysis	Minimize aspect ratio	(Wang et al., 2019)
Electrospinning	Simple and cost-effective process.	(Borrego et al., 2022)
Enzymatic Method	Costly because of the enzyme isolation process, and favorable hydrolysis is required for long-term enzymatic treatment	(Ribeiro et al., 2019)

Mechanical Methods

In the mechanical method, the plant cell wall is subjected to intense mechanical deformation; the cellulose fiber's initial structure is broken down into nanofibrils or bundles of microfibrils with a diameter of 10-100 nm, depending on the amount of degradation force. The length of fibrils can be several microns. Several mechanical techniques, namely homogenization, microfluidization, grinding, cryo-crushing, and sonication, can extract carbon nanofibril (CNF) or cellulose microfibril (CMF) from various raw materials, as described below (Fernandes et al., 2023).

High-Pressure Homogenization (HPH) Method

One technique frequently used to produce CNF and for laboratory nanofibril synthesis is high-pressure homogenization (HPH) (Gupta and Shukla, 2020). This method uses a tiny nozzle to feed cellulose slurry into a container under high pressure. The liquid is then subjected to shear and stress, causing fibres to shrink at the nanoscale. Here, a cellulose slurry is pushed through a small nozzle under high pressure (50 to 2000 bar), creating shear and impact forces that cause the fibres to fibrillate into highly thin nanofibrils typically 20-100 nm in diameter (Hansini et al., 2025). HPH is a straightforward and efficient method for separating nanoparticles without organic solvents. The main drawbacks of the HPH method include high energy absorption, clogging, and mechanical damage to the CNF crystal structure. As a result, certain pre-treatments are required before utilizing the HPH technology (Lunardi et al., 2021).

Microfluidization Method

Microfluidization is another method for preparing CNF or CMF formulations. The microfluidizer mainly consists of a pump that accelerates the slurry at high pressure in the chamber. This method defibrillates the fibre at the nanoscale through high shear rates and impact forces, unlike impinging flows or channel walls. The fixed-geometry chamber (normally Y- or Z-shaped) and constantly maintained shear rates force the cellulose suspension through at high pressure (1,500-2,100 bar). This can provide consistent sub-100 nm fibre diameter with minimal clogging and offers uniform fibrillation. These nanoparticles have uniform dimensions below 100 nm. This process requires significant energy; therefore, the suggested pretreatments help reduce energy consumption (Djafari Petroudy et al., 2021).

Grinding Method

Another process for producing nanocellulose fibers is grinding. Here, cellulose fibres are fed through an upper, stationary grindstone and a tilting one. The fibers are recognized as nanofibers because of the ensuing shear stresses that rupture the cell wall. The length between millstones, the shape of the stones, and the quantity of mill strokes are a few variables that influence fibrillation. However, this method mechanically wears down the fibres. (Camargo et al., 2021)

Cryocrushing Method

Cryocrushing is a mechanical fibrillation method that uses frozen cellulose. The fibrils that are generated have a diameter of 0.1-1 µm, which is relatively large. Water-filled cellulose fibers are crushed in liquid nitrogen after freezing. Under pressure, ice crystals form on frozen cellulose fibres; strong impact pressures cause the cell walls to burst. Nanofibers are released as a result. A common disperser can then be used to disperse the cryopreserved fibres uniformly in water. This technique works well with a variety of cellulosic materials and can be applied as a fiber pretreatment step before homogenization. According to the study, the nanofibers were prepared from soybean pulp using high-pressure fibrillation and cryocrushing. TEM showed that the nanofiber diameter ranged from 50 to 100 nm. The prepared nanofibers showed improved dispersibility in acrylic emulsion compared with water. However, the cryocrushing technique is not very effective and requires a significant amount of energy (Pradhan et al., 2024).

High-intensity Ultrasonication (HIUS) Method

The high-intensity ultrasound approach isolates the cellulose fibrils using the hydrodynamic forces of ultrasound vibration. Strong, intense oscillating waves emerge as a result of cavitation during the process. The cellulose fibers are broken when minute gas bubbles are created by the absorption of this ultrasonic energy by water molecules. These bubbles expand and split (Rotaru et al., 2024). Recent studies show that CNFs can be produced efficiently by combining deep eutectic solvent (DES) pretreatment and wet grinding with HIUS (45 kHz for about 40 minutes). The fibril diameters were less than 100 nm, and the nanofibrillation yield was over 80 per cent. The procedure is more sustainable than purely mechanical alternatives and improves purity (more than 90%) and fibrillation efficiency (Pradhan et al., 2024). HIUS also plays a significant role in fabricating CNF-derived hydrogels and aerogels (Liu et al., 2024).

Steam Explosion Method

Thermomechanical steam explosion is a method used to separate CNF. In this method, the pulp is briefly exposed to high-pressure steam before the pressure is suddenly released, creating shear stress that forms CNFs. This not only forms CNF but also doubles surface area and porosity, making it more accessible to further fibrillation or hydrolysis. Recent studies indicate that steam explosion has an efficiency of about 70% in extracting cellulose out of rice straw as well as effective recovery of lignin, showing high efficiency of biomass valorization (Serrano-Martínez et al., 2024). Because a steam explosion utilizes fewer hazardous chemicals and requires less energy, its environmental impact is much lower[35]. Combining

steam explosion and acid hydrolysis also substantially increases CNC yield by about 2.5-fold and improves crystallinity and thermal stability; however, it does not reduce the quality of the resulting particle structure and appearance (Ghamari et al., 2025). Energy efficiency is also significant because steam explosion requires only about 30 per cent of the energy compared to conventional mechanical pulverization to achieve a similar reduction in particle size. Overall, steam explosion is a promising method of achieving high structural modification efficiency, reduced chemical inputs, and increased energy savings in CNF production (Wang et al., 2024).

Electrospinning Method

Electrospinning is an alternative to mechanical force for separating nanocellulose. Here, a strong electric field extracts nanofibers from a cellulose dispersion. This is an easy, affordable method. The electrospinning process, dissolution rate, applied electric field, and tip-to-collector distance all affect nanofiber diameter and morphology (Medeiros et al., 2022).

Chemical Method

Acid Hydrolysis

Crystalline particles are recovered by acid hydrolysis from cellulose found in wood fibers, plant fibers, tunicates, algae, and bacteria, among other sources. Usually, a specific acid concentration is added to deionized water before introducing the "purified" starting material. The main reason sulfuric acid is used is that it gives particles a negative surface charge, which increases suspension stability. Mix the mixture with deionized water and let it react for a while before quenching. Subsequently, the mixture undergoes multiple stages of separation, filtration, and cleaning, then is dialyzed with deionised water to remove residual acidity or neutralizing salts. The final suspension of cellulose nanoparticles can be further processed to remove larger agglomerates through centrifugal separation or filtration (Peng et al., 2021).

