

Review

Cellulose Nanomaterials: Characterization Methods, Isolation Techniques, and Strategies

Bogdan-Marian Tofanica ¹, Aleksandra Mikhailidi ², Maria E. Fortună ^{3,*}, Răzvan Rotaru ³,
Ovidiu C. Ungureanu ⁴ and Elena Ungureanu ^{1,*}

¹ “Ion Ionescu de la Brad” Iasi University of Life Sciences, 3 Mihail Sadoveanu Alley, 700490 Iasi, Romania; bogdan.tofanica@iuls.ro

² IF2000 Academic Foundation, 73 Prof. Dr. Docent D. Mangeron Boulevard, 700050 Iasi, Romania; amikhailidi@gmail.com

³ Department of Inorganic Polymers, “Petru Poni” Institute of Macromolecular Chemistry, 41A Grigore Ghica Voda Alley, 700487 Iasi, Romania; rotaru.razvan@icmpp.ro

⁴ “Vasile Goldis” Western University of Arad, 94 the Boulevard of the Revolution, 310025 Arad, Romania; ungureanu.ovidiu@uvvg.ro

* Correspondence: fortuna.maria@icmpp.ro (M.E.F.); elena.ungureanu@iuls.ro (E.U.)

Abstract: Nanocellulose, including cellulose nanofibers (CNFs), cellulose nanocrystals (CNCs), and bacterial nanocellulose (BNC), represents a promising class of bio-based nanomaterials derived from natural sources. These materials, derived from plant-based cellulose, are characterized by exceptional mechanical strength, high surface area, biodegradability, and the ability to form stable nanoparticle networks, making them suitable for use in composites, biomedicine, electronics, and many other fields. In this review, we present the latest advancements in the production of nanocellulose, including preparation technologies and methods for chemical and physical modifications to enhance the performance of these materials. We also discuss various applications, such as its use in nanocomposites, sustainable packaging materials, flexible electronic devices, and as a support for biological media. Additionally, the challenges and opportunities related to the scalability of production and their integration into industries with growing economic and ecological demands are explored. The review provides a comprehensive overview of the potential of nanocellulose, highlighting its importance in the context of emerging technologies and sustainability.

Keywords: nanocellulose; cellulose nanomaterials; cellulose nanofibers; cellulose nanofibrils; cellulose nanocrystals; nanocrystalline cellulose; cellulose nanowhiskers; cellulose nanoparticles; bacterial nanocellulose



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1. Introduction

Nanocellulose (NC) is a versatile and sustainable nanomaterial derived from cellulose, the most abundant natural polymer found in plant cell walls, some algae, and bacteria [1]. It can be classified into three main types based on its source, structure, and production methods: cellulose nanofibers (CNFs), cellulose nanocrystals (CNCs), and bacterial nanocellulose (BNC) [2]. Due to its exceptional properties, including high mechanical strength, large surface area, and biodegradability, NC has acquired significant attention for its potential in various applications [3]. Sourced from renewable materials, nanocellulose is increasingly recognized as a promising solution for eco-friendly and sustainable technologies, contributing to global efforts to reduce environmental impact and promote green alternatives [4].

The discovery of cellulose as a distinct polymer dates to 1838 and is attributed to French chemist Anselme Payen, followed by the first commercial-scale production of cellulose derivatives like celluloid (a thermoplastic) in 1870 by the Hyatt Manufacturing Company. However, the isolation and characterization of nanocellulose lagged by nearly a century, hindered by technological limitations [5].

Building upon the historical development of cellulose as a distinct polymer and its subsequent derivatives, Figure 1 provides a schematic representation of the hierarchical structure of lignocellulose biomass. It illustrates the organization of cellulose molecules within the biomass, from their molecular arrangement to their incorporation into larger, more complex structures that contribute to the formation of cellulose-based materials. Understanding this hierarchical structure is essential for comprehending the properties and behavior of lignocellulosic biomass, which has long been a focus of scientific research, particularly as advancements in nanocellulose production have revealed new insights into its potential applications

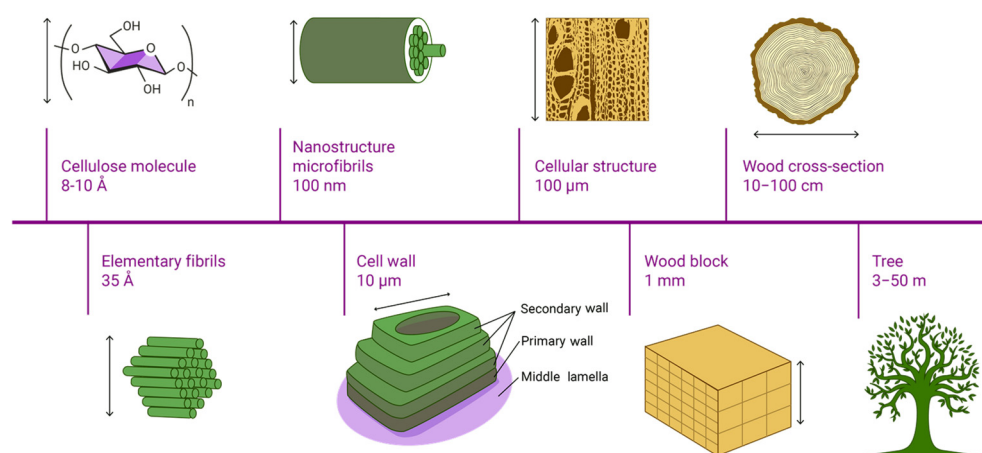


Figure 1. A schematic representation of the hierarchical structure of lignocellulose biomass from cellulose molecules to cellulose-based material.

Initial breakthroughs emerged in the mid-20th century: in 1950, Bengt Ranby pioneered the sulfuric acid hydrolysis of cellulose to yield a milky suspension termed “cellulose micelles” [6], and in 1953, Mukherjee et al. [7] provided the first electron micrographs revealing the rod-like morphology of nanocellulose. The term “*nanocellulose*” was formally introduced in the early 1980s by Turbak, Snyder, and Sandberg at ITT Rayonier Labs (Whippany, NJ, USA), who homogenized plant-based cellulose under high pressure and temperature to produce a gel-like material [8].

Research accelerated in the 1990s with discoveries such as the liquid crystalline behavior of cellulose nanocrystals (CNCs) and their application as reinforcing agents in composites by 1995. Industrial scalability advanced significantly in the 2010s: Canada established the world’s first commercial CNC production plant in 2012, building on pilot-scale efforts by FPIInnovations [9].

Concurrently, standardization became critical due to variability in nanocellulose properties influenced by biomass precursors (e.g., cellulose/hemicellulose/lignin ratios subject to seasonal variation) and cellulose polymorphs (I, II, III, IV), which alter morphology and physicochemical behavior [10].

To address these challenges, TAPPI’s International Nanocellulose Standards Coordination Committee (INSCC) was formed in 2011, establishing protocols for nomenclature, testing, and quality control, while the European Commission in 2014 defined nanocellulose

as “cellulose-derived materials with at least one dimension ≤ 100 nm”. Further harmonization came to classify nanotechnology terminology, including nanocellulose classifications.

However, the classification of nanocellulose as a “nanomaterial” can be nuanced, as the definition of nanomaterials varies depending on regulatory and scientific contexts. The European Commission (EC) defines nanomaterials as those that have specific properties due to their nanoscale structure, typically with at least 50% of the material existing in the nanoparticle range (less than 100 nanometers) [11].

Since the emergence of nanocellulose as a material, there has been a significant proliferation of terminology used to describe these substances. We will aim to adhere to the terminology established by the International Organization for Standardization (ISO) regarding cellulose nanomaterials (CNMs), wherever possible, while relying on commonly accepted terms when necessary to avoid ambiguity. To maintain clarity and consistency, we will adopt the terminology recommended in recent comprehensive reviews on the techniques for analyzing what should collectively be referred to as cellulose nanomaterials (CNMs). This acronym will be used to encompass the various forms of nanocellulose in this context.

