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A Review on Nanocellulose: Sources, Types, and Applications

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Graphical abstract:

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Abstract

Cellulose in nanostructures is the most significant ecologically friendly resource globally and the most plentiful renewable polymer source. Cellulose possesses numerous desirable characteristics, rendering it an inexhaustible source of raw materials. The kind of lignocellulosic biomass and the method of processing affect the range of cellulose allomorphs. A novel substance, nanocellulose originates from the essential natural polymer cellulose. It possesses unique properties and functionalities such as sustainability, nontoxicity, renewability, a high area of a specific surface, good modifiability, tunable surface features, and exceptional optical properties. Various types of nanoscale cellulose can be generated by isolating cellulose fibers according to their origins, degree of crystallinity, extraction method, and production process. This review concentrates on nanocellulose and its most current applications. Begin with a basic overview of cellulose, its origins, and the many forms of nanocellulose and its sources. Finally, the review overviews the most recent advances in many nanocellulose applications, such as water treatments, heavy metal sensing, environmental remediation, and biosensing devices in many fields, including medical diagnostics and bioimaging applications.

Keywords: nanocellulose, biomedical applications, cellulose nanocrystal, cellulose nanofiber, bacterial nanocellulose.

1. Introduction

Cellulose is the most critical element in almost all plants since it is all cell walls' structural basis. It is a biopolymer consisting of repeated connections of the glucose building blocks. Cellulose is characterized by many attractive properties, making it an endless supply of raw materials. It is Earth's most abundant renewable natural resource [**1–2]**. In this review, we will shed light on nanocellulose, one of the renewable materials with many properties that make it one of the most critical materials used in many fields and their sources. We will discuss some types of nanocellulose and finally present some applications that depend on nanocellulose. Cellulose is characterized by many unique properties, such as its ease of availability, environmental friendliness, and renewability, being a fully recyclable and biologically compatible material with a large surface area, being a nontoxic material, having a hydrophilic nature, chirality, good mechanical properties, and a wide chemical variability. In addition, cellulose can increase nanoparticle stability and manage its development while retaining its unique morphology **[3–4]**. Moreover, there is much potential for using agricultural wastes as cellulosic sources **[5]**. Cellulose is the most resistant to the breakdown of all the other plant-based carbohydrates **[6]**. This feature allows biodegradability after disposal, benefiting many consumers' products' robustness.

2. Surface chemistry

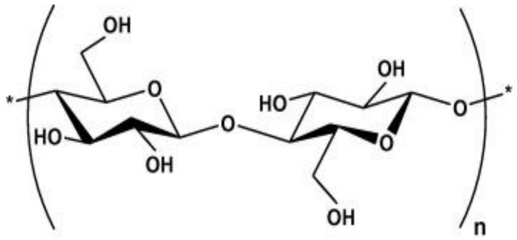

Fig. 1: Cellulose structure

Regarding structure, cellulose is a homo-polysaccharide with units of "(1, 4-anhydro-D-glucopyranose)" with a significant molecular weight **Fig.1**. They form a chair structure with consecutive residues of glucose rotating 180° along the molecular axes and the hydroxyl group laying within an equatorial place rather than within the structure's plane. The critical physical characteristics of this highly cohesive material are determined by the formation of semicrystalline and fibrillar packing, it does not dissolve in water and is resistant to a large number of the organic solvents present in the plant cell walls, which mainly depend on the power of hydroxyl groups to establish hydrogen bonding networks, which are densely organized in the crystalline portions of cellulose fibers **[7–9]**. Different cellulose allomorphs emerge from the broad orientation of cellulose's hydrogen bonding networks and glucose molecules **[8]**. Cellulose is the primary sustainable resource for creating essential chemicals and materials based on carbon, textiles, sheets, and other items due to its availability of monomers of glucose, hydroxyl groups, and carbon **[9–10]**.

3. Cellulose types

The lignocellulosic biomass source and the manner of processing influence the variety of cellulose allomorphs. Cellulose allomorphs generally fall into four categories: Type I, is the generic shape of the original cellulose packed in the parallel hydrogen-bond network. Using a solvent for dissolving or swelling in an alkaline or acidic solution, this type is chemically regenerated to produce cellulose type II. After these chemical regenerations, the ant parallel-packing hydrogen-bond network configurations make up type II cellulose. To have cellulose type III, cellulose I or II can be treated using an ammonia solution. Cellulose IV can be created by heating up to 260 °C cellulose III with glycerol **[9]**.