Enzymatic Method

Alkaline Hydrolysis

Using nanomaterials derived from cellulose and hemicellulose consumption is a novel approach to sustainable development across multiple industrial sectors. Cellulose nanocrystals and cellulose nanofibrils are especially useful for biocomposites, paper products, and drug delivery due to their high mechanical properties, flexibility, and biodegradability. Because of their exceptional strength and thermal stability, these chemically and mechanically generated nanomaterials are perfect for controlled medication release and material reinforcement in biomedical contexts. Because of their distinct molecular structure and water solubility, hemicelluloses have potential applications in biofuel and biopolymer production. Combining NaOH with enzymatic hydrolysis has demonstrated the effectiveness of cellulose nanofibril manufacturing. Compared with acidic treatment, combining enzymatic hydrolysis with cellulose fibre homogenization produces cellulose nanoparticles with a higher aspect ratio and less harsh properties. Fabricating nanocellulose fibres requires both alkaline and enzymatic hydrolysis, and combining the two indicates the potential for effective and environmentally friendly nanocellulose synthesis (Liang et al., 2025).

Radioisotopes

Certain radioisotopes, such as caesium-137 or cobalt-60, have been used to pretreat lignocellulose and typically produce gamma radiation. Gamma radiation penetrates lignocellulose and creates free radicals by breaking the crystal structure. After radiation exposure, the free radicals in the amorphous areas quickly disintegrate, causing the biomass to deteriorate as well. Liquid plasma, ultrasonography, and gamma radiation have also been employed to minimize particle size. To eliminate contaminants added to the nanoparticles, it is crucial not to use chemical reducing agents in this procedure (Olatunji et al., 2021).

Method of Extraction and Preparation of Hemicellulose Nanoparticles

Scientific studies have documented the utilization of various isolation techniques to isolate high-purity hemicelluloses from plant sources. Hemicelluloses are classified into two categories: water-soluble and water-insoluble. The ability of these molecules to dissolve in neutral or alkaline solutions is essential for extracting hemicelluloses from cell walls. The presence of ferulic acid bridges in hemicelluloses and hydrogen bonds between unsubstituted xylose residues, as well as cellulose chains, makes it challenging to extract cereal bran xylans from water.

Several methods exist for obtaining hemicellulose microparticles and nanoparticles, depending on the polymer isolation technique used. One approach dissolves the hemicellulose in an alkaline solution, then adds alcohol to neutralize it, causing supersaturation and precipitation of the hemicellulose. A coacervation process was used to generate nanoscale corncob xylan particles, with a size range of 120 to 1790 nm. The technique involved neutralizing an acidic solution. Adding either hydrochloric acid (HCl) or acetic acid to neutralize the xylan solution produced micro- and nanoparticles, but surfactant concentration affected both particle size and texture. Xylan can be very beneficial in the pharmaceutical industry, especially for making colon-specific drug carriers like film-coating nanoparticles. Nano-xylan is also used in foods; it can improve taste and smell and change food colour and texture. Several factors affect nanoparticle size, including hemicellulose and neutralizing-agent concentration, pH, impurities, lignin monomers, and polymerising enzymes. Other methods used to obtain nano

hemicelluloses include dissolving xyloglucans in dimethyl sulfoxide, dimethylacetamide, or acetone; supercritical antisolvent precipitation (SAS); particles from gas-saturated solutions; and emulsions. According to the study, the SAS method was developed recently(Haimer et al., 2008). This technique is relatively new for precipitating xylan or mannan material with a narrow particle size distribution; the particles are spherical, form in DMSO/H_2O mixtures, and use carbon dioxide as the antisolvent. The size and morphology of the precipitated particles are determined by their supersaturation rate, type of hemicellulose, DMSO/H_2O ratio, and atmospheric conditions. These factors include water pressure and temperature(Gautam et al., 2025).

Emerging Applications of Nanocelluloses

Nanoparticle-based products hold promise in almost every field today. Figure 2 presents some emerging applications of cellulose and hemicellulose nanoparticles.

