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Review Article

A Comprehensive Review on Important Preparation and Application of Nanocellulose

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Abstract

Recent years have seen the emergence of nanocellulose (NC), or cellulose in the form of nanostructures, as one of the most significant green materials now accessible. Due to their enticing and extraordinary characteristics, such as their abundance, high aspect ratio, outstanding mechanical capabilities, renewability, and biocompatibility, NC materials have garnered increased interest. This Review paper provides in detail information about the production method of nanocellulose, such as chemical methods, mechanical techniques, and from Feedstock for nanocellulose production. Each section includes a summary of the theme's related field and the most recent work done by the entities mentioned. Currently, on an industrial scale at tonnes per day, nanocellulose can be used in a various application in our daily lives, including tissue engineering, water purification, food packaging, Drug delivery, environmental protection field, electronic sensors, batteries, as well as in paper, polymer, medical, food processing industry, and more.

Keywords: Nanocellulose; Bacterial cellulose; Nanocomposites; Cellulose nanofibrils (CNF); Nanofibrillated cellulose (NFC); Cellulose nanocrystals (CNC)

Introduction

The most prevalent, least priced, and easily accessible carbohydrate polymer in the world is cellulose, which is often obtained from plants or their byproducts. This polymer must undergo an unpleasant chemical process with harsh alkali and acid treatment, which generally branches with hemicellulose and lignin to produce a pure result. Although plants are the primary source of cellulose, other microorganisms can also manufacture it. Brown (1988) was the first to describe bacterial cellulose (BC), identifying it as the formation of an unbranched pellicle with a chemically similar structure to plant cellulose [1]. Wood and plants are cellular hierarchical bio composites created by nature and are essentially semicrystalline cellulose microfibril-reinforced amorphous matrices made of hemicellulose, lignin, waxes, extractive, and trace elements.

Therefore, lignocellulosic fibers are made up of an aggregate of cemented microfibrils. As a result, plant structures span various length scales to give optimum strength with the least amount of material. Demand for goods made from non-petroleum-based, sustainable, and renewable resources is increasing. Earth sea, the most common polymer on the planet, is non-toxic, renewable, and degradable. Plant fibers must undergo chemical processes such as bleaching and alkali extraction to purify the cellulose [2]. It creates the fundamental structural matrix of practically all plants, numerous fungi, and some algae cell walls. According to strains from the genera, Acetobacter, Agrobacterium, Pseudomonas, Rhizobium, and Sarcina-the last of which is the only genus of Gram-positive bacteria in this collection-several bacteria are under conditions to make cellulose [3].

Natural cellulose's Higher plant's morphological and physical structure is complicated and varied, despite its relative chemical simplicity. The tight interaction of cellulose molecules with other polysaccharides and lignin in plant cell walls results in more complex morphologies. Because of their biodegradability, renewability, and low weight in combination with their great strength and stiffness [4]. A glucose polymer, cellulose is produced by bacteria as a secondary metabolite. 1+4p-glucan chains are used to connect the glucose molecules. nanoscale cellulose fiber. manufacturing and their use in composite materials have drawn increasing attention xylinum has the same chemical makeup as that of higher plants and is polymerized into long microfibrils outside the cell wall [5].

Due to its unique structural and mechanical characteristics compared to higher plant cellulose, BC is projected to become an attractive material for use in a variety of fields. The BC fibers are 20-100 nm in diameter and have a high aspect ratio [6]. Cellulosic nanoparticles made from wood have been recognized as having tremendous potential for pulp and paper manufacturing. The term "forest nanotechnology for renewable materials" is frequently used to describe this area of study [7]. The repeating glucose units that make up the cellulose macromolecule produce a startling level of specificity and an astounding range of topologies, reactivities, and functions [8]. Composting the majority of petroleum-based materials takes too long.

It appears pretty likely that materials of the far future-so-called "biomimetic science and engineering"- will mimic natural materials like wood and bone [9]. The most prevalent organic polymer, cellulose, accounts for around 1.5×10^12 tonnes of the annual biomass output and is thought to provide a virtually limitless source of raw materials for the growing market for environmentally and biologically compatible goods [10]. Due to cellulose's insolubility in water and the majority of organic solvents, its hygroscopic nature, and lack of melting, it is still uncommon to employ it in high-value applications [11]. The functionalization and practical application of nanocellulose depend on its surface characteristics and interfacial compatibility. Additionally, some reviews on the surface modification of nanocellulose to increase interfacial compatibility have been published [12].