4. Sources of cellulose

The origin of lignocellulosic biomass wood and plants are natural sources of cellulose because they are made up of microfibril-reinforced semicrystalline cellulose amorphous matrixes consisting of waxes, hemicellulose, extracts, lignin, and a few other components. The different types of cellulose allomorphs depend on how the materials are treated. Hemicellulose comprises various cyclic saccharides, like glucose, mannose, and xylose. It results in a highly branching and random structure. **[11]**. Most lignocellulosic biomass comprises cellulose at a concentration of 35–50% **[12]**. Wood contains 40–50 percent cellulose, of which about half is nanocrystalline and the other half is amorphous **[13]**. Plant fibers that are not wood, like cotton, jute, hemp, ramie, and flax, are an additional cellulose source with much promise for cellulose compounds. Various plants contain high amounts of cellulose, such as bio-residue from industry and agricultural waste. Moreover, cellulose can also come from non-plant sources. For example, tunicates, microorganisms, algae, and some bacteria can create cellulose. The quantity of glucose units influences many features of cellulose in a single polymer molecule, as well as the length of the chain or polymerization degree. The fundamental structural constituent of cellulose is the cellulose primary fiber, which is created throughout the biosynthesis process **[13–14]**. Furthermore, because it is more readily available and less expensive than food crops, cellulose, contained in almost all the lignocellulosic biomass generated by forest remains, agricultural waste, and crops used for energy, offers an excellent alternative as a sustainable resource for producing new materials **[15]**.

5. Nanocellulose

Nanocellulose is defined as the crystalline or cellulosic fiber with one dimension at least in the range of (1–100 nm) and ranging (3–50 nm) in width, and it consequently it has large ratios of length-to-width **[3, 8, 16]**. The preparation circumstances and cellulose resource affect their morphology **[17]**. Various materials are employed to produce them, including wood, cotton, algae, bamboo, spruce bark, tunicates, and more **[18].** High thermal properties with transparency and lightweight **[19]**, large specific surface area **[20]**, large aspect ratio, sizeable crystalline order and chirality, exceptional mechanical strength, and tunable surface chemistry **[8, 21]** are all characteristics of nanocellulose-based nanocomposite materials. Furthermore, their renewability, recyclability, and non-toxicity make them widely available industrially **[22]**.

6. Nanocellulose types

Numerous varieties of nanoscale cellulose may be produced by separating cellulose fibers based on the sources, level of crystallinity, method of extraction, and production process. Bacterial nanocellulose (BNC), cellulose nanocrystal (CNC), and cellulose nanofibrillated (CNF) are the three kinds of nanocellulose. Because of the various sources and extraction techniques, all varieties have comparable chemical properties but vary in particle size, characteristics, morphology, and crystallinity **[8, 9]**.

6.1. Cellulose Nanofiber (CNF)

Nanofibrillated cellulose (CNF) is mechanically treated cellulose to create a braiding network structure. It is composed of flexible and longer fibers having a low crystalline index of 88%, dimensions of length >10,000 nm, and width of 20–100 nm **[3, 8, 16, 23].** There are many sources of cellulose from which nanofibrillated cellulose can be extracted, like wood-based pulps involving bleached Kraft and bleached sulfite pulp, non-wood, crops and their byproducts such as wheat straw, soy hulls, sugar beet pulp, ramie, sisal, palm trees, cotton, carrots, banana rachis, potato tuber cells, bagasse, maize, lemon, flax fibers, rutabaga, hemp fibers, and pea hull fibers **[24–25]**. After mechanical pretreatment of highly pure pulp using enzymatic or chemical-mechanical methods, CNF is formed. This is when forces peel off the fibers and break the interfibrillar connections between the cellulose molecules. Plant raw materials are often purified and fibrillated as part of production methods. The process of purifying plant raw materials involves removing non-cellulose materials like lignin, pectin, and hemicellulose, which are components of cell walls. Although hemicellulose does not considerably inhibit the fibrillation process, the high amount of remaining lignin does **[26].** Highly shear mechanical techniques, such as high-pressure homogenization, milling, grinding, or refining cryo crushing, high-intensity ultrasonic treatment, microfluidization, and aqueous counter collision, are often simple ways to prepare it **[27]**.