Specifically, we will use the terms cellulose nanofibers (CNFs) and cellulose nanocrystals (CNCs) to describe the fibrous and rod-like forms of cellulosic materials. It is important to note that CNFs have also been referred to as nanofibrils and fibrillar cellulose, while CNCs have also been referred to as whiskers, needles, and nanocrystalline cellulose in the literature; however, we will avoid using these terms to prevent confusion. For materials produced by bacterial sources, we will use the term bacterial cellulose (BC) to refer to the cellulose produced by Gram-negative bacteria such as *Gluconacetobacter xylinum*.

In this context, nanocellulose can be considered a nanomaterial, as it is produced at the nanoscale and exhibits unique properties due to its structure. However, the inclusion of nanocellulose-based composites and other larger-scale materials with nanoscale features, such as nanocellulose sponges, presents a more complex issue. While these larger structures may contain nanoscale components that impart unique functionalities, they may not meet the EC’s definition of a nanomaterial due to their overall size. For example, nanocellulose sponges, used in applications like oil spill immobilization or filtration, may have nanoscale features but exceed the size threshold typically associated with nanomaterials [11].

Similarly, composites incorporating nanoscale components, such as polymer nanocomposites with nanocellulose, aerogels featuring nanoscale porosity, nanoparticle-infused films, or multilayer coatings with nanoscale characteristics, may not be classified as nanomaterials under these definitions. Although these materials contain nanoscale components—such as nanofibers, nanocrystals, or nanoparticles—they often exist at larger scales (in the micrometer or millimeter range), which may lead to their exclusion from official nanomaterial classifications in regulatory frameworks.

Initial research on nanocellulose focused on industrial scale-up, biomass pre-treatment optimization, and applications in established fields such as paper and packaging, where nanocellulose has long been utilized for its reinforcing properties [12]. More recently, nanocellulose has gathered attention for its potential in emerging technologies, including biomedicine and green electronics [13–15]. These new applications, while promising, are still under development and face challenges related to cost reduction, circular economy integration, and regulatory alignment.

This article provides a comprehensive review of the various types of nanocellulose, exploring their fundamental properties, characterization methods, and the various techniques employed for their isolation and purification. The review also highlights the challenges and opportunities associated with the large-scale production and commercialization of nanocellulose, addressing issues such as cost-effectiveness, scalability, and environmen-

tal sustainability. By providing a detailed analysis of the current state of research and future prospects, this article aims to contribute to the growing body of knowledge on nanocellulose and its role in advancing sustainable material science.

2. Characterization Methods of Nanocellulose

Nanocellulose, derived from wood and plant biomass, is a heterogeneous material whose properties—morphology, crystallinity, surface chemistry, and mechanical performance—are dictated by its source, isolation method, and post-treatment [16]. Among these characteristics, summarized in Figure 2 and Table 1, the dimension of the material is particularly crucial for determining whether the cellulose-based material falls within the nanoscale range. Precise characterization is essential to link structure–function relationships; however, the complexity of nanocellulose (e.g., polydispersity, lignin residues, and polymorphic cellulose) necessitates a comprehensive approach, as relying on a single method is insufficient to capture the full spectrum of its structural and chemical properties. Multiple techniques must be employed to obtain a complete understanding of its characteristics [17].

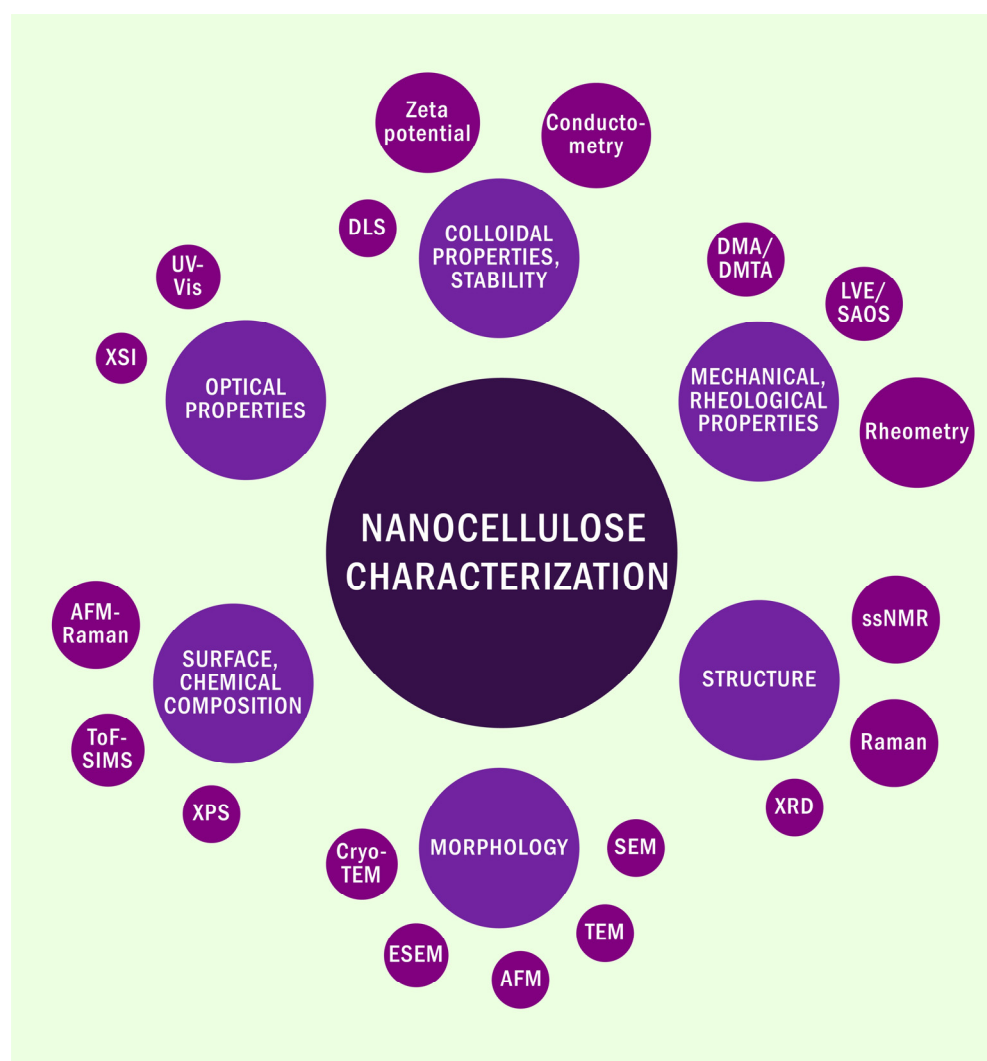


Figure 2. Nanocellulose analysis—from molecular structure to material properties.

Table 1. Methods for characterizing nanocellulose.

Method	Primary Application	Information Provided
Scanning electron microscopy (SEM)	Morphology visualization	Surface morphology, fibril dimensions, and distribution
Transmission electron microscopy (TEM)	Morphology visualization	Dimensions, shape, crystalline structure
Atomic force microscopy (AFM)	Surface topography	Fibril dimensions, surface roughness
X-ray diffraction (XRD)	Crystallinity analysis, crystal structure	Crystallinity index (CrI), crystal phases, distinguishes amorphous/crystalline regions
X-ray photoelectron spectroscopy (XPS)	Surface chemistry analysis	Elemental composition, chemical bonding, functional groups
Infrared spectroscopy (FTIR)	Chemical composition	Identifies surface modifications/impurities
Nuclear magnetic resonance (NMR)	Molecular structure analysis	Crystalline vs. amorphous regions, surface chemistry
Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC)	Thermal stability	Decomposition temperatures, thermal resistance

Electron microscopy techniques, such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM), provide high-resolution imaging capabilities essential for characterizing the morphology of cellulose nanocrystals (CNCs) and cellulose nanofibrils (CNFs) [18]. CNCs typically exhibit rod-like shapes with widths ranging from 3 to 20 nm, while CNFs form fibrillar networks with widths between 5 and 50 nm [19]. Cryo-TEM is particularly valuable in preserving the hydrated state of bacterial nanocellulose (BNC), avoiding drying artifacts that can distort structural information [20]. However, these techniques have limitations, such as the potential alteration of native morphology during sample preparation, which often requires metal coating and vacuum conditions. Additionally, the presence of lignin residues in unbleached CNFs can obscure the fibril boundaries, complicating structural analysis [21]. Recent advancements include environmental SEM (ESEM), which allows imaging under controlled humidity conditions, thus maintaining the hygroscopic behavior of wood-derived nanocellulose, a crucial feature for understanding its interactions in various environments [22].