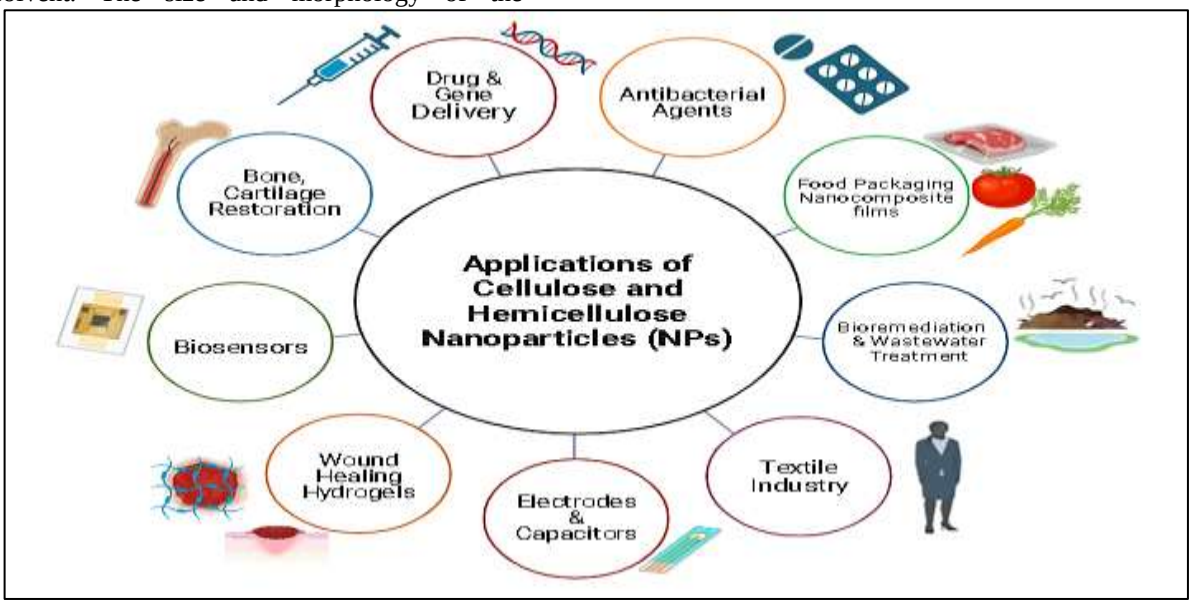


Figure 2. Applications of Cellulose and Hemicellulose Nanoparticles

Nanocellulose in Biomedical Applications

Cellulose Nanoparticles as Antibacterial Agents

Aldehydes and carboxyl groups in cellulose-based materials enhance their antibacterial activity. In cytotoxicity studies, dialdehyde nano-fibrillated cellulose (DANFC) and carboxylated cellulose nanofibers (CNFs) have been found to effectively inhibit various bacteria, including *Staphylococcus aureus* and *Escherichia coli*, with minimal adverse effects. These modifications enhance antibacterial properties by lowering pH and entrapping bacteria in cellulose networks (Chinga-Carrasco et al., 2021; Mou et al., 2017). One effective method for photodynamic inactivation (PDI) of antibiotic-resistant bacteria and viruses is to use cellulose-based materials treated with photosensitizers. As an illustration of its potential for scalable antibacterial applications, cationic porphyrin-conjugated cellulose has demonstrated remarkable potency (> 99.9%) against several pathogens under visible light. These materials can be used in a variety of ways, such as creating textiles with antibacterial properties (Carpenter et al., 2015). Chemists can chemically modify cellulose to increase its antibacterial activity by adding organic bioactive molecules such as polymers, bacteriophages, N-halamines, antimicrobial peptides, antibiotics, and aminoalkyl groups. Numerous applications exist for cellulose modified to include antibiotics and other antimicrobial agents. Because of its long-lasting antibacterial properties, antibiotic-grafted cellulose, such as ciprofloxacin-modified cellulose and benzylpenicillin-modified cellulose, has potential uses in wound dressings and medical textiles (Saini et al., 2015). Furthermore, because of its long-lasting antimicrobial activity against pathogens such as S. aureus and E. coli, N-halamine-modified cellulose is used in water filtration systems (Jiang et al., 2017). The specific antibacterial action of enzyme-modified cellulose, such as lysozyme-immobilized cellulose, is essential for applications involving medical implants and wound healing (Ahmed et al., 2013).

Researchers have used inorganic nanoparticles such as carbon, metallic nanomaterials, and metal-organic frameworks to modify cellulose. Most of these materials show high activity against both Gram-positive and Gram-negative microbes because they have inherent antibacterial activity. These strong antibacterial properties make cellulose modified with different inorganic nanoparticles useful for a range of applications. Different examples of these NPs include carbon, graphene oxide (GO), titanium dioxide (TiO_2), montmorillonite (MMT), zinc oxide (ZnO), and silver nanoparticles (Ag NPs). Graphene oxide cellulose has sharp edges that can break bacterial membranes, and GO-cellulose composites are

effective against *E. coli* and *S. aureus*(Akhavan and Ghaderi, 2010). ZnO nanoparticles incorporated into cellulose membranes using in situ techniques demonstrate significant antibacterial action against E. coli (Shao et al., 2015). Similarly, cellulose acetate membranes treated with TiO_2 efficiently filter bacterially polluted water(Ahmad et al., 2022; Gao et al., 2020; Ul-Islam et al., 2013). CuO- and montmorillonite (MMT)-containing cellulose composites have shown improved antibacterial activity against a range of pathogens. Because of their strong antibacterial properties, silver nanoparticles are frequently used in cellulose matrices and have been highly effective against a wide variety of bacteria (Alavi and Varma, 2021; Son et al., 2004). By adding these nanoparticles to cellulose fabrics and membranes, biodegradable solutions for medicinal and water purification settings can be achieved (Dankovich and Gray, 2011; Liu et al., 2021). Because some metal-based nanoparticles release harmful ions, it is important to carefully evaluate their potential effects on human health and the environment, even with their effectiveness (Abdelhamid and Mathew, 2022).

Gene and Drug Delivery by Cellulose Nanoparticles

Advanced drug delivery methods are possible with cellulose-based materials. They can be used with magnetic nanoparticles (MNPs) for various applications. Drugs can be delivered by encapsulating them in cellulose(Sheikhi et al., 2019). The functional groups on carboxymethyl cellulose (CMC) allow the anticancer drug (5-FU) to be administered with folate and to be selectively released from CMC. When folic acid is introduced to cellulose, a folate receptor-regulated cellular mechanism promotes targeted cell binding and absorption (Colacino et al., 2015; Dong et al., 2014). The use of hydroxypropyl methylcellulose enhanced the treatment of prostate cancer with curcumin (CUR). Cellulose combined with CUR significantly influenced apoptosis compared with CUR alone. Compared with other carriers such as dendrimers, MNPs, polylactic-co-glycolic acid (PLGA), and β-cyclodextrin (CD), cellulose also showed the highest cellular absorption. TOCNF/ZIF-8 underwent material transformation into a 3D network by 3D printing. Using cellulose MOF powder, printing becomes accessible. It can be used as a template or MOF binder during in situ synthesis. These components can release the CUR medicine at physiological pH 5.5. Researchers also delivered oligonucleotide siRNAs using cellulose-based materials. These can be classified as non-viral vectors (Yallapu et al., 2012). For pDNA delivery, CNCs were modified using atom transfer radical polymerization and poly(2-dimethylamino)ethyl methacrylate. Disulfide linkages formed during polymerization, yielding CNC-SS-PDs. The product showed low cytotoxicity and good transfection efficacy (Drinevskyi et al., 2023). Cellulose-based materials offer several benefits for drug delivery. They can release ionizable and hydrophobic medications, as well as those insoluble in water. As such, they allow for the co-administration of two medications.

Additionally, cellulose showed the highest cellular absorption compared with other carriers such as poly (lactic-co-glycolic acid) and β-cyclodextrin (CD). CNC hydrogels demonstrated sustainable qualities and enabled locally targeted drug release. Gelatin cannot be used to make cellulose capsules. Oral medication delivery is one application. Cellulose-based hydrogels can simulate drug delivery for temperature- and pH-responsive release (Abdelhamid and Mathew, 2022).

Dental, Bone, and Cartilage Restoration

Cellulose nanoparticles have been utilized to regenerate bone. They have several properties that support efficient bone regeneration, but the most important are those that facilitate phosphate and calcium deposition. Researchers used a nanocomposite with strong adhesive properties, using collagen and bacterial cellulose as an effective replacement to bind collagen to apatite for bone regeneration (Drinevskyi et al., 2023). Studies have shown that BC-COL-apatite supports regeneration without exerting any deleterious, genotoxic, or mutagenic effects. Because cartilage is avascular, it cannot regenerate as easily as other tissues. 3D bioprinting is one of the most recent methods for cartilage regeneration or repair; it demands a specific bio-ink with specific viscoelastic characteristics. Current research on cartilage regeneration has proposed CNF-based bio-ink containing human bone marrow-derived stem cells and nasal chondrocytes, bio-printed using alginate and CNF. The findings showed that CNF could be used as a bio-ink for the process of 3D bio-printing of living cells, which was promising. Materials used in dental procedures need to be highly resilient, and because nanocellulose has a reinforcing function, it can be a feasible option. Despite CNF's inadequate integration into the structure, CNC significantly improved the composite's mechanical properties, establishing it as a useful additive for dental restorations (Mishra, 2024).