6.2. Cellulose Nanocrystal CNC

CNCs are typically cylindrical, elongated, rigid, rod-like (or needle-like) nanoparticles that result from hydrolysis. Their dimensions are 100–6000 nm long and 4–70 nm wide, with a crystalline index of about 54–88% **[3, 23]**. Acid hydrolysis usually extracts cellulose nanocrystals (CNCs) from cellulose fibrils **[28]**. CNC preparation depends on the kind of strong acid and its concentration, reaction duration, and temperature **[9, 29]**. The crystalline sections are preserved, while the amorphous parts are eliminated after acid hydrolysis **[8]**. In the beginning stages of hydrolysis, the acid flows into the cellulose fiber's non-crystalline sections and breaks down the glycosidic linkages. Following these, the polymer's more accessible glycosidic linkages undergo hydrolysis, ultimately occurring at the nanocrystals' surface and the reducing end group. Hydrolyzing the glycosidic linkages by acid is more complicated if the process is slower **[30]**. Following the reaction, the suspension is diluted using distilled water and centrifuged before dialyzing to eliminate the remaining free acidic molecules **[29, 31]**. Depending on the acid employed, hydrolysis of the nanocrystal's surface and the reducing end groups cause the crystals to become charged. The composition and features of the nanocrystals generated by the different cellulose sources vary, as does the aspect ratio between the sources. There are several sources of cellulose hydrolyzed to produce nanocrystal cellulose, including sugar beet **[32],** banana fibers **[33],** softwood pulp **[34]**, hardwood pulp **[30, 35]**, cotton **[34, 36]**, microcrystalline cellulose (MCC) **[37–38]**, sisal **[39]**, tunicin **[2, 34, 40]**, yellow pea **[41]**, wheat straw **[42]**, rice straw **[36, 42],** bacterial cellulose **[34, 43],** potato pulp **[44]**, algae **[37]**, chitin **[45]**, and waxy maize **[46]**.

6.3. Bacterial Nanocellulose (BNC)

Bacterial nanocellulose is another kind of nanocellulose with a comparable chemical constitution to the other two types. Unlike CNC and CNF preparation, BC biosynthesis builds from the atomic scale (Å) to the nanoscale (nm). Gluconacetobacter xylinus forms the glucose chains in the bacterial body for some days to two weeks (the bottom-up method), then extrudes them via tiny holes onto the cell membrane during BC biosynthesis. Microfibril is generated by the combination of glucose chains and assembled as twisting ribbons with typical diameters of 20–100 nm wide and micrometer-longs and have a significant surface area. These twisting ribbons create different web-shaped network structures with cellulose fibers. Bacterial nanocellulose is continually produced in its purest form, with no extra process required to eliminate impurities or pollutants such as hemicelluloses, lignin, and pectin **[3, 19, 23, 47–48]**. Unique characteristics of BNC include polymerization with a high degree of up to 8,000, an incredibly pure and refined fiber network structure, strong mechanical qualities, biocompatibility, and capacity for holding water **[49]**. A few drawbacks of BNC include its expensive nature, the limited supply of bacterial cellulose, the ineffective method of producing it, and its low yield, making it challenging to make BNC economically attractive **[50].** Bacterial nanocellulose has significant uses in medicine and surgery applications, such as making bandages for burns or wounds or replacing medical elements like blood vessels. The food sector and the paper and packaging industries are other industries that use BNC **[51]**.

7. Nanocellulose sources

While it is stated that the source of cellulose does not affect the final characteristics of CNF **[52]**, which is likely process-specific and correct only in some instances **[53]**. However, because CNC characteristics vary according to the source, the best cellulosic raw materials and extraction methods should be determined according to the intended ultimate CNC attribute and application **[54]**.

7.1. Algae

Using green algae, or Cladophora algae, as it is scientifically known, to produce nanocellulose is attractive because it can boost cellulose production considerably and cheaply. Additionally, it can assist in addressing water pollution issues in coastal regions because it absorbs carbon dioxide more efficiently than bacteria can, thereby reducing greenhouse gas emissions. Compared to cellulose obtained by traditional land plants, most Cladophorales algae are highly crystalline, suggesting increased cellulose inertness and limiting their ability to undergo chemical treatments **[55]**.

7.2. Bacteria

BC can be generated from a few common species of bacteria, like Gluconacetobacter medellinensis and Acetobacter xylinum (now known as Gluconacetobacter xylinus or Komagataeibacter medellinensis). Like cellulose derived from algae, BC is highly pure since it has no additional polymers or functional groups compared to the alcoholic group **[47, 56]**. Cellulose manufacture in the standard BC method can require as much as two weeks **[57]**. Furthermore, BC-produced nanocellulose has a higher crystallinity than nanocellulose derived from plants **[58]**.