Atomic force microscopy (AFM) is another powerful tool for characterizing nanocellulose, providing insights into morphology—the length of individual fibrils (typically 0.5–2 nm for CNFs), surface roughness, and mechanical properties such as modulus mapping [23]. AFM phase contrast is particularly useful for distinguishing lignin-rich domains (which appear darker) from cellulose in unbleached nanocellulose, providing valuable insight into the composition of lignocellulosic materials [24].

Hyperspectral imaging (HSI) [25] is an emerging technique that combines spatial and spectral data to map lignin distribution in nanocellulose films, helping to address the heterogeneity of wood fibers [26]. This method, based on UV–vis absorption, is particularly promising for analyzing the complex composition of nanocellulose derived from wood [27].

Crystallinity and polymorphism are also key properties of nanocellulose that can be analyzed using various techniques. X-ray diffraction (XRD) quantifies the crystallinity index (CrI) and cellulose I β /I α ratios, revealing differences between softwood and hardwood CNCs [28]. Softwood CNCs generally exhibit a higher CrI (85–90%) compared to hardwood CNCs (70–80%) [29]. However, amorphous contributions from hemicellulose and lignin

can introduce errors in CrI calculations [30]. Innovations such as synchrotron XRD have enabled the resolution of polymorphic transitions, such as the conversion of cellulose I to cellulose II, during in situ tensile testing.

Solid-state nuclear magnetic resonance (ssNMR) spectroscopy distinguishes cellulose allomorphs (I α vs. I β) and provides insights into the surface versus bulk crystallinity of nanocellulose. This technique is particularly valuable for understanding the impact of hemicellulose, as ssNMR can detect acetyl groups that influence the hydrophilicity of CNFs [31]. Raman spectroscopy, an emerging technique, uses polarized Raman to identify microfibril orientation in wood-derived CNFs, which correlates with their anisotropic mechanical properties [32].

In terms of surface chemistry and functionality, X-ray photoelectron spectroscopy (XPS) is widely used to quantify surface functional groups, such as sulfate ($-\text{OSO}_3^-$) or carboxyl ($-\text{COOH}$) groups, typically introduced by acid or TEMPO treatments [33]. However, the aromatic carbons in lignin can mask the C–O signals of cellulose, posing a challenge in analyzing unbleached nanocellulose.

Zeta potential measurements and conductometric titration are crucial for assessing the stability of nanocellulose dispersions. Sulfated CNCs typically exhibit zeta potentials between -30 and -50 mV, while carboxylated CNFs have more negative values (-50 to -70 mV), indicating their colloidal stability [34]. The presence of residual extractives, such as terpenes in softwood CNFs, can reduce colloidal stability, which is important for processing and application.

Time-of-flight secondary ion mass spectrometry (ToF-SIMS) is an emerging technique that maps lignin sulfonate residues on CNC surfaces at ppm sensitivity, providing critical information for biocompatibility studies in biomedical applications [35].

For assessing the mechanical properties of nanocellulose, nanoindentation is a common technique used to measure the elastic modulus (ranging from 10 to 50 GPa for CNCs) and hardness of single fibrils [36]. However, substrate effects can dominate in thin films, and cross-sectioned wood–CNF composites may require focused ion beam (FIB) milling for accurate measurements [37]. In situ AFM-Raman spectroscopy is a cutting-edge approach that correlates real-time stress–strain behavior with molecular deformation, such as cellulose chain slippage, in CNF films, providing a deeper understanding of their mechanical properties under load [38].

Colloidal and rheological behavior of nanocellulose can be studied using dynamic light scattering (DLS) and rheometry. However, DLS has limitations, often overestimating the sizes of CNCs and CNFs due to aggregation, though nanoparticle tracking analysis (NTA) improves accuracy, particularly for polydisperse systems [39]. Rheometry is a key method for characterizing the shear-thinning behavior of CNF suspensions, which exhibit a viscosity range of approximately 0.1–1 Pa·s and yield stress between 1 and 10 Pa [40]. These properties are crucial for applications such as additive manufacturing (also known as 3D printing), where the rheological behavior of the nanocellulose suspension is a critical factor. The presence of residual hemicellulose acts as a natural plasticizer, reducing the stiffness of CNF gels by approximately 30%, influencing their performance in applications requiring flexibility or deformability [41].

Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) are critical for evaluating nanocellulose's thermal stability and decomposition behavior. TGA reveals decomposition temperatures (typically 200–333 °C for nanocellulose), with variations depending on extraction methods, due to different amorphous content. DSC complements this by identifying endothermic events, such as water evaporation near 100 °C and the onset of cellulose degradation over 250 °C, aligning with TGA data [10].

3. Types and Properties of Nanocellulose

Cellulose nanomaterials are primarily classified into three main categories: cellulose nanofibers (CNFs), cellulose nanocrystals (CNCs), and bacterial nanocellulose (BNC). The classification of these materials is illustrated in Table 2. These categories are the most commonly studied and utilized in scientific literature. However, it is important to note that several other synonyms and variations of these terms can be found in the literature, reflecting the diversity of research and different isolation methods used.

Table 2. Key information for each type of nanocellulose.

Type of Nanocellulose	Cellulose Nanofibers (CNFs)	Cellulose Nanocrystals (CNCs)	Bacterial Nanocellulose (BNC)
Synonyms	Cellulose nanofibrils (CNF), nanofibrillated cellulose (NFC)	Nanocrystalline cellulose (NCC), cellulose nanoparticles (CNPs), cellulose nanowhiskers (CNWs)	Cellulose nanoribbon (CNR)
Characteristics	- Lower crystallinity (20–60%) - Diameter: 5–100 nm; length: several micrometers - High aspect ratio and flexibility - High surface area and water retention capacity	- High crystallinity (60–90%) - Diameter: 3–20 nm; length: 100–500 nm - High mechanical strength and thermal stability - Surface functionalized	- High purity and crystallinity (80–90%) - Diameter: 20–100 nm; length: continuous web-like structure - Biocompatible and biodegradable - High water-holding capacity
Isolation Method	- Mechanical treatment: high-pressure homogenization, microfluidization, and ultrasonication - Enzymatic pre-Treatment: partial hydrolysis for reduced energy consumption - Chemical pre-treatment: TEMPO-mediated oxidation or carboxymethylation	- Acid hydrolysis: using sulfuric acid, hydrochloric acid, or phosphoric acid - Enzymatic hydrolysis: cellulase enzymes for gentler isolation - Oxidation processes: using TEMPO (2,2,6,6-tetramethylpiperidine-1-oxyl) to oxidize cellulose	- Biosynthesis: fermentation of glucose or other carbon sources using cellulose-producing bacteria - Post-treatment: washing, purification, and mechanical processing for structural tuning
Yield	70–90%	30–50%	<60 g/L
Energy Demand	High (20–30 MWh/ton)	Low (chemical-driven)	Moderate (fermentation)
Main Application	- Rheology modifiers and thickeners in cosmetics and food - Biodegradable packaging - Flexible electronics - Tissue engineering scaffolds	- Reinforcement in composites - Drug delivery systems - Packaging materials and coatings - Optical and electronic devices	- Wound dressings and artificial skin - Biomedical implants and drug delivery - Food and cosmetic stabilizers - Flexible membranes for filtration
Scalability	Industrial (CNF)	Pilot-scale	Lab-to-pilot

The major categories of nanocellulose that have been extensively studied in the literature include the following:

- **Cellulose nanofibers (CNFs):** CNFs, also referred to as cellulose nanofibrils or fibrillated cellulose, are obtained by mechanically disintegrating cellulose fibers into nanoscale fibrils. These fibrils retain a significant portion of the cellulose's original crystallinity and are characterized by their flexibility and high surface area, which makes them suitable for use in hydrogels, paper, and composite materials.
- **Cellulose nanofibrils (CNFs):** also known as nanofibrillated cellulose (NFC), CNFs are nanoscale, elongated fibers derived from cellulose. These fibrils are typically a few nanometers in diameter and several micrometers in length. They result from the mechanical disintegration of cellulose fibers, which can be achieved through methods

such as high-pressure homogenization, grinding, or ultrasonication. Cellulose nanofibrils retain much of the cellulose's crystalline structure, while the amorphous regions of the fiber are partially disrupted during processing. As a result, CNFs possess a high surface area, flexibility, and mechanical strength, making them ideal for a range of applications such as in nanocomposites, coatings, films, hydrogels, and as a reinforcing agent in various materials. They are renewable, biodegradable, and environmentally friendly, further enhancing their appeal for sustainable product development.