Cancer Treatment and Drug Delivery

Studies show that CNF can improve drug-release kinetics. CNF-formed hydrogels have been used as carriers or antitumor agents in anticancer medicines. CNF has also been used to improve the penetration force of films utilized for drug delivery in colon cancer or other diseases. Researchers have used CNF's binding properties for antimetastatic or anticancer purposes. Metformin, a cancer drug, was added to the nanocellulose surface and formed a "Met-CNF gel" that limits invasion, adhesion, and migration of melanoma cells implanted near the tumour area. By changing the surface charge on CNC, it can be utilized to deliver small interfering RNAs

(siRNAs) with therapeutic effects. Naked RNAs cannot be transported into diseased cells and are quickly degraded. Still, CNC, as a non-toxic, biodegradable material, can promote therapeutic effects by binding to RNA or acting as a nanocarrier to facilitate intracellular transport (Mishra, 2024). The reported study investigated the drug-delivery function of CNF, CNC, and BC and found that while CNC and CNF could bind strongly to water-loving drugs through ionic interactions, the BC function was not very promising (Kumar et al., 2017).

Biosensors

Nanocellulose can immobilize biological molecules, which are beneficial for biosensors and diagnostic devices. In this case, an aqueous composite was produced from gold BNC utilizing a one-step biomatrix. This chemical was extremely conductive and biocompatible. The enzyme Horseradish peroxidase activity can be captured and sustained by its smooth nanofiber architecture. Horseradish peroxidase (HRP)- based biosensors can detect hydrogen peroxide at a 1 µm lower concentration. Antibodies have been immobilized using nanocellulose films that are first carboxylated and then activated with protein. This active layer can bind and physically adsorb antibodies targeted toward human immunoglobulin G. The nanocellulose layers can be activated by copolymer grafts. The IgG peptide, which has a high affinity for human antibodies, is placed on the grafted polymer to improve the specificity and selectivity of the layer on nanocellulose. To enhance biocompatibility, researchers immobilize proteins and growth factors using nanocellulose. Amino acid sequences have been used to enhance adhesive properties. Electrochemical sensors that detect DNA hybridization also use nanocellulose. The cotton-derived nanocellulose was used to bind the DNA. Agglomeration produced by DNA-encapsulated nanocellulose is significantly larger than predicted. Researchers coated nanocellulose with AgNPs using sodium borohydride as a reducing agent. The researchers restricted agglomeration by including nanocellulose (Kaczmarek and Białkowska, 2025).

Wound Healing

Wound healing proceeds through multiple stages, including hemostasis, inflammation, granulation, proliferation, maturation, and remodelling. Growth factors and cytokines can be integrated to promote angiogenesis and re-epithelialization. As a result, nanocellulose materials can be used to treat each stage, functioning as antibacterial, anti-inflammatory, or hemostatic agents. Researchers have studied and used bacterial cellulose as a suitable biomaterial for repair and wound healing. As we already know, it offers unique features such as high biocompatibility, high purity, and strong water retention. They are used in reconstructive surgery to make artificial blood vessels, track the healing process of chronic wounds with bandages, and patch major burns with artificial skin (Portela et al., 2019). Researchers used different kinds of nanocellulose, such as CNC and CNF, to prepare the semi-IPN composite. In hydrogels, non-cytotoxicity, strong mechanical strength, and efficient antimicrobial activity are important for accelerating wound healing and preventing infection. Nanocellulose scaffolds with tunable stiffness were printed in 3D form and crosslinked by a double crosslinking method: one as chemical crosslinking with 1,4-butanediol diglycidyl ether and another as in situ calcium (Ca^{2+}) crosslinking to control the stiffness of the scaffold, which affects cell behavior in wound healing(de Amorim et al., 2022). Gelatin methacrylate incorporated into a nano-cellulose-based hydrogel was stated to facilitate engineering and promote cell proliferation (Naomi et al., 2020).

Nanocellulose in Electronic and Energy Storage Devices

Green energy storage systems that are inexpensive, have a high energy density, can be recycled, and can be disposed of safely are in high demand. Researchers have proposed using biodegradable polymers, such as cellulose, in devices such as batteries, body electrode binders, and electrolyte materials to achieve these goals (Bhattacharyya and Babu, 2017).

Cellulose Nanomaterial as Electrode Binder

Despite being a renewable polymer, CNF can assemble into a continuous film with high stability and low thermal expansion. Consequently, CNF can be used as a binder in energy storage devices. For example, Li-ion battery electrodes are used to replace petroleum-based polymers. Nanocrystalline cellulose (NCC) can be converted into carbon materials for lithium-ion battery (LIB) production and can serve as a substrate for adding transition metal oxides (TMO) to prevent volume growth, which is one of the most effective approaches. Major challenges for TMO-based LIBs. The lithium-ion battery study used electrolyte-impregnated paper and distributed cellulose nanofibrils as an electrode binder and separator. The resulting bond quality was comparable to polyvinylidene fluoride (PVDF). To ensure the porosity, flexibility, and high chargeability of the graphite anode, a CNF network that serves as a binder was positioned around the graphite flakes using a straightforward water-casting technique. The resulting independent electrodes showed high electrochemical performance comparable to conventional PVDF-based electrodes. Microfibrillar cellulose (MFC) was coated on polypyrrole with the help of in situ polymerization to create an MFC polypyrrole (PPy) electrode composite, which is a self-sufficient conductive paper for an eco-friendly connection system (Hong et al., 2025).

CNF Substrate for Supercapacitors

Devices that have temporary storage systems for electrochemical energy, such as supercapacitors, are

used at the electrolyte-electrode interface for rapid charging and discharging during rapid charge/discharge cycles. They generally withstand a wide range of operating temperatures and are classified as electrochemical pseudocapacitors or electrical double-layer capacitors, depending on the storage mechanism. Researchers have made many attempts to synthesize non-toxic, flexible, lightweight supercapacitors for portable and stretchable electronic devices. Various alternatives to commercial electric double-layer capacitors (EDLCs) have been suggested, including polydimethylsiloxane (PDMS), graphene paper, and cellulose. In capacitors, binders are important components that help maintain the mechanical strength of the electrodes. Common binders that are employed in commercial supercapacitors include carboxymethyl cellulose (CMC), polytetrafluoroethylene (PTFE), and polyvinyl alcohol (PVA), but their non-conductive nature may reduce electrode efficiency. Alternatively, several studies have suggested using CNF in these devices to improve the strength and electrical properties of the capacitors. One study reported an extremely porous electrode substrate using polypyrrole-coated cellulose nanocrystals (Bhattacharyya and Babu, 2017). According to the study, CNF is remarkably efficient at attaching graphite electrodes to electronic substrates by dipping them in a liquid electrolyte solution (Hong et al., 2025). In another work, researchers prepared an ionic gel by gelling microcellulose thin films with numerous methyl phosphonate ionic liquids, which are bio-friendly. The resulting stretchy ion gel acts as an insulator with high capacitance at low voltage levels and can be used in paper-based supercapacitors (Thiemann et al., 2014). In general, nanocellulose has been successfully used as a binder in capacitors and can provide both flexibility and strength to electronic devices(Bhattacharyya and Babu, 2017).