7.3. Plants

Plant cellulose fibers are a more researched and used primary source for nanocellulose synthesis. In most cases, it is preferred to cellulose based on BC and tunicate when applications call for thinner nanofiber **[59]**. Six categories of plant fibers are utilized as sources of cellulose: fibers of bast, core, grass, reed, leaf, seed, and others **[54]**. Wood pulps are the most extensively utilized plant fiber for cellulose fabrication due to their superior physical qualities, flexible and robust networks, and superior cellulose purity compared to other plant-based sources **[60]**.

7.4. Tunicates

Another source of nanocellulose is tunicates, which are marine or sea invertebrate species. For example, the utilization of sea squirts has been discovered in several investigations as a modern substitute for the manufacturing of nanocellulose. Cellulose is mainly composed of the CIβ allomorph type crystalline cellulose and is typically generated on the exterior tissue of tunicates **[47]**. Researchers have employed a variety of sea squirt species, including Halocynthia roretzi **[61]**, Halocynthia papillosa **[62]**, and Metandroxarpa uedai **[63]**, to generate CMF. Tunicate nanocellulose has been used in several attempts to remediate environmental issues.

8. Applications

Nanocellulose is a tunable material that finds extensive use in a broad range of industries, such as construction, textiles, clothing, food, paper making, energy production, and products such as tiles, furniture, optoelectronics, time-temperature integrators, freshness indicators, gas and leakage detectors, bioprinting, and environmental remediation. Nanocellulose is currently being adapted and used in biosensing devices in many fields, including forensic analysis, environmental monitoring, physical/mechanical sensing, clinical/medical diagnostics, labeling and bioimaging applications, detectors to monitor food, signal processors for biochemical pathways, wound dressing, cosmetics, regenerative medicine, tissue engineering, and more **[54, 64–66].** In this review, some of these applications will be highlighted.

8.1 Purification of water

Because of its increased surface area, crystalline structure, and abundance of functional groups, nanocellulose is an effective natural biomaterial adsorbent for treating wastewater and freshwater. It has a propensity for adsorbing organic contaminants and heavy metal ions. The molecular reaction of opposite charges facilitates the aggregation of particles in wastewater treatments; modifying nanocellulose to create such cationic equivalents is particularly helpful for removing anionic particles **[2]**. Many different types of hazardous pollutants have already been removed using nanocellulose as an adsorbent, which has a high adsorption capacity, is environmentally acceptable, and is inexpensive **[67]**. **Putro et al.** discussed recent studies on applying nanocellulose-based adsorbents for dyes, heavy metals, and organic chemicals. Additionally, he thoroughly explained the adsorption processes of harmful contaminants onto nanocellulose and its modified forms using equilibrium and kinetic investigations **[66]**. For water purification operations, **Cruz-Tato et al.** used platinum and silver nanoparticles with nanocellulose (NC)-based composites to create a thin film composite membrane as a support layer **[68]**. **Karim et al.** created multi-layered nanocellulose membranes by vacuum-filtering cellulose nanofiber solutions and dipping them in cellulose nanocrystals with carboxyl or sulfate groups on the surface. The highest strength of tensile (95 MPa) was shown by cellulose nanofiber covered with cellulose nanocrystals with carboxyl groups on the surface. The membranes demonstrated exceptional ability (close to 100%) to eliminate Ag^{+}, Fe^{3+}, Fe^{2+}, and Cu^{2+} ions from mirror manufacturing effluents. The potential mechanism of ion elimination was surface adsorption, followed by micro-precipitation **[65]**.