- **Nanofibrillated cellulose (NFC):** Also known as cellulose nanofibers (CNFs), NFC refers to cellulose fibers that have been mechanically disintegrated into nanoscale fibrils. These fibrils retain a significant portion of the cellulose's crystalline structure, while the amorphous regions are partially broken down. The resulting material consists of flexible, thin, and elongated fibers that are typically a few nanometers in diameter and several micrometers in length. NFC is produced through mechanical processes such as high-pressure homogenization, grinding, or ultrasonication, which separate the cellulose fibers into individual nanofibrils. It has high surface area, excellent mechanical properties, and is biodegradable and renewable. Due to these characteristics, NFC has promising applications in various industries, including composites, films, coatings, hydrogels, and even as a reinforcement material in bioplastics and paper products.
- **Cellulose nanocrystals (CNCs):** Also known as cellulose nanowhiskers or nanocrystalline cellulose, CNCs are highly crystalline nanoparticles derived from the hydrolysis of cellulose using strong acids. They exhibit high mechanical strength, rigidity, and optical transparency, making them ideal for applications in nanocomposites, coatings, and drug delivery.
- **Nanocrystalline cellulose (NCC):** Also known as cellulose nanocrystals (CNCs), NCC refers to the crystalline portion of cellulose that has been isolated at the nanoscale through chemical methods, typically acid hydrolysis, using strong acids such as sulfuric or hydrochloric acid. During this process, the amorphous regions of cellulose are selectively broken down, leaving behind highly crystalline, stiff nanoparticles with a rod-like or whisker-like structure. NCC exhibits high mechanical strength, rigidity, and optical transparency, making it ideal for applications in nanocomposites, coatings, and drug delivery systems.
- **Cellulose nanoparticles (CNPs):** This is a general term used to describe any nanocellulose material that has been reduced to nanoparticle size. This category can encompass both CNCs and CNFs, depending on the specific isolation method used. CNPs are generally characterized by their small size and high surface area, making them suitable for a variety of applications.
- **Cellulose nanowhiskers:** These are similar to CNCs, but the term is often used to describe very small, rod-like particles isolated from cellulose sources through acid hydrolysis. Their distinct shape allows them to form highly ordered structures, making them ideal for reinforcing composites.
- **Bacterial nanocellulose (BNC):** BNC is produced by bacterial fermentation, primarily by species such as *Gluconacetobacter* and *Acetobacter*. Unlike plant-based cellulose, BNC is highly pure, has excellent water retention capacity, and exhibits high tensile strength. Its unique properties make it an attractive material for biomedical applications such as wound dressings, tissue scaffolds, and drug delivery systems.
- **Cellulose nanoribbons:** The term cellulose nanoribbon is specifically used to describe cellulose nanofibrils derived from bacterial sources, particularly bacterial nanocellulose (BNC). These nanoribbons are characterized by their flat, ribbon-like shape, and they retain a high degree of crystallinity and purity. Cellulose nanoribbons are

typically produced through bacterial fermentation processes, where microorganisms like *Gluconacetobacter* or *Acetobacter* synthesize highly pure cellulose in the form of nanoscale fibrils. These nanoribbons possess excellent mechanical strength, high surface area, and significant water retention capacity, making them suitable for various applications, including biomedical uses, such as wound dressings and tissue scaffolds, as well as in the development of sustainable materials and nanocomposites.

Each type of nanocellulose exhibits distinct structural, mechanical, and chemical properties that can be leveraged for specific applications across industries such as biomedicine, packaging, electronics, and nanocomposite materials.

Table 3 provides a detailed comparison of the distinct characteristics of three types of nanocellulose. These characteristics play a significant role in determining the suitability of each type of nanocellulose for various applications.

Table 3. Distinct characteristics of each type of nanocellulose.

Type of Nanocellulose	Cellulose Nanofibrils (CNFs)	Cellulose Nanocrystals (CNCs)	Bacterial Nanocellulose (BNC)
Crystallinity	Low to moderate (20–60%)	High (60–90%)	High (80–90%)
Diameter	5–100 nm	3–20 nm	20–100 nm
Length	Several micrometers	100–500 nm	Continuous, web-like structure
Surface Area		High	
Aspect Ratio	High	High	Low (web-like structure)
Flexibility	High (flexible and entangled)	Rigid (rod-shaped particles)	High (flexible, can form films)
Mechanical Strength	Moderate	High (rigid and strong)	Moderate to high
Water Holding Capacity	High	Moderate	Very high
Biodegradability		Biodegradable	
Purity	Varies (depends on isolation method)	High (depending on hydrolysis conditions)	Very high (due to biosynthesis process)

Crystallinity is a key differentiator between these types. CNCs and BNCs exhibit high crystallinity (60–90% for CNCs and 80–90% for BNCs), which contributes to their rigidity and high strength. In contrast, CNFs have a lower to moderate crystallinity (20–60%), providing greater flexibility but less mechanical strength compared to CNCs and BNCs. This difference in crystallinity influences their overall mechanical properties and their performance in various material applications.

Diameter is another distinguishing characteristic. CNCs have the smallest diameter (3–20 nm), while CNFs and BNCs have larger diameters, ranging from 5 to 100 nm and 20 to 100 nm, respectively. The smaller size of CNCs lends them to applications requiring high surface area and high crystallinity, whereas the larger diameters of CNFs and BNCs make them more suitable for applications that demand greater flexibility or higher water retention.

The length of the nanocellulose varies significantly. CNFs can be several micrometers in length, CNCs are much shorter (100–500 nm), and BNCs have a continuous, web-like structure. This continuous nature of BNC makes it unique and particularly useful for applications like tissue engineering, where such structures are desired for their ability to form films and scaffolds. In contrast, the shorter lengths of CNCs and CNFs influ-

ence their performance in composites and films, where shorter, rod-shaped particles are often preferred.

All three types of nanocellulose possess high surface area, which is crucial for applications that involve interaction with other materials, such as composite formation or biomedical applications. The aspect ratio is high for CNFs and CNCs, indicating that they have long, narrow shapes ideal for reinforcing materials. However, BNC has a low aspect ratio due to its web-like structure, which impacts its behavior in certain applications, such as structural reinforcement.

In terms of flexibility, CNFs and BNCs are highly flexible, with CNFs being entangled and flexible and BNCs being flexible enough to form films, which makes them suitable for applications in textiles and biomedical fields. In contrast, CNCs are rigid, rod-shaped particles, which grants them high strength but limits their flexibility. This rigidity makes CNCs ideal for structural applications where high mechanical strength is required.

Mechanical strength is highest for CNCs, which are rigid and strong, making them suitable for applications requiring high load-bearing capabilities. BNCs also exhibit moderate to high mechanical strength, while CNFs have moderate strength due to their more flexible and entangled structure. This difference in mechanical strength is crucial for selecting the appropriate nanocellulose for specific structural or functional applications.

The water-holding capacity of BNC is the highest, making it useful in applications where high moisture retention is needed, such as in tissue scaffolds or hydrogels. CNFs also have a high water retention capacity, which contributes to their flexibility and versatility. CNCs, however, have moderate water-holding capacity, reflecting their more rigid and crystalline nature [42].