Nanocellulose in Conductive Polymers

When combined with conducting polymers, cellulose NPs become a promising material for electronics. Flexible, green, biodegradable conducting polymers have gained interest because of their many potential uses in electrodes and display devices (Brooke et al., 2023). Researchers have created a biocompatible, flexible, self-healing, nanocellulose-based electroconductive hydrogel intended for implantable electronic devices (Han et al., 2019). In this regard, blending the strength, flexibility, and eco-friendliness of nanocellulose with the thermal stability and conductivity of conducting polymers has enabled the development of new materials for a more sustainable future (Ding et al., 2018; Lin et al., 2019).

Nanocellulose-Based Luminescent Materials

In recent years, researchers have explored alternative methods for creating light-emitting materials, including conjugated or non-conjugated polymers and nanomaterials with different chemical assemblies that emit colours across the visible spectrum. Breakthroughs in biosensors, organic field-emission transistors, and organic solar cells are expected to accelerate the shift from conventional to flexible and foldable conductive and luminous devices (Dias et al., 2020; Li et al., 2022). To increase its viability for complex applications such as flexible devices embellished with luminous components, researchers have produced fluorescently functionalized nanocellulose (Guo et al., 2017; Junka et al., 2014).

Nanocellulose in Construction Materials

Cellulose and its derivatives have been added to cement-based materials to improve mechanical properties, reduce the environmental impact of cement products, and decrease the use of traditional virgin materials in the construction sector, such as sand, gravel, and clay. Wood is one of the major sources of bio-based plant fibres. We still believe this poses a danger to forests. We need a different way to make cellulose or nanocellulose without endangering trees by using more virgin resources. Notably, cellulose material and nanocellulose can also be extracted from algae as an alternative to trees. Algae also demonstrated the capacity to absorb. This may help maintain equilibrium in the building sector and address shortcomings in the infrastructure that is in place now.

Nanocellulose in Cultural Inheritance

The value of cultural inheritance is immeasurable and encompasses a vast array of items, objects, and intangible assets that each state has recognized as essential. These include values related to science, art, literature, archeology, folklore, anthropology, and more. Maintaining intellectual and cultural advancement while conserving and passing down ancient customs and knowledge to future generations is important; cultural heritage must be protected from mechanisms that degrade it and from the passage of time. This makes cultural heritage an invaluable asset. Cultural heritage is therefore a precious good. Recently, new revolutionary materials based on nanotechnology research have improved the presentation and practical sustainability of materials used in cultural heritage protection. Consequently, researchers have achieved non-invasive, non-destructive cleaning methods, stable consolidation, and durable, selective conservation. A key area of cultural heritage conservation is preserving cellulose-based artworks because most collections of items and artefacts in the global artistic heritage are made of cellulosic materials such as paper, wood, canvases, and fabrics. These materials are also linked to anthropological values and the world's historical memory. The diversity of degradation events affecting artworks reflects the wide range of materials used in human heritage. Preventing these phenomena benefits various artworks, including books, manuscripts, maps, drawings, textiles, and wooden artefacts like shipwrecks and sculptures. Due to

various factors, a large number of these artworks need immediate restoration; additionally, those that are outdoors are especially irreversibly exposed to various degrading agents, like temperature, humidity, air pollutants, and microorganisms, all of which cause damage to art materials(Fornari et al., 2022; Marques et al., 2024). Mainly, acidity reduces the degree of polymerization, resulting in the loss of mechanical properties; air pollution-induced nitric oxide and sulfur dioxide degradation makes cellulosic fibres more brittle; and photolysis, microbes, and fungi-induced thermal degradation are other issues (Kryg et al., 2024).

Additionally, almost all the utilized materials in previous conservation treatments are acidic or may produce byproducts as they age, which will deteriorate the artwork; additionally, these materials need to be changeable or at least allow the things to be coverable, which is not always achievable with conventional consolidation products(Kolman et al., 2018; Semenzin et al., 2019).

Therefore, conservation science has explored various avenues and developed several technical options to overcome conservation challenges arising from the diversity of artistic substrates; one such option is nanocellulose-based materials. Recently, partly due to nanotechnology, researchers have attempted to create environmentally friendly and sustainable solutions to these issues. According to the study, a viable alternative method for creating novel nano-based consolidants would help produce harmless nanomaterials for conservation while maintaining their ability and function. There is a creative flowsheet that comprises multiple significant steps, each of which influences a different feature of the process, such as the state-of-the-art study; the first consolidant formulation; the screening of the danger valuations; consequently, the optimization of the final artifact; and, lastly, the safety and sustainability assessments of the products(Semenzin et al., 2019). Nanocellulose, a material with many desirable properties, is highly valuable for the conservation of cellulose-based works for several reasons the compact hydrogen bonding network it provides makes it possible to add functional groups simply for a further targeted conservation action, which can improve the mechanical and physical properties of the treated cellulose-based item; second, transparent films created by consolidants based on nanocellulose can generate barrier effects against oxygen, water vapor, and oil, which could harm artistic substrates, without changing the visible look of artworks; and, lastly, a huge benefit of these restoration strategies is that they can be easily reversed(Antonelli et al., 2020; Operamolla et al., 2021).

Nanocellulose Applications in Food Packaging

Packaging protects and contains food throughout the processing, production, distribution, handling, and storage phases of the food supply chain, all the way to the final consumer. As a result, both business and academia have been developing competitive, sustainable, and renewable alternatives. Nanocellulose is becoming increasingly popular as a component of sensory systems and as a support for additional functions, such as antibacterial and antioxidant activity, in intelligent and active packaging. NC can be utilized in the processing of food packaging nanocomposites as a coating and filler. Coating is the process of applying a thin film to the surface of a substrate to create a multilayered material. Many food packaging applications, including pet food, bakery goods, and fast food, require good grease and oxygen barriers. Reports have described NC-based coatings used on paper and cardboard. Using NC as a filler in a continuous polymeric stage is another tactic. For this reason, researchers have investigated biopolymers such as polylactic acid, polyhydroxybutyrate, and thermoplastic starch (TPS). Nevertheless, enhancing compatibility between matrices with varying hydrophobicity is essential, and NC modification is frequently used to achieve this. Compared with pure TPS film, the combination of NC and TPS improved mechanical performance. However, NC-TPS complexes still showed poor moisture-barrier performance. Researchers find active and intelligent packaging quite appealing. Active packaging releases or absorbs materials to extend shelf life, such as antioxidants or antibacterial agents. That type of active packaging monitors the state of the packaged food or its surroundings and provides information, such as the food's freshness. Although nanocellulose is inert in these capacities, it is a strong support for materials that can be intelligent or active in the food packaging system (Soares da Silva et al., 2020).