8.2. Heavy metal sensing

Dong et al. demonstrated that sulfonated cellulose can remove Pb^{2+}, Cu^{2+}, and Fe^{3+} with high selectivity and efficiency, which is compatible with the adsorbent's affinity **[69]**. **Taleb et al.** created a high-performance arsenic adsorbent based on magnetite by precipitating magnetite on an amino-terminal branching organic construction, L, connected by maleic acid residues on the nanocellulose surface. It demonstrated that the surface of nanocellulose has more adsorption sites when amino groups are available for iron coordination **[70]**. **Hokkanen et al.** evaluated the elimination of chromium ions from aqueous solutions by a synthetic composite of hydroxyapatite microfibrillated cellulose **[71]**. **Pourreza et al.** revealed a new method for creating a bionanocomposite plasmonic sensor based on embedded silver nanoparticles into bacterial cellulose nanopaper. The generated sensor was successfully applied as a novel optical probe to detect 2-mercaptobenzothiazole and the cyanide ion in a water sample **[72]**. **Suopajärv et al.** used wheat straw pulp refined cellulose to create a biosorbent to eliminate Pb (II) in an aqueous solution after sulfonation and nanofibrillation pretreatments **[73]**. **Song et al.** created a fluorescent sensor by covalently bonding 1,8-naphthalimide dye and nanocrystal cellulose. The fluorescent nanocrystal cellulose has strikingly increased emission intensity and a selective and sensitive response to Pb (II) **[74]**. **Milindanuth and Pisitsak** synthesized a new "Rhodamine B" derivative and bacterial cellulose as a selective colorimetric sensor for Cu^{2+}. A noticeable shift was observed from colorless to pink when using it to detect Cu (II) ions in water **[75]**. **Mautner et al.** developed a nanofiber cellulose composite filter generated from flax and agave fibers with extremely high permeances due to their high porosity. Continuous filtration allows these filters to absorb large quantities of Cu (II) ions **[76]**. To remove Sr^{2+} for low-level radioactive wastewater treatment, **Cheng et al.** modified the membrane of bacterial cellulose and ethylenediaminetetraacetic acid (EDTA), utilizing a crosslinker of (3-aminopropyl) triethoxysilane **[77]**. Hassan et al. fabricated non-oxic biotemplate bacterial cellulose to co-precipitate polygonal magnetite nanoparticles with 6–14 nm sizes using their newly discovered co-precipitation method. Then, they used it in the elimination of antimony (Sb (III)) from aqueous solutions **[78]**. **Abbasi-Moayed et al.** demonstrated that employing bacterial cellulose nanopapers as a substrate for the immobilization of carbon dots-rhodamine nanohybrids made it able to quickly optically discriminate heavy metal ions (Cu (II), Cd (II), Pb (II), Fe (III), and Hg (II)). Each heavy metal showed a fingerprint color within a concentration range of up to 100 M based on the photoluminescent feature of the nanohybrid, which was recorded using a smartphone following UV irradiation. This device was known as an "artificial tongue" and may be used to screen fish water **[79]** quickly. **Mohammed et al.** described synthesizing using a new system: gold nanoclusters loaded with cellulose nanocrystal-alginate hydrogel beads and protected with bovine serum albumin. This system is a luminous and atomically accurate cluster-cellulose nanocrystal composite. The dynamic of fluorescence quenching was monitored when Hg^{2+} ion binding produced quenching in the sensor's photoluminescence proportional to an increase in ion concentration. It can detect and remove some heavy metal ions concurrently, specifically mercury ions Hg^{2+}, at low concentrations in contaminated water **[80].**

8.3. Hazardous dyes and antibiotics sensing

The carboxylation process may enhance nanocellulose adsorption ability for the elimination of toxic metal ions from wastewater and several cationic dyes from aqueous solutions, including crystal violet, basic fuchsin, methylene blue, and malachite green, by forming a bidentate structure between the adsorbent's carboxy groups and the dye **[81]**. Additionally, removing anionic dyes is typically accomplished via cationic functionality, such as nanocellulose functionalized with an amine. According to **Zhu et al.,** cationic hyperbranched poly ethylenimine functionalized cellulose had a high ability to absorb Basic yellow (1860 mg/g) and Congo red (2100 mg/g) **[82]**. For water purification processes, **Karim et al.** created fully biobased composite membranes by compacting cellulose nanocrystals in a chitosan matrix after freeze-drying. The membranes effectively removed 98%, 84%, and 70% of positively charged dyes such as Methyl Violet 2B, Victoria Blue 2B, and Rhodamine 6G after 24 hours of contact **[83]**. By reacting manufactured nanohybrid Fe_3O_4-cellulose, 1-methylimidazole, and epichlorohydrin, **Beyki et al.** created a core-shell-structured magnetic nanocellulose based ionic liquid that was used as a green adsorbent for effective Congo red dye biosorption **[84]**. **Kousar et al.** used the in-situ hydrothermal process to synthesize cellulose-supported bismuth oxide nanocomposites extracted from cotton linters using sulfuric acid hydrolysis for enhanced methylene blue photodegradation for water remediation **[85]**. **Mohammed**

et al. investigated the adsorption behavior of methylene blue by beads of cellulose nanocrystal-alginate hydrogel in a column with a fixed bed by altering the starting dye concentrations, flow rates, and bed depths **[86]**. **Rohani et al.** used a green and efficient solid acid such as sodium 30-tungstopentaphosphate to extract cellulose from rice husk and create hybrid Preyssler heteropolyacid-cellulose acetate nanofibers. Methyl orange, a widely found environmental pollutant azo dye, was efficiently photodegraded utilizing electrospun nanofibers **[87]**. Tetra-amino cobalt phthalocyanine (CoPc) was adsorbed on bacterial cellulose (BC) and synthesized as a series of functional nanocomposites (CoPc@s-BC) by **Teng et al.** for the decolorization of dye wastewater **[88]**. **Zhang et al.** fabricated a multifunctional porous membrane from cellulose nanofiber (CNF) biomaterials with gold nanorods. It has been demonstrated to detect rhodamine 6G dye down to picomolar concentration **[89]**. **Putro et al.** prepared nanocrystalline cellulose from wasted printing paper using an organic solvent. They employed it as an azo dye adsorbent for hydroxynaphthalol blue and Congo red in aqueous solutions **[90]**.