All types of nanocellulose are biodegradable, making them environmentally friendly alternatives to synthetic materials in a variety of applications. However, their purity varies significantly: CNCs are highly pure, depending on the hydrolysis conditions used during their production, while CNFs exhibit variable purity depending on the isolation method. BNCs have very high purity due to the biosynthesis process, which ensures that the nanocellulose produced is free from most contaminants, making BNC particularly attractive for applications requiring high purity, such as in medical or food-related products.

The unique features of nanocellulose make these materials promising candidates for developing sustainable, eco-friendly technologies, with potential to replace synthetic polymers in numerous applications.

4. Production and Isolation Techniques for Nanocellulose

Nanocellulose production has historically relied on three core approaches: acid hydrolysis, mechanical fibrillation, and enzymatic/biological processes (as seen in Table 4). Additionally, there are various characterization methods used to evaluate nanocellulose, with each method being influenced by the specific type of nanocellulose produced, impacting its structure, properties, and potential applications.

Acid hydrolysis leverages concentrated acids (e.g., H_2SO_4 , HCl) to selectively cleave the β -1,4-glycosidic bonds in cellulose's amorphous regions, preserving crystalline domains. This method, pioneered by Ranby in the 1950s, remains dominant for isolating cellulose nanocrystals (CNCs) due to its reproducibility and high crystallinity (60–90%) [6]. Sulfuric acid (60–65% *w/w*, 45–60 °C, 30–90 min) introduces sulfate ester groups ($-\text{OSO}_3^-$) on CNC surfaces, enhancing colloidal stability but compromising thermal stability (>200 °C decomposition).

Table 4. Distinct isolation methods and characterization methods for each type of nanocellulose.

Type of Nanocellulose	Cellulose Nanofibrils (CNFs)	Cellulose Nanocrystals (CNCs)	Bacterial Nanocellulose (BNC)
Isolation Methods	- Mechanical treatment (high-pressure homogenization, microfluidization, ultrasonication) - Enzymatic pre-treatment (e.g., cellulase) - Chemical pre-treatment (e.g., TEMPO-mediated oxidation)	- Acid hydrolysis (e.g., sulfuric acid, hydrochloric acid) - Enzymatic hydrolysis (cellulase) - Oxidation processes (e.g., TEMPO oxidation)	- Biosynthesis (fermentation using bacteria such as <i>Komagataeibacter xylinus</i>) - Post-treatment (washing, purification, mechanical processing)
Characterization Methods	- Atomic force microscopy (AFM) - Scanning electron microscopy (SEM) - Transmission electron microscopy (TEM) - X-ray diffraction (XRD) - Fourier transform infrared spectroscopy (FTIR) - Dynamic light scattering (DLS)	- X-ray diffraction (XRD) - Transmission electron microscopy (TEM) - Atomic force microscopy (AFM) - Scanning electron microscopy (SEM) - Fourier transform infrared spectroscopy (FTIR)	- Scanning electron microscopy (SEM) - Atomic force microscopy (AFM) - Transmission electron microscopy (TEM) - X-ray diffraction (XRD) - FTIR

Recent innovations in the production of cellulose nanocrystals (CNCs) have focused on enhancing their properties and improving the sustainability of the synthesis process. One such development is the use of alternative acids, such as phosphoric acid (H_3PO_4), which introduces phosphate groups onto the CNC surface [43]. This modification improves the thermal stability of CNCs, allowing them to withstand temperatures up to 280 °C, and enhances their compatibility with hydrophobic polymers.

Additionally, the use of solid acid catalysts, such as sulfonated carbonaceous catalysts (e.g., biochar- SO_3H), has gained attention for enabling milder reaction conditions (e.g., 80 °C for 6 h). These catalysts also significantly reduce acid waste by approximately 40%, aligning with principles of a circular economy by minimizing environmental impact [44].

Another advancement is the incorporation of ultrasonic-assisted hydrolysis, where acid treatment is coupled with ultrasonication at frequencies of 20–40 kHz [45]. This technique reduces reaction time by 50% and results in CNCs with narrower size distributions, with widths ranging from 5 to 15 nm. Despite these promising innovations, several critical limitations remain. For instance, sulfate groups attached to CNCs during sulfation processes tend to degrade under humid or alkaline conditions, which compromises the long-term stability of sulfated CNCs.

The presence of residual lignin in wood pulp, particularly in kraft or sulfite pulps, can hinder the penetration of acids into cellulose fibers, necessitating harsh bleaching processes (e.g., using NaClO_2). These bleaching methods, however, can degrade the degree of polymerization (DP) of cellulose, affecting the quality of the CNCs produced [46].

Furthermore, the neutralization of spent acids generates gypsum (CaSO_4) sludge, which poses a disposal challenge due to the associated costs. These limitations highlight the need for continued research to optimize the synthesis process and mitigate environmental impacts while maintaining the desired properties of CNCs.

Mechanical methods, such as high-pressure homogenization (HPH) and microfluidization, excel in producing cellulose nanofibrils (CNFs) with high aspect ratios but suffer from excessive energy consumption (20–30 MWh/ton) and inconsistent fibrillation, often requiring pre-treatments like enzymatic or TEMPO-mediated oxidation [47]. These processes preserve native cellulose I β crystallinity but produce fibrils with heterogeneous widths (5–50 nm) and high amorphous content.

Recent innovations in the production of cellulose nanofibrils (CNFs) have focused on improving pre-treatment methods and optimizing fibrillation processes to reduce energy consumption and enhance product quality. One notable advancement is TEMPO-mediated oxidation, a pre-treatment that uses sodium hypochlorite (NaClO) and sodium bromide (NaBr) at pH 10 to introduce carboxyl groups (–COOH) onto the cellulose surface. This modification not only improves the dispersion and uniformity of the resulting CNFs, which have widths of 3 to 5 nm, but also reduces energy demand by approximately 70% [48].

Another promising approach is the use of deep eutectic solvent (DES) swelling, where a choline chloride-urea DES is employed to swell the fiber walls at 80 °C. This method enables fibrillation at energy levels below 10 MWh/ton, significantly reducing the energy required compared to the 30 MWh/ton typically needed for native fibers [49].

Enzyme-assisted fibrillation using endoglucanases, such as EG II, has also shown potential for selectively hydrolyzing the amorphous regions of cellulose, producing CNFs with higher aspect ratios (ranging from 200 to 500) and fewer fines, which are typically problematic in the production process [50].

However, several critical limitations remain. Despite the efficiency of these pre-treatment strategies, high-pressure homogenization (HPH), a key step in fibrillation, still consumes around 10 MWh/ton, an energy demand comparable to the costs associated with steel production [51].

Additionally, repeated shear cycles during fibrillation can cause significant fibril damage, leading to a reduction in tensile strength, from approximately 2 GPa to less than 1 GPa [52]. The retention of hemicellulose (5 to 15%) in unbleached pulp also poses challenges, as while it enhances the flexibility of the resulting CNFs, it complicates surface functionalization processes [53].

From a wood chemistry perspective, mechanical methods are most effective when applied to low-lignin feedstocks, such as bleached kraft pulp. In contrast, for lignin-rich biomass, such as thermomechanical pulp, steam explosion (at 200 °C, 15 bar, for 5 min) is a beneficial pre-treatment that loosens the fiber structure, reducing the number of fibrillation cycles required by 50% [54]. Furthermore, twin-screw extrusion, a technique adapted from polymer processing, is emerging as a promising scalable, continuous alternative to batch homogenization, offering potential for improved process efficiency and scalability [55].

Bacterial nanocellulose (BNC), synthesized via static or agitated fermentation, offers unparalleled purity and biocompatibility but is hampered by low yields (<40 g/L) and high substrate costs. *Komagataeibacter xylinus* synthesizes BNC via extracellular polymerization of glucose into β -1,4-glucan chains, forming a 3D nanofibrillar network (20–100 nm width, >90% crystallinity). Static fermentation yields thick pellicles, while agitated cultures produce fibrous suspensions [56].