Nanocellulose Applications in Environmental Remediation

Nanomaterials have recently shown promise for efficiently detecting and eliminating biological agents, chemical pollutants, organic pollutants, and greenhouse gases. Numerous hybrid inorganic-organic nanostructured composites have emerged, offering unique optical, mechanical, electrical, and thermal properties that make them promising photocatalysts. Environment-friendly nanomaterials like cellulose-based materials are replacing petrochemical-based feedstocks, moving toward a cleaner and more sustainable environment. Because cellulose is an abundant, renewable biological resource, compounds derived from it are recognized as a nearly infinite source of chemical raw materials. Cellulose's remarkable chirality, hydrophilicity, and broad chemical diversity demonstrate its compelling potential as an environmentally benign, biocompatible support. Various semiconductors have been made from cellulose to increase photocatalytic activity, even though cellulose alone only shows modest photocatalytic activity when exposed to UV

or visible light. Several research teams have used cellulose-formed metal oxide nanomaterials such as thin films, fibers, and membranes, and hybrid substances in visible and UV light to demonstrate photocatalytic wastewater treatment. Compared with individual components, nanocellulose Fe_2O_3 compounds have been used as photocatalysts to increase the rate of organic pollutant degradation. Scientists are becoming increasingly interested in biopolymer-based flocculants, such as cellulose, chitosan, alginate, and tannins. Bio-based flocculants are known for their high specific surface area and nanoscale dimensions in addition to their biodegradability. Two main categories of flocculants are derived from natural polymers. One method involves making natural polymers, such as polyacrylamide-grafted hydroxypropyl methylcellulose, to produce semi-natural flocculants. To produce better natural flocculants, the other type of nanocellulose, known as dicarboxylic acid nanocellulose, is made by directly modifying natural polymers. To functionalize the material and create effective flocculants, researchers add hydrophobic, cationic, or anionic functional groups to nanocellulose surfaces using a charge-neutralisation technique. The cellulose OH group facilitates nanocellulose functionalization, adding the required functionality and producing extraordinarily strong flocculants. Adding more functional groups to cellulose can increase its hydrophilicity and surface polarity, enhancing its ability to interact with other substances. Cellulose nanofibers and nanocrystals have been studied for their potential applications in gas separation, adsorption, ion exchange, dye removal, wastewater treatment, and heavy metal removal as membrane building blocks (Voisin et al., 2017). The study reported using metallic nanocellulose composites to shape the functionality of a forward osmosis membrane for wastewater treatment (Cruz-Tato et al., 2017).

Nanocellulose in the Textile Industry

Reinforcing Agents

Studies of nanocellulose fibres as reinforcement in cotton composites have shown notable improvements in mechanical properties. Cotton fibres were effectively fibrillated into nanofibers, improving the polypropylene composites' modulus, flexural strength, and tensile strength (Liang et al., 2023). These developments show how nanocellulose can improve the structural integrity of textile composites. Researchers have focused on incorporating nanocellulose fibres into polyester composites to improve mechanical, barrier, and thermal properties. Research has focused on creating hybrid fibres and adding nanocellulose to other nanomaterials to enhance the overall performance of composites (Biranje et al., 2024). Nanocellulose is valued for its high aspect ratio, biocompatibility, mechanical toughness, and non-toxicity, including cellulose nanofibers and nanocrystals. These properties make them suitable for composites incorporating metal nanoparticles, biomedical implants, and stable Pickering emulsions (Khalid et al., 2021). Reinforcing nylon composites with nanocellulose fibres has also shown potential, especially when the nanocellulose is caprolactone- or polyisocyanate-modified. These changes improve the modulus, tensile strength, and flexural strength of nylon matrices (Biranje et al., 2024). Also, researchers have produced a considerable amount of value-added goods on a large scale by combining nanocellulose fibres with hybrid fibres and organic materials. Furthermore, with improved thermal and mechanical properties, nanocellulose-reinforced starch biopolymers provide eco-friendly substitutes for non-biodegradable plastics. Studies have also shown that textile waste can be successfully used to create nanocomposites that efficiently enhance the mechanical properties of the materials (Spagnuolo et al., 2022).

Coating Agents

For creating protective barriers against a variety of chemicals, such as water drops, gases (O2 and CO2), volatile compounds, and grease, nanocellulose fibres have shown great promise as a material for water-resistant coatings. Because of their robustness and barrier properties, these coatings are especially well-suited for food packaging. Nanocellulose is a viable alternative to synthetic and fossil-derived polymers for developing cellulosic surface coatings because of its potential. Developing dual-function coatings with water-repellent properties and additional functionalities will continue to pose hurdles (Ahankari et al., 2021; Spagnuolo et al., 2022). Researchers have enhanced textile substrates with water-repellent properties by creating hydrophobic coatings using cellulose nanofibers (Iqbal et al., 2022).

Antimicrobial coatings are intended to prevent the growth of bacteria, mould, mildew, and algae on a variety of surfaces by treating them with specific antimicrobial chemicals. These coatings, which offer extended surface protection, improved aesthetics, and reduced risk of microbe-related diseases, are widely used in healthcare facilities, public areas, residential buildings, and medical devices. Antimicrobial chemicals damage microorganisms' cellular membranes, preventing them from proliferating. Additives such as silver ions improve the resilience and effectiveness of these coatings against repeated exposure to water and cleaning procedures. Applications include medical equipment, decorative paints, protective coatings, and interior surfaces that must adhere to strict hygiene regulations, especially in humid conditions. Antimicrobial coatings significantly improve indoor air quality by inhibiting mould growth and providing long-term pathogen protection. To prevent the spread of illnesses on surfaces and equipment, their use is essential in

medical settings. The use of nanocellulose fibres in nonflammable coatings has made significant progress in improving the fire resistance of thermal insulating materials. For example, nanoclays and sulfonated kraft lignin are components of bio-based fire retardants that improve the flammability properties of insulating substances (Zheng et al., 2019). Produced by silylation methods, nanocrystalline cellulose has outstanding thermal insulation qualities and is environmentally friendly. Aerogels made of cellulose nanofibrils have successfully incorporated sodium bicarbonate to increase fire resistance without sacrificing aerogel stiffness (Farooq et al., 2018). Furthermore, researchers have created low-density, flame-retardant porous networks through layer-by-layer functionalization of cellulose fibres, as shown by single-flame source and cone calorimetry testing. These developments highlight nanocellulose's potential to raise fire safety standards across a range of industrial settings.