8.4. Microbial loading sensing packing food

The paper and packaging industries mainly adopt nanocellulose applications to replace artificial polymers generated from petrochemical resources **[91]**. **Trifol et al.** used a matrix of nano clay and polylactic acid with a reinforcing agent like nanocellulose to create a nano-biocomposite film for packaging food. The material's oxygen and water barrier qualities were greatly enhanced**.** The matrix of carboxymethyl guar, agar, or semi-interpenetrating polymer networks of poly (vinyl alcohol)/polyacrylamide can enhance the packing film's mechanical and gas barrier features **[92]**. **Valencia et al.** created a film of low-concentration oil-in-water emulsions for use in packaging systems reinforced by cellulose nanofibril isolated from plant sources via solvent casting. Curcumin's encapsulation in the composite film increases its antibacterial and antioxidant capabilities, preventing the growth of microorganisms found in food, such as Escherichia coli **[93]**.

8.5. Nanocellulose as an optical sensor

Nanocellulose is being customized and used in biosensing technologies, the output of which is intended to present analytical data about several domains, including food safety, environmental monitoring, clinical and medical diagnostics, forensic analysis, labeling, and bioimaging applications **[65]**. Because BC nanopaper has remarkable qualities, including optical transparency, flexibility, porosity, sustainability, and printing capability, it is a suitable contender to be an outstanding platform for creating optical biosensors. **Naghdi et al.** developed a transparent bacterial cellulose nanopaper impregnated with curcumin to visually detect albumin in human serum **[94]**. **Ruiz-Palomero et al.** designed an afluorimetric platform based on graphene's sulfur and nitrogen-codoped quantum dots submerged in nanocellulosic hydrogels to detect the laccase enzyme **[95]**. **Cennamo et al**. produced a Plasmon Resonance Sensor using bacterial cellulose, which can be exploited to realize disposable biosensors **[96]**. **Abbasi-Moayed et al.** produced a ratiometric fluorescent probe that used bacterial nanocellulose as a nano paper-based artificial tongue to identify the heavy metal ions (i.e., Hg (II), Pb (II), Cd (II), Fe (III), and Cu (II)) in the water and fish samples **[79]**. **Pouzesh et al.** fabricated an optical plasmonic chemosensor by combining stable copper nanoparticles into flexible nanocellulose film to detect cyanide ions in water samples **[97]**. Based on the adsorption of silver ions on the nanopaper of bacterial cellulose, **Pourreza et al.** produced a bionanocomposite known as integrated silver nanoparticles in transparent nanopaper. They employed it as a sensitive sensor for the optical sensing of 2-mercaptobenzothiazole and cyanide ions in water samples **[72]**. By integrating curcumin into a transparent nanopaper of bacterial cellulose, **Faham et al.** fabricated an analytical device that functions as a colorimetric detection kit for measuring levels of iron and deferoxamine, an iron-chelating medication, in biological fluids **[98]**. **Faham et al.** created a chemosensor based on curcumin-doped bacterial cellulose nanopaper, and hydrophilic testing areas were formed on the chemosensor by laser-printing hydrophobic walls. Then, they used it to determine zoledronic acid in pharmaceutical samples, saliva, serum, and urine that had been spiked **[99]**. **Tabatabaee et al.** produced a sensor based on a highly photoluminescent carbon dot placed in a bacterial cellulose nanopaper substrate to detect blood bilirubin **[100].** **Zhou et al.** developed nanocomposites of bacterial cellulose and gold nanoparticles as a surface-enhancing Raman scattering substrate using a simple one-step photoinduction approach. While a tetrachloroauric (III) acid solution was present, well-dispersed gold nanoparticles were produced in situ on the BC hydrogel network under xenon light. Then, the hydrogel was dried to create a transparent nanopaper. In forensic investigations and art conservation, nanopaper can be imprinted on yarn or paper **[101]**. Using a one-step esterification process to create a covalent contact between bacterial cellulose (BC) and amino-functionalized graphene (AmG), **Abdali et al.** created a nanocomposite of connected bacterial cellulose-amino graphene/polyaniline (CLBC-AmG/PANI). Following this, in situ chemical polymerization was used to grow the aniline monomer on the surface of CLBC-AmG. Compared to the BC/PANI nanopaper composites, the CLBC-AmG/PANI had a better electrical-resistance response to carbon dioxide (CO_2) at ambient temperature **[102]**.