In various transdisciplinary fields like the pharmaceutical, automotive, food, and other industries, nanotechnology is now widely acknowledged as one of the critical drivers of a new industrial revolution. Nanomaterials have distinct chemical, physical, and biological characteristics and are at least one nanometer, or 100 nm, or smaller, than bulk materials [13]. The large surface area, nanoscale size, unusual shape, special high strength and modulus, renewability, and strong optical qualities of nanocellulose are all advantageous [14]. Based on the methods used for production, nanocellulose may be categorized into three groups: cellulose nanocrystals (CNC), cellulose nanofiber (CNF), and bacterial nanocellulose (BNC) [15]. Their structure, size, and characteristics are largely determined by the preparation techniques. While CNF and CNC preparation is a top-down approach, BNC preparation is a bottom-up one. In the top-down approach, the cellulose fibers from lignocellulosic sources are broken down to a nano size to produce nanocellulose. While in the bottom-up method, bacteria build nanofibers from low molecular weight carbohydrates to create nanocellulose [11, 16].

Cellulosic materials, the most prevalent, renewable, and biodegradable biopolymer on Earth, are the area the red to as nanocellulose (NC), a word used to describe nanoscale phenomena. The largest source of industrial cellulose, the organized arrangement of the fiber components that make up cells, is now wood [4, 17]. The cellulose also has high crystallinity, excellent biocompatibility, low density, and robust strength [18]. It is also cheap and odorless. Depending on the source, cellulose's composition and properties can change [19]. First discovered by Turbak, Herrick, and colleagues, high-pressure homogenization of softwood cellulose fiber slurry might produce a translucent, remarkably uniform gel known as nanofibrillated cellulose (NFC) [20, 21]. This finding was made possible by decades of theoretical and technological advancements.

Production Methods

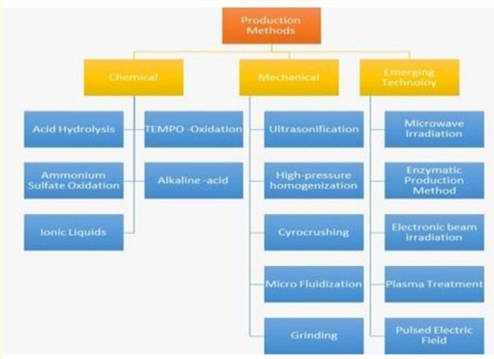

Figure 1: Production Methods for nanocellulose.

Feedstock for nanocellulose production

Lignocellulosic biomass is a heterogeneous substance used as a feedstock to create several different biopolymers. Lignocellulosic biomass is a possible raw source for manufacturing biopolymers that tend to replace conventional plastics. Similarly, the availability and affordability of lignocellulosic materials make it possible to utilize them in manufacturing biopolymers. To design an economically feasible and technically workable nanocellulose isolation technique for commercialization, it is necessary to close vital information gaps in areas such as total biomass use, complete life cycle analysis, and health/safety [22]. Hemi cells, celluloses, and lignin are the three main components of LCB in addition to cellulose [23]. Nanocellulose is derived from various agricultural and industrial wastes [24]. A typical LCB typically contains between 30 and 60, 20 to 40, and 15 to 25 percent of cellulose, hemicellulose, and lignin, respectively [25]. Materials of high surface area, high strength, high thermal coefficient, low toxicity and biodegradability, transparency, and high barrier characteristics, nanocellulose materials have received much attention [26].

Nanocellulose production by using chemical methods

Chemical methods, including Acid hydrolysis, TEMPO oxidation, and Ammonium Sulfate Oxidation, are used to produce nanocellulose.

Nanocellulose Production Using Acid Hydrolysis

The production of nanocellulose using Acid hydrolysis is the simplest and earliest chemical methods for producing nanocellulose with the help of different materials and takes place during the manufacturing of nanocellulose.

The transparent and unstructured portions of cellulose are present in nanofibrillated cellulose (NFC), which is created via mechanical processes. When the acid dissolves, the transparent portion is regained, and the unstructured portion of cellulose is gone [22]. The acid which is mainly used for the process is sulfuric acid (H2SO4) because sulfuric acid can be mainly used for robustly isolating nanocellulose, and also, due to the esterification of hydroxyl groups by using sulphate ions, the NC can be dispersed into a firm, solid system, and the properties of gained nanocellulose are mainly affected by different criteria such as concentration of acid, temperature and time required for it [27].