Nanocellulose-based Nonwovens

Awareness of nanocellulose fibres as a way to advance manufacturing environmentally friendly textile resources has increased significantly, especially in nanocellulose-based nonwovens. These fibres offer several advantages, including biodegradability, environmental safety, and exceptional mechanical properties. Bioinspired designs enable the creation of novel materials with multifunctional properties. Cellulose nanofibrils and nanocrystals can mimic the composition or properties of natural fibres like cotton. These nanocellulose fibres also offer tunable characteristics. The fibres mentioned above have high aspect ratios and excellent wicking properties, and can be easily modified to provide advantageous surface properties. Nonwoven materials based on nanocellulose have the potential to transform the textile sector by providing sustainable alternatives to traditional materials.

Emerging Applications of Hemicellulose Nanoparticles

Pharmaceutical and Biomedical Applications of Hemicellulose Nanoparticles

Biomedical Applications

Cross-linking or the hydrophobic nature of hemicellulose has attracted significant attention for biomedical applications of modified hemicellulose. Specific hemicelluloses have been used to stimulate the host immune system, helping prevent the formation of various malignancies. A typical form of hemicellulose-based polymer may have antibacterial and anticancer effects. Galactomans may enhance the cytotoxic activity of natural killer cells, hence inducing an immunological response against tumour cells, which is the mechanism of antitumor activity. One study suggests that mannose can be conjugated to vaccines, indicating it could be used as a target immunotherapy for cancer. Another application for hemicellulose is as a wound dressing. An optimal wound dressing should relieve pain, maintain moisture, and allow adequate ventilation. A Veloderm is a similar invention with a biofilm of polymeric assembly made up of hemicellulose microfibers, and is available on the market. It is made using a biotechnological method using sugarcane. It has been introduced to the market to rival existing wound treatments. According to the company, Veloderm is a wound dressing that selectively permits gas and vapour permeability while blocking water and microbial penetration. They explain that it can adhere to the site or form a sealing mechanism that shields the wound from bacteria or dirt on the outside (Liu et al., 2019).

Xylan Nanoparticles (XNPs) for Drug Delivery System

Like many nanoparticles, XNPs can bind medicines chemically through specific links or physically through adsorption. XNPs and medicines typically interact chemically through ester (covalent) bonds, whereas other nanoparticles typically interact chemically by hydrogen bonding, hydrophobic interaction, or π-π stacking. Because of this unique quality, XNPs and medications interact more strongly, and they are more resistant to acid than other nanoparticles. Because the colon's microflora produces multiple enzymes, including β-glucuronidase, β-galactosidase, β-xylosidase, α-arabinosidase, azoreductase, nitroreductase, deaminase, and urea dehydroxylase, only the colon can break down XNPs, making them more suitable as colon-specific drug carriers. This specific interaction makes in vitro drug loading more precise for incorporating medications into the biopolymer framework. Earlier research used XNPs to transport prodrugs such as curcumin, 5-aminosalicylic acid (5-ASA), 5-fluorouracil (5-FU), doxorubicin, ibuprofen, and ketoprofen. These drugs were then rendered active at the intended site by the destruction of XNPs. Research showcasing the disintegration of XNPs by digestive enzymes revealed that 5-FU and 5-ASA discharges tended to be non-pH-sensitive. Less than 2% of 5-ASA was free from the XNPs prodrug at pH 1.2 or 7.4(Wijaya et al., 2021b). Additional research to create more realistic release scenarios using rats' gastrointestinal, cecal, and colonic contents improved this work. The 5-FU can be released only 3 to 4% in a gastric environment with pH 4.5, 5to7% in an intestinal condition with pH 7.4, and 53 to 61% in a colonic and cecal condition with pH 5.36, demonstrating that the role of colonic enzymes helps to break down the XNPs or liberate the medication. To improve targeting capacity, more recent studies are further developing the functionalization of drug-loaded XNPs.

One study used stearic acid to improve the hydrophobic interface of 5-FU prodrug XNPs. This meant that over 60 hours, the medication released around 28% at pH 2 and 58% at pH 5.0, without an

initial release. The colon's pH environment is shared by tumour and cancer cells; therefore, the large release at pH 5.0 facilitates XNP application to target tumour and cancer cells. To better understand the prodrug XNPs' ability to target cancer cells, we further functionalized the drug using 3-3′-dithiodipropionic acid. This functionalization introduced disulfide linkages into the prodrug XNPs structure, enabling redox-responsive breakdown in cancer cells. To examine the effects of curcumin and the 5-FU XNPs prodrug, we added glutathione (GSH) to the release medium at pH 7.4. An extraordinary result showed that the major releases (74% of 5-FU and 80% of curcumin) may have been generated by GSH, which broke the disulfide bonds during the degradation of XNPs. This promising outcome raises the possibility of using XNPs to target cancer cells with high concentrations of GSH (Wijaya et al., 2021b). Cytotoxicity is a crucial assay in drug delivery systems to evaluate the safety of medicines or their carriers. Prior research has examined the cytotoxicity of XNPs and prodrug XNPs. The cytotoxicity of 5-FU prodrug XNPs and curcumin to colon cancer cells, such as HCT-116 and HT-29, was examined. Curcumin prodrug XNPs exhibited more cytotoxicity than free curcumin, as demonstrated. A cytotoxicity investigation employing 5-FU prodrug XNPs also revealed the same outcome. They demonstrated the previously mentioned anticancer properties of xylan. Drug-conjugated XNPs increased therapeutic effectiveness against cancer cells (Ciolacu and Darie, 2016).

Hemicellulose as Nanocomposite Film

The term "hemicellulose-based nanocomposite film" refers to hemicellulose whose organic matrix is improved by adding nanoparticles. Because of their high surface area-to-volume ratio, NPs may form strong interfacial bonds with the polymer matrix when evenly dispersed in the continuous hemicellulose phase. Even though hemicellulose films made from various types of hemicellulose have variable mechanical and barrier qualities, these qualities can be greatly improved by the addition of nanomaterials. This technique, one of the primary ways to physically modify hemicellulose, offers the benefits of easy operation and mild conditions. The three primary types of nanomaterials utilized to modify hemicellulose are silicates, metal oxide NPs, and organic nanoparticles (Ciolacu and Darie-Nita, 2016).