8.6. Biomedical applications

Nanocellulose offers tunable surface functionalization, excellent mechanical strength, high hydrophilicity, and biocompatibility. It can also easily create hydrogen bond networks **[103–110]**. Therefore, nanocellulose is receiving a deep interest in biological applications, where it can be used as a carrier for the successful delivery of drugs to damaged tissues and other biomedical applications **[111–113]**. Accordingly, nanocellulose-based material is extensively used in biomedical applications like medication delivery, regenerative treatment, and disease diagnostics. **Hakkarainen et al.,** for example, employed nanofibrillated cellulose from bleaching birch pulp for wound treatment. They discovered that it is highly biocompatible with donor sites for skin transplantation. Nanocellulose sauce adheres nicely to wounds and is readily removed once the skin has healed **[114]**. **Dong et al.** proposed a superficial wound dressing approach based on chitosan-dialdehyde cellulose nanocrystal-silver nanoparticles as a straightforward method. It was suitable for wound dressings because it had low cytotoxicity, vigorous antibacterial activity, good mechanical strength, and hydrophobicity **[115]**. Using a stent scaffold, **Rendon et al.** created a biocompatible, robust, and viable hydrogel membrane based on the production of BNC impregnated with magnetic nanoparticles for neuroendovascular applications; minimum cytotoxicity and cell viability were attained **[116].** In addition to the biomedical uses already covered, nanocellulose has tried to be used in some new areas with particular purposes in the medical field, such as soft tissue implants, replacement of blood vessels, haemostatic agents used in surgical procedures, drug delivery into the targeted cells, replacement of nucleus pulposus, repair of skin tissue, antimicrobial and antibacterial nanomaterials, the hemodialysis membranes to cleanse the blood, dental roots canal therapy **[117]**. **Tichi and Razavi** examined how nanocellulose affected cement and walnut shell composites' morphological, mechanical, and physical characteristics.

Compared to cement boards without nanoreinforcement, the results demonstrated that boards containing nanocellulose had improved mechanical qualities, as nanocellulose may fill the composite's pores and provide a homogeneous structure, increasing the boards' strength **[118]**. Bacterial nanocellulose is an appropriate carrier because of its capacity to carry and distribute antimicrobial active chemicals, like zinc oxide nanoparticles (ZnO). BNC-ZnO films were tested on gram-positive and gram-negative bacteria, where they were efficient against E. coli and Listeria monocytogenes and could be used in food packaging **[119]**. Several publications described the creation of NC-ZnO and BNC-ZnO films to produce an effective nanocomposite with antibacterial activity that might be utilized as a replacement for plastics made from petroleum (such as polyethylene with a low density and polypropylene) in the packaging of active food **[120]**. As a substitute for human donor corneal tissue in uses requiring long-term hydrogel stability, **Xeroudaki et al.** developed a bioengineered hydrogel using pig skin collagen. They reinforced the hydrogel using cellulose nanofiber derived from the sea invertebrate Ciona intestinalis, which is then crosslinked twice chemically and photochemically. Dexamethasone is added to the hydrogel to give it a long-term anti-inflammatory effect. Compared to non-reinforced hydrogels, the reinforced double-crosslinked hydrogel retained excellent optical transparency and dramatically enhanced mechanical properties after drug loading **[121]**. **Zhang et al.** used solvent-free/mechanical foaming with a high-speed method to create very light 3D hierarchical frame adsorbent nanocellulose aerogel foam by adding sodium dodecyl sulfate as a promising candidate in environmental control for oil adsorption **[122].**