Different acids such as phosphoric acids and nitric acids were also endorsed, but sulfuric acid has the main advantage of doing esterification process as a hydrolyzing agent, and during the further process, the presence of anion groups prompted the building of a negative electrostatic layer on a particular surface of NC and also for their dispersion in water, but the drawback is that it decreases the thermostability of Nanoparticles and it can be increased or improved by neutralizing by sodium hydroxide [15].

Different studies suggested different results regarding the increase or decrease in the yield by the experiment of acid concentrations. The duration of reaction, temperature, type of acid, and concentration are used to maintain the pattern and size of nanocellulose during the acid hydrolysis process [28]. Since different commercial inorganic acids are used during the process, acid hydrolysis has several drawbacks, including lower thermal stability and a tendency to be environmentally hazardous. Another drawback is that it is expensive to operate and maintain, leading to corrosion of processing equipment [29].

Nanocellulose production using TEMPO -Mediated oxidation

One of the crucial chemical steps for the creation of nanocellulose is temporally mediated oxidation. Nanocellulose is subjected to tempo-mediated oxidation as a means for selective modification. This reaction can lower the energy cost of mechanical defibrillation in the production of CNFs from lignocellulosic feedstocks by weakening the hydrogen bonds between CNFs and facilitating the splintering of cellulose microfibrils because of the mutual electrostatic repulsion. It is primarily used in mild climates to convert primary hydroxyl groups of cellulose into carboxyl derivatives [16].

One-half of the primary hydroxyl groups on the particular portion of cellulose chains are pointing to the central of the transparent field and thus so they are mainly not available for the method of oxidation, and the distinctive attribute of cellulose nanocrystals is that the carboxylic groups which are generated on the surface of nanocrystal should be 1.0 nm separate in the direction of breadth. The cellulose molecule's packing design can only control the rate of oxidation occurring on the surface of native crystalline cellulose [30].

Tempo oxidation is used to characterize cellulose nanofibers derived from empty fruit branches of oil palm. This method was carried out by maintaining the pH at 10 when the different amounts of oxidant were applied at room temperature for two hours, and the process was productive in making the NFC with utilizing surface-modified nanocellulose with the help of various functional groups, long, and cellulose fibrils which are individualized are dispersed in water [31].

Tempo is mainly used to create acid-free CNCs, and it is also claimed that, under the right circumstances, every C6-OH group of ball-milled cellulose can oxidize a sodium salt of cellouronic acids that is water soluble. Microcrystalline cellulose (MCC) and softwood bleached kraft pulp (SBKP) were both utilized in the TEMPO oxidation system to create CNCs, but instead of sodium chlorite, sodium borohydride was used as a reducing agent to post-treat the oxidized cellulose [32].

Ammonium persulfate oxidation

The ammonium persulfate oxidation technique is also one conventional technique used in gaining the product in the form of nanocellulose evaluation for the effects of cellulose nanocrystals by using different fibers like kapok and back. APS oxidation was used for their production, and higher oxidation times resulted in small diameters and lesser CNC [33].

Cellulose nanocrystals (CNC) have been used during the ammonium persulfate oxidation technique, which gives a proxy method for the production of nanocellulose [34]. Rice straw was used for isolating the oxidized nanocellulose, and it was done with the help of the ammonium persulfate method. Different effects on the processes, such as pretreatment with the help of NaOH, and H_2O_2, were studied thoroughly, and the nanocellulose obtained from this method showed the greatest crystallinity [35].

Ammonium persulfate method is mainly used for fabricating the CNCs because of its simple one-step method. It is also non-hazardous and has minimal cost compared to other methods. CNCs are fabricated using different fiber-based cellulose materials like sugarcane, bagasse pulp, and cotton linters. The characteristics of the CNCs prepared with the help of APS oxidation methods are significantly influenced by the oxidation criteria like the APS concentration, oxidation temperature, and oxidation time [36].

Production of nanocellulose by mechanical techniques

Extraction of nanocellulose takes place with the help of various mechanical methods like Ultrasound irradiation, cryo-crushing, high-pressure homogenization, grinding, ball milling, and micro fluidization. The technologies mentioned earlier produce nanocellulose from various lignocellulosic materials. The different methodologies for production are as follows.

Ultrasonication

Nanocellulose extraction takes place with the help of the ultrasound's hydrodynamic forces. Hydrodynamic forces result in the defibrillation of cellulose fibers [22, 37]. This process is called Ultrasonication. In the Ultrasonication process, liquid particles take in ultrasonic energy, which results from microscale gas's expansion, formation, and implosion [22]. This process is normally accomplished