Food Packaging by Hemicellulose films

The food industry depends heavily on the food packaging sector. Packaging materials must protect food from physical, chemical, and biological influences during distribution. Plastics are frequently used in food packaging because of their affordability, superior printability, and lightweight nature. Nonetheless, the plastics sector relies heavily on fossil fuels. Overuse of plastics will unavoidably increase the use of non-renewable fossil fuels and pollute the environment (Lebreton et al., 2018). Because they are abundant and renewable, biopolymers are considered a useful alternative for addressing these issues (Asgher et al., 2020). As a polar polymer, hemicellulose can provide films with an effective barrier against nonpolar molecules (O_2). The polymer's degradability and barrier performance make it an impressive option in food packaging. However, developing low-cost, biodegradable films with characteristics akin to conventional plastics remains challenging, particularly when improving overall performance (mechanical, thermal, and hydrophobic). To enhance barrier, mechanical, and thermal properties, nanoparticles are currently used as additives in a range of food-contact packaging and containers (Bumbudsanpharoke et al., 2015; Nazrin et al., 2020). Hemicellulose was physically altered by nanoparticles(Nazrin et al., 2020), which facilitated the functionalization and utilization of hemicellulose films. According to the study, researchers made reinforced hemicellulose and chitosan edible films using green, nontoxic cellulose nanofibers (CNFs) (Xu et al., 2019). The study suggested using these hemicellulose/chitosan edible films for food packaging because of their strong mechanical strength and flexibility. Combining ZnO NPs with polyvinyl alcohol and hemicellulose produced a functional hemicellulose film with improved mechanical properties, thermoplasticity, and UV-shielding performance. This technique enhanced the potential of hemicellulose and enabled its use in the food packaging industry. Thus, expanding the use of hemicellulose in food packaging and leveraging biomass resources depends largely on developing hemicellulose-based nanocomposite films (Liu et al., 2023a; Liu et al., 2023b; Zhang et al., 2020).

Hemicellulose-Based Hydrogels

Biomedical Application

Hemicellulose's potential in biomedical applications is enhanced by its notable biological activity. For example, because of their ability to release drugs under physiological conditions, hydrogels based on xylan have been investigated for use in drug delivery applications. Because of their diffusion coefficient and porous nature, these hydrogels can encapsulate medications and release them at specific locations. Furthermore, employing photodynamic antimicrobial chemotherapy (PACT), xylan-based hydrogels with antimicrobial qualities have been created, exhibiting effectiveness against a range of bacterial strains. Glycidyl methacrylate (GMAX) is one modification that has improved drug release and encapsulation effectiveness in xylan hydrogels, making them appropriate for applications involving sustained drug administration. Furthermore, researchers have produced new derivatives with potential for gastrointestinal drug release, such as maleic anhydride-modified xylan (MAHX), for dual temperature- and pH-responsive hydrogels. These

developments demonstrate the adaptability of hemicellulose-based hydrogels in biomedicine, with most uses in tissue engineering, wound dressings, or other areas (Gao et al., 2015; Kong et al., 2017; Liao and Huang, 2020).

Industrial Absorption

Hemicellulose-based hydrogels offer a viable solution for industrial wastewater, especially for removing heavy metal ions and colour. These hydrogels provide effective adsorption capabilities because of their distinctive structure and content (Xu et al., 2023a). For example, hydrogels made from xylan and other polymers show strong adsorption capacity for metals such as Pb^{2+}, Cd^{2+}, Cu^{2+}, and Zn^{2+}. Adding chemicals such as acrylamide and acrylic acid further increases their adsorption endurance and effectiveness, enabling multiple adsorption-desorption cycles. Additionally, adding nanoparticles such as Fe_3O_4 or graphene oxide improves mechanical strength and increases the ability to adsorb dyes like methylene blue. Furthermore, adding nanoparticles such as Fe_3O_4 or graphene oxide strengthens them mechanically and increases their ability to adsorb dyes like methylene blue (Sun et al., 2015). These developments highlight their potential for environmentally friendly water treatment applications, though further work is needed before they can be widely used in industrial settings (Xu et al., 2023b).

Sensors

Recent developments in hemicellulose-based hydrogel sensors have shown promise for flexible and wearable applications, meeting a range of sensing requirements from monitoring medical signals to detecting human motion. Using a conductive network that responds to strain fluctuations, Gong et al. (2022ab) created a PAA-TA@HC-Al3+ hydrogel sensor that can detect a variety of movements, including finger bending and wrist pulses. This sensor's usefulness as an ionic hydrogel electrode and for skin tension-induced electrical signals was further demonstrated by its ability to detect physiological signals like ECG and EMG. Folic acid was used in a hemicellulose-based hydrogel, increasing its mechanical strength and adding antibacterial properties, thereby increasing its potential for wearable sensors (Ling et al., 2022). Furthermore, Chang et al. (2022) used xylan-based hydrogels for soft strain sensors, which showed superior adhesion without further fixation and were well-suited for tracking human movement. Future studies should focus on developing novel hemicellulose derivatives and incorporating nanoparticles to improve sensor performance and biocompatibility further, expanding applications in the medical field and beyond (Xu et al., 2018).

Hemicellulose Nanoparticles in Conductive Polymers

Conductive polymers can conduct electricity. Because they contain conjugated double or triple bonds and can conduct both electrically and ionically, conductive polymers are frequently used to create electrochemical biosensors. Another class of conducting materials combines a non-conducting polymer with conducting particles to achieve conductivity. Because of their extensive applications in drug delivery, soft materials, electrochemical biosensors, brain interfaces, bioerodible materials, tissues, and other fields, composites and conducting polymers have attracted considerable attention. In one study, conductive aniline pentamer (AP) was used to cross-link O-acetyl-galactoglucomannan with epichlorohydrin in water at room temperature to create electrically conductive hemicellulose hydrogels (ECHHs). More holes, controlled conductivity, swelling behaviour, and medium-strength mechanical properties make these polymers suitable for biomedical applications. Zhao and his associates use alternative synthetic methods to generate conductive hydrogels with high-strength hemicellulose foundations (Sihang et al., 2019).

Conclusion

This study focused on applications and innovative strategies for the sustainable development and use of nanomaterials across various industrial domains. Cellulose nanofibrils and cellulose nanocrystals are remarkable for their strong mechanical strength, biodegradability, and adaptability in applications such as drug delivery systems, paper goods, and biocomposites. These chemically and mechanically produced nanomaterials have excellent strength and thermal stability, making them ideal for controlled drug release and material reinforcement in biomedical contexts. Their water-soluble nature and diverse molecular makeup make hemicellulose a material with potential for biofuel production and biopolymer formation. Xylan nanoparticles (XNPs) derived from hemicellulose showed biocompatibility and potential applications in drug delivery systems, wound dressings, and food packaging. Synthesizing these nanoparticles supports sustainability and minimizes environmental impact, aligning with global efforts toward eco-friendly manufacturing. Preparation methods such as high-pressure homogenization and enzymatic hydrolysis enable precise control over particle size and enhance efficacy in specialized applications. Cellulose and hemicellulose nanoparticles are used in advanced high-tech materials for manufacturing biomedical devices, electronic energy-storing devices, textiles, and construction materials, highlighting their potential significance across industrial sectors. To conclude, further research and development are needed in the area of nanoparticles and their applications, which opens new platforms for sustainable solutions and economic growth at a global level.

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Statements and Declarations

Author Contributions

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Conflict of interest

The investigation was undertaken without any financial conflicts of interest or any other commercial relationships that could be seen as such by any of the authors.

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During the preparation of this work, the author(s) have not used any ChatGPT (OpenAI) tool.



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