While these methods have enabled pilot-scale commercialization (e.g., CelluForce's CNCs, Nippon Paper's CNFs), they highlight a critical trade-off: scalability often compromises sustainability or material performance.

5. Market Overview and Production Landscape of Nanocellulose

This section aims to provide researchers with an overview of how nanocellulose-related study is being transferred into commercial products and industrial use. Understanding the market, production challenges, and pricing dynamics can help identify research gaps and new opportunities for scientific and technological advancements, such as areas where existing production methods are inefficient, certain types of nanocellulose need improvement for specific applications, or scalable solutions are lacking to reduce production costs. Moreover, market trends and key players can assist researchers in as-

sessing the commercial potential of their research projects and identifying the potential industrial partnerships.

The global nanocellulose market was valued at USD 351.5 million in 2022 with a compound annual growth rate (CAGR) of 20.1% from 2023 to 2030 [57]. However, the actual growth exceeded forecasts, reaching USD 0.6 billion in 2024. Currently, the market is projected to grow to USD 3.4 billion by 2032, exhibiting a CAGR of 23.7% [58]. Cellulose nanofibers dominated the market with a revenue share of more than 51% in 2022 [57], while bacterial nanocellulose is gaining attention for its superior mechanical strength and biocompatibility. Although the size of the nanocellulose market is smaller than that of other innovative sustainable materials (such as bioplastics, which includes a variety of products and was valued at USD 13 billion in 2022 [59]), the growth rate of the nanocellulose market is higher, as the bioplastics market is expected to grow at a CAGR of 17.43% from 2023 to 2030.

The rapid growth of sustainable materials market, including nanocellulose and bioplastics, is largely driven by regulatory initiatives promoting sustainability. Industries such as pulp and paperboard (particularly packaging), textiles, automotive, electronics, food and beverage, and healthcare are shifting towards eco-friendly alternatives in response to policies like the European Green Deal [60] and the Circular Economy Action Plan [61]. As a result, companies are increasing investments in research and development, particularly in bio-based materials.

The United States is currently the largest market, particularly due to applications in food packaging. North America and Europe are leading regions, benefiting from well-developed research infrastructure and strong regulatory frameworks that support the adoption of sustainable materials. Meanwhile, the Asia Pacific region is expected to experience significant growth due to increasing industrial production and rising interest in eco-friendly technologies, positioning it as a crucial player in the future of the nanocellulose market [57,58].

The global nanocellulose market is experiencing steady growth driven by increasing demand for eco-friendly materials and expanding applications. It is expected to continue evolving in the coming years, attracting investments and fostering innovations across packaging, composites, biomedical, food, and electronics industries.

A more detailed understanding of the current market status and the development level of production technologies can be obtained by examining NC manufacturing companies (Table 5). This information reflects the scaling potential of existing technologies and the commercial viability of innovative solutions. Additionally, the data on production capacities allows researchers and practitioners to evaluate possible opportunities for the implementation of nanocellulose technologies in industry.

Table 5. Overview of innovative startups and enterprises in nanocellulose production.

Product	Company	Country	Description	Implementation Stage	References
CNF					
Papira®	Stora Enso	Finland–Sweden	Wood-based foam for packaging was initially made from CNF, but due to challenges, the R&D team switched to pulp fibers, refining the Papira® formulation by 2019.	Commercial production (capacity is not mentioned in the open sources)	storaenso.com [62,63]
Exilva®	Borregaard	Norway	The product is made from microfibrillated cellulose derived from wood fibers and serves as an additive in resins and adhesives. It improves viscosity and substrate wetting, enhancing adhesive strength and sustainability, and provides resistance to harsh conditions (pH, temperature, and shear forces).	Commercial production of 50,000 tons of MFC dispersion per annum (or 1000 tons in dry matter)	borregaard.com [64–66]
FiberLean®	FiberLean Technologies	United Kingdom	Microfibrillated cellulose derived from wood pulp, used as a performance-enhancing additive in paper, packaging, coatings, and composites.	Commercial production of 1000–10,000 tons per annum	fiberlean.com [67–70]
Cellulose nanofiber	NIPPON PAPER INDUSTRIES CO., LTD.	Japan	Produced from wood pulp using the TEMPO catalytic oxidation method. Applications include reinforced plastics, food and cosmetics additives, and packaging materials.	Commercial production (capacity is not mentioned in the open sources)	nipponpapergroup.com [71,72]
FiloCell™	Kruger Biomaterials Inc.	Canada	CNFs are derived from kraft wood pulp through a mechanical process and released in wet pulp, dry and dispersed fluff, or water suspension for packaging and coatings.	Commercial production of 6000 tons per annum for all the products	biomaterials.kruger.com [73]
Re:ancel™ T-CNF	ANPOLY Inc.	South Korea	TEMPO-modified cellulose nanofiber (CNF) at 2% consistency in water. Transparent, high-viscosity hydrogel material used for packaging, filtration, and medical biomaterials.	Commercial production (capacity is not mentioned in the open sources)	anpolyinc.com (based on the Isogai method [74])
Suzano biofiber	Suzano	Brazil	CNF is made from eucalyptus cellulose pulp for personal care products, textiles, different types of paper, and other industries.	Commercial production (capacity is not mentioned in the open sources)	suzano.com.br [75]
Mechanical cellulose (lignocellulose, wood) nanofiber gels, oxidized cellulose nanofiber gel	Nano Novin Polymer Co.	Iran	Chemo-mechanically produced nanofiber gels (5–8%) are derived from wood and agricultural residues according to the customer's order.	Custom-order production	nanonovin.com [76,77]

Table 5. Cont.

Product	Company	Country	Description	Implementation Stage	References
Curran®	CelluComp Ltd.	Scotland	CNF is derived from the residual pulp of root vegetables, such as sugar beets, through a proprietary extraction process. It is used in packaging and composite materials, offering performance characteristics comparable to carbon fiber. Curran®-based biocomposites can be formulated with conventional resins such as epoxy, polyurethane, and polyester. Its platelet structure enhances rheology in applications like paints.	Scaling production with ongoing collaboration	https://www.cellucomp.com [78]
CNC					
CelluRods®	CelluForce Inc.	Canada	CNC is produced from wood pulp using mechanochemical processes for application in the oil and gas industry, coatings, packaging, and biopolymers.	Commercial production, 300 tons per annum	celluforce.com [79–82]
DextraCel	Anomera Inc.	Canada	CNC is available as an aqueous suspension or as dispersible powders. The surface contains carboxylate and hydroxyl groups. Applications include bioplastics, coatings, and adhesives.	Commercial production, 150+ tons per annum for all the products	anomera.ca [83,84]
MelOx™ VBcoat™	Melodea Ltd.	Israel	A CNC-based coating that provides a sustainable barrier against oxygen and oil for packaging applications.	Commercial production (capacity is not mentioned in the open sources)	melodea.eu [85,86]
BioPlus® with AVAP® and BioPlus® with GreenBox®	GranBio Technologies (USA), a subsidiary of GranBio Investimentos S.A. (Brazil)	USA–Brazil	NC is extracted from wood, hemp, and agricultural residues. CNF and CNC have adjustable particle size and composition, ranging from hydrophilic pure cellulose to hydrophobic cellulose coated with lignin. The GreenBox process results in particularly low production costs. GranBio's NC can be surface-modified to enhance compatibility with non-aqueous media, such as plastics and oils, and is offered in water-free masterbatch formulations.	Commercial production, ½ tons per day	granbio.com.br [87,88]
BGB Ultra™	Blue Goose Biorefineries Inc.	Canada	CNC is produced using a transition metal-catalyzed oxidation process on viscose-grade hardwood pulp and lignocellulosic biomass such as wood, hemp, flax, and wheat straw. The product is an aqueous suspension of type I cellulose nanocrystals that forms a gel at 8.0% <i>w/w</i> .	Pilot plant	bluegoosebiorefineries.com [89]

Table 5. Cont.