8.7. Nanocellulose aerogels

At the moment, nanocellulose aerogels offer a very intriguing platform for many functional uses in many domains, such as energy storage, adsorption, separation, thermal insulation, shielding against electromagnetic interference, and medicinal applications. Nanocellulose-based aerogels combine cellulose's outstanding properties with the highly porous nature and specific surface area of traditional aerogels **[123]**. Recent oil and water separation adsorbents research and development has concentrated on polymer materials, such as the third generation of nanocellulose aerogels **[124]**. By wet-spinning hollow fibers and infusing them with an aerogel precursor, **Zhou** and **Hsieh** generated robust, continuous, and extremely porous coaxial fiber with a cellulose nanofibril aerogel core and cellulose-rich sheath for a high-performance thermal insulator **[125]**. Based on nanocellulose aerogels, **Ji et al.** created flexible piezoresistive pressure sensors and used them to detect human motion **[126]**. **Mo et al.** used electrostatic-regulated interface covalent bonding and freeze-drying techniques to create a compressible, recoverable cellulose nanofiber, carboxymethyl cellulose, and branching polyethyleneimine aerogel. The porous aerogel demonstrated superior mechanical compression and metal-chelating groups with high density, which showed rapid and significant kinetic adsorption capacity in the static adsorption of copper ions **[127]**. **Zhang et al.** used extraction of benzyl alcohol, bleaching of sodium chlorite, potassium hydroxide alkaline treatment, and ultrasonic crushing to create nanocellulose aerogels from banana pseudo-stems. Adding konjac glucomannan to a 0.8 wt% nanocellulose solution was followed by freeze-drying to generate a composite aerogel. According to antibacterial and biocompatibility data, the composite aerogel of nanocellulose displayed impressive inhibitory effects on E. coli and S. aureus, good hemolysis, and negligible cytotoxicity. As a result, it can potentially be used in wound treatment **[128]**.

9. Conclusion

Nanocellulose is a substance that has positive effects on the environment. Because of its exceptional chemical and physical properties, biodegradability, unique template structure, nontoxicity, large aspect ratio, renewability, and more, nano-cellulose is considered a substance that has positive effects on the environment. Thus, it has become the most significant nonmaterial generated from natural resources. The first part of this review presented the structure of cellulose and its characteristics at the nanoscale. Subsequently, many forms of nanocellulose and their respective sources were shown. Finally, this review highlighted the impact of nanocellulose applications in many fields, including packaging products, pharmaceuticals, biological medicine, water purification, and commercial products. The effective design approach for creating practical goods from nanocellulose materials that are appropriate for many areas relies on recognizing and fixing current issues. More study on applying nanocellulose for sustainable uses is needed, along with a collaborative effort by experts in two or more fields, such as scientists, professionals, engineers, and designers. There is a bright future for the commercial production of nanocellulose tailored to various end uses in the context of growing worldwide technological advancement, provided that industry and academia work together closely.

10. Author contributions

Authors make equal contributions. All authors read and approved the manuscript before submission.

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12. Conflicts of Interest

The authors declare no conflict of interest.

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الملخص العربي

مراجعة للنانوسليلوز: المصادر والأنواع والتطبيقات

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الملخص العربى:

يعد السليلوز في الهياكل النانوية أهم الموارد الصديقة للبيئة على مستوى العالم وأكثر مصادر البوليمر المتجددة وفرة. يمتلك السليلوز العديد من الخصائص المرغوبة، مما يجعله مصدرًا لا ينضب للمواد الخام. يؤثر نوع الكتلة الحيوية اللجنوسليلوزية وطريقة المعالجة على نطاق أشكال السليلوز. النانوسليلوز هي مادة جديدة تنبع من السليلوز البوليمر الطبيعي الأساسي. حيث أنها تمتلك خصائص ووظائف فريدة مثل الاستدامة، وعدم السمية، والتجديد، ومساحة سطح عالية، وقابلية تعديل جيدة، وميزات سطحية قابلة للضبط، وخصائص بصرية استثنائية. يمكن إنتاج أنواع مختلفة من السليلوز النانوي عن طريق عزل ألياف السليلوز وفقًا لأصلها ودرجة تبلورها وطريقة استخلاصها وعملية الإنتاج. تركز هذه المراجعة على النانو سليلوز وأحدث تطبيقاته. حيث تبدأ بنظرة عامة أساسية على السليلوز وأصوله والأشكال المتعددة للسليلوز النانوي ومصادره. وأخيرًا، تستعرض المراجعة أحدث التطورات في العديد من تطبيقات النانوسليلوز، مثل معالجة المياه، واستشعار المعادن الثقيلة، والمعالجة البيئية، وأجهزة الاستشعار الحيوي في العديد من المجالات، بما في ذلك التشخيص الطبي وتطبيقات التصوير الحيوي.

الكلمات المفتاحية: النانوسليلوز، التطبيقات الطبية الحيوية، بلورات السليلوز النانوية، ألياف السليلوز النانوية، السليلوز النانوي البكتيري.