Product	Company	Country	Description	Implementation Stage	References
Nanolinter®	Nanolinter	Turkey	Lignocellulosic materials, including cotton plant-derived linter and paper pulp, are used for CNC production. It is applied as reinforcement material in composites, pharmaceuticals, cosmetics, chemicals, materials, and paints.	Custom-order production	nanolinter.com
Nanocrystacell	Navitas	Slovenia	Produced from tree cellulose, this material is available as either an aqueous suspension (2–5 wt.%) or a powder for adhesives, paper production, cement, and composite industries.	Custom-order production	nanocrystacell.eu
Bacterial cellulose nanofiber sheet, oxidized bacterial cellulose nanofiber gel	Nano Novin Polymer Co.	Iran	Bacterial nanocellulose The sheets are produced through bacterial synthesis in proper culture mediums followed by treating with chemical treatments. The oxidized gel contains 2% of the solid matter.	Custom-order production	nanonovin.com [90]
Biomaterial based on bacterial nanocellulose	Modern Synthesis Ltd.	United Kingdom	Nanocellulose materials are produced using bacteria; the product demonstrates excellent performance characteristics for applications in the fashion industry.	Scaling production, validated product–market fit, successful integration of materials into real products	modernsynthesis.com [91]
Biomaterial based on bacterial nanocellulose	Volkswagen Group Innovation	Germany	Biotechnological production of bacterial nanocellulose as a sustainable leather-like material for interior applications, using a fermentation-based process with bacterial cultures, yeast, and carbohydrates, followed by post-processing treatments.	Material optimization and experimental validation	volkswagen-group.com [92,93]
Biovolokno (biofiber)	byScoby	Russia	Biotechnological production of bacterial cellulose with post-cultivation processing to enhance mechanical properties, creating a sustainable alternative to leather and synthetic materials.	Limited commercial release; product introduced through brand partnerships, with initial market sales and further validation before scaling to full production	vk.com/byscoby [94]

All websites were accessed on 15 January 2025. The authors have no financial interests or advertising agreements with the companies mentioned.

It is important to note that the NC market is represented by a significant number of large manufacturers, mid-sized companies, and emerging startups, as well as initiatives being developed by major companies for internal use. The aim of this search was not to provide a comprehensive review of all manufacturers worldwide (this was performed in a commercially available micro- and nanocellulose market report [95]), but to highlight the overall market landscape, mention major market players, and include those at the early stages of development from various regions.

Table 5 lists the patents or publications on which the product is based, if the information is available. Some large companies obviously hold much more patents; for example, Anomera, QC (Canada) has 35 patents in its portfolio. Only a few relevant to NC were included to this study.

As shown in Table 5, many NC production companies have already reached industrial scale, though production volumes vary. Often, these companies specialize in other areas, such as pulp and paper, like NIPPON PAPER INDUSTRIES (Tokyo, Japan) or Suzano (São Paulo, Brazil), and establish an additional production line for nanocellulose products.

For example, Nippon patented a method for anionic modification of cellulose nanofibers to produce dry solid particles with good re-dispersibility [71,72]. The product retains properties such as solubility, dispersibility, sedimentation rate, and viscosity after redispersion in water. The CNFs are thin fibers (4–500 nm wide) with an aspect ratio of 100 or more, obtained by defibrating anionically modified cellulose (carboxylated, carboxymethylated, or phosphorylated). Usually, surface charges on CNFs ensure electrostatic repulsion and water stability, but uneven charge distribution leads to aggregation during drying, reducing re-dispersibility. Adding 5–300 wt.% of a water-soluble polymer covers low-charge areas, prevents hydrogen bond formation, and improves re-dispersibility. This approach allows for more cost-effective storage and transportation of nanocellulose, as shipping it in low-concentration suspensions is significantly more expensive than in powder form.

A common practice is integrating an external startup into the ecosystem of a large company to launch a new product. For instance, Stora Enso (Stockholm–Helsinki, Sweden–Finland) developed its Papira[®] product together with the startup Cellutec (here and below, the information is sourced from the company website, and the references are provided in Table 5).

Another approach is the creation of a university spin-off, originating from a strong cellulose department. The startup is developed in collaboration with industrial partners and/or with government support, which enables scaling production to a pilot facility with the potential for further transformation into modern industrial production. An example of this is Blue Goose Biorefineries Inc. (Montreal, QC, Canada), which emerged from McGill University (Montreal, QC, Canada). Initially focusing on the production of biodiesel and ethanol from agricultural waste, the company shifted its focus to crystalline cellulose forms. In 2012, Blue Goose Biorefineries received a grant from the Canadian Ministry of Agriculture and Food to scale up this technology. As a result, in 2014, the company opened a pilot plant in Saskatoon, SK, (Canada). This facility manufactures cellulose nanocrystals for sale on demand and plans to operate plants that can supply product up to 100 tons or more per day in the future.

The patented technology includes the production of nanocellulose from lignocellulosic biomass (agricultural crops, residues, and by-products). In the first step, an alkaline pre-treatment of the biomass is carried out with a simultaneous redox reaction in a one-pot process. Sodium hypochlorite (NaOCl) is used at an optimal concentration of 0.1–0.5 M, with the reaction occurring at up to 95 °C, using a metal catalyst (e.g., iron or copper sulfate). After filtration and removal of oxidation products, a second round of alkaline extraction

may be performed to ensure higher-quality crystalline cellulose. The resulting CNC has an average length of approximately 100–150 nm and an average diameter of about 10 nm [89].

Similarly, close ties with a university are reflected in the history of the Iranian company Nano Novin Polymer Co., which was founded based on the doctoral dissertation of its CEO, Dr. Hossein Yousefi (University of Tehran, Iran). The company is currently based at the Mazandaran Science and Technology Park (Sari, Iran). They offer a wide range of NC materials, likely customized to order, allowing them to adapt to customer demands, although this extends delivery times. On the other hand, this approach allows for continuous product optimization and the search for a sustainable market demand before transitioning to mass production.

Thus, most startups have emerged from universities, which is not surprising given the high scientific intensity of the product. This underscores the enormous importance of organizing technology transfer in higher education institutions to create more innovative enterprises. However, some startups do not link themselves to universities, such as Modern Synthesis (London, UK). Although their founders have worked in academia, they develop independently, securing funding from venture capital firms, business accelerators, and forming their own partnerships.

Another example of an independent startup is byScoby (Saint Petersburg, Russia), which specializes in bacterial cellulose-based materials. Their process, based on the cultivation of *Komagataeibacter xylinus*, produces a BC material with mechanical properties comparable to leather, particularly excelling in tear resistance. The process is scalable beyond 50 L, with further yield improvements possible through in situ modifications. Additionally, an ex situ optimization approach is being explored, involving post-cultivation treatments such as mercerization, washing, plastification (with 2–10% glycerol), hydrophobization (with 1–4% saturated fatty acids), and drying. This method achieves a final BC yield of 3.8 ± 0.5 g/L [94].

The same as Modern Synthesis, byScoby has formed partnerships with dynamic fashion brands and is targeting the niche of eco-friendly fabrics for the fashion industry. This technology could also support the development of bio-based materials for automotive and medical applications.

In some cases, NC is developed not as a separate business but as part of a large industrial corporation. For example, Volkswagen Group (Wolfsburg, Germany) has developed a biotechnological process for producing bacterial nanocellulose through fermentation, using bacterial cultures, yeast, and carbohydrates. This material, which mimics leather in texture and strength while being fully biodegradable, offers a sustainable alternative for automotive, furniture, and fashion industries. Post-treatment modifications enhance its durability, while further optimization with plasticizers and crosslinking agents improves its mechanical properties. Characterization methods confirm its potential as a sustainable biomaterial with leather-like qualities [92,93].

Nanocellulose is produced both from traditional wood and from premium types such as eucalyptus, as in the case of Suzano (São Paulo, Brazil). Additionally, raw materials can include waste from wood pulp, agricultural by-products (e.g., hemp, flax, etc.), and bacterial synthesis. The production processes involve mechanical, chemical, and enzymatic treatments, which influence the properties and applications of the materials (Table 5).

One such mechanical process is based on repeated defibrillation of cellulose fibers in suspension. High-speed impacts between concentrically arranged rings with non-cutting rods transfer kinetic energy to the fibers, producing microfibrillated cellulose. This approach, which can be applied to various cellulose sources, including kraft fibers and CNF, allows for the efficient production of stable MFC suspensions while optimizing fibrillation through multiple processing cycles [71].

The geographical distribution found in Table 5 shows that the majority of production facilities are concentrated in Canada and Europe, with some plants emerging in South America, East Asia, and the Middle East. The pricing policy of these producers is more flexible, which can be attributed to lower costs for rent, electricity, raw materials, and possibly labor.

According to publicly available data as of February 2025, the price of nanocellulose is quite high and varies depending on the type and form of delivery. For instance, the cost of dry CNC powder ranges from EUR 470 to EUR 1102 per kg. Aqueous CNC suspensions (6–8%) are priced at approximately EUR 120 per liter, while cosmetic-grade NFC (1%) is priced at USD 150 per liter. However, more affordable products are available. For example, the price of cellulose nanofiber gel (8%) with $\geq 99.9\%$ purity, produced in Iran, starts at USD 39 per kg, while a 2% aqueous suspension produced in China can be shipped from USD 57.2 per liter. Bacterial cellulose (Iran) is available in sheets of $200 \times 300 \times 2$ mm, priced at USD 10 per unit.

We assume that the high cost may be due to relatively low production volumes, which restrict economies of scale. Additionally, the use of specific chemical reagents, such as TEMPO oxidants, increases manufacturing expenses. While the equipment required for nanocellulose production is not sophisticated, the process usually involves energy consumption, multi-step treatment, and stringent quality control. Furthermore, transportation and storage—especially for aqueous suspensions—may require special conditions, adding to the overall cost.

It is reasonable to assume that as production volumes increase and technological advancements are made, prices may decrease, making nanocellulose more accessible. However, this remains a projection and will depend on multiple economic and technological factors.

6. Strategies for Modification and Enhancement of Nanocellulose

A wide array of functionalization techniques has been developed, each offering specific advantages and challenges. Covalent modifications such as esterification and silylation improve hydrophobicity and dispersion in non-polar media. Oxidation strategies, including TEMPO-mediated oxidation and periodate-chlorite treatments, enhance colloidal stability and introduce reactive groups for further modifications. Polymer grafting techniques, utilizing controlled radical polymerization methods, provide precise surface modifications. In addition to chemical functionalization, physical and mechanical treatments, such as high-pressure homogenization and electrospinning, refine NC morphology for specific applications, albeit with challenges related to fibril fragmentation and fiber uniformity. The development of hybrid composites incorporating NC with nanocarbons or minerals has demonstrated enhanced functionalities, including improved electrical conductivity and fire resistance. Emerging green modification approaches, including enzymatic treatments, deep eutectic solvents (DES), and ionic liquids, present promising alternatives by reducing energy consumption and chemical waste.

Surface functionalization of nanocellulose (NC) is predominantly achieved through esterification/silylation, where hydroxyl groups are grafted with acetyl, maleic, or silane ($-\text{Si}(\text{OR})_3$) moieties [96,97]. This approach enhances hydrophobicity (water contact angles $> 110^\circ$), enabling compatibility with non-polar polymer matrices. For instance, acetylated cellulose nanocrystals (CNCs) in polylactic acid (PLA) composites improve tensile strength by $\sim 40\%$ while retaining biodegradability [98]. However, solvent-intensive protocols (e.g., pyridine for acetylation) and low grafting efficiencies ($< 50\%$) limit scalability.

Oxidation strategies, such as TEMPO-mediated [74,86] or periodate-chlorite treatments, introduce carboxyl ($-\text{COOH}$) or aldehyde ($-\text{CHO}$) groups, improving colloidal sta-

bility and enabling Schiff-base crosslinking for hydrogels. While effective, over-oxidation risks reducing crystallinity and mechanical integrity. Polymer grafting via controlled radical polymerization (e.g., ATRP, RAFT) allows precise growth of polymer brushes (e.g., PEG, PMMA) from NC surfaces (“grafting from”) or covalent attachment of pre-synthesized polymers (e.g., PCL, chitosan; “grafting to”) [99,100]. Recent advances in photoinduced electron/energy transfer (PET-RAFT) enable solvent-free grafting under visible light, though challenges persist in controlling grafting density and avoiding chain termination.

Crosslinking strategies employ chemical agents like epichlorohydrin, glutaraldehyde, or genipin to form covalent networks in NC aerogels, elevating compressive strength from 0.5 MPa to 5 MPa [101]. However, residual toxic crosslinkers (e.g., glutaraldehyde) restrict biomedical applications. Dynamic crosslinking via reversible imine or boronate ester bonds introduces self-healing capabilities in NC films, which is promising for wearable sensors but limited by slow bond reformation kinetics.

Mechanical treatments such as high-pressure homogenization (HPH) reduce fibril diameters from ~50 nm to 10 nm but risk fibril fragmentation, compromising mechanical performance [102]. Electrospinning produces aligned NC nanofibers (100–500 nm diameter) for tissue engineering scaffolds, though fiber uniformity remains inconsistent [103]. Hybrid composites integrate NC with nanocarbons (e.g., graphene oxide, carbon nanotubes) or minerals (e.g., montmorillonite, hydroxyapatite), achieving electrical conductivity ($\sim 10^{-3}$ S/cm) or enhanced fire resistance [104]. However, interfacial incompatibility between NC and inorganic phases often necessitates additional compatibilizers. Plasma/irradiation treatments, including cold plasma (introducing $-NH_2$ or $-CF_x$ groups) and gamma irradiation (radical-mediated grafting), enhance surface functionality without solvents but face scalability hurdles [105].

Enzymatic modifications leverage laccase-mediated grafting to oxidize lignin residues on NC, enabling covalent coupling with phenols (e.g., tannins for UV shielding) [106]. Cellulase-assisted defibrillation yields ultra-fine cellulose nanofibrils (CNFs; 3–5 nm width) with retained hemicellulose, improving ductility but requiring costly enzyme cocktails [107]. Deep eutectic solvents (DES), such as choline chloride-urea, swell cellulose fibers for low-energy fibrillation (<5 MWh/ton) and in situ functionalization (e.g., quaternization for antimicrobial NC) [108]. Ionic liquids (e.g., [Emim] [OAc]) dissolve cellulose for regeneration into aligned CNFs with tunable crystallinity (40–80%), though solvent recovery remains a critical bottleneck [109].

While these methods show potential for sustainable NC processing, challenges related to cost, scalability, and solvent recovery still need to be addressed.

7. Challenges and Future Outlook

Despite recent advances in nanocellulose research, several challenges still prevent its widespread adoption. Balancing sustainability with scalability remains difficult. Traditional isolation methods, acid hydrolysis, mechanical fibrillation, and enzymatic/biological processes, consume too much energy and create toxic by-products, making the products expensive. Feedstock varies too much between seasons and species, leading to inconsistent properties that hinder industrial use.

Another critical challenge is the lack of adoption of standardized characterization methods. While some properties are well documented, others like interfacial adhesion and biodegradation rates are not properly standardized. This makes comparing studies difficult and slows regulatory approval. Nanocellulose’s natural hydrophilicity and limited heat resistance restrict its use with hydrophobic polymers and high-temperature processes. Its dynamic functions often suffer from slow bond reformation and poor cyclability.

To overcome these obstacles, researchers should focus on sustainable innovations, advanced manufacturing, and systems-level design. Green chemistry approaches like plasma functionalization and deep eutectic solvent hydrolysis could reduce toxic reagent use. Using agricultural waste as feedstock would improve resource efficiency while cutting costs. Machine learning and AI could optimize reaction parameters and automate quality control, helping bridge the gap between laboratory discovery and industrial production.

Advanced manufacturing techniques, particularly additive manufacturing (also known as 3D printing) of nanocellulose, could create customized structures for medical scaffolds or flexible electronics. Taking inspiration from nature—like nacre’s layered structure or spider silk’s toughness—might enhance performance while using less material. Adding stimuli-responsive elements could enable applications in smart packaging and energy harvesting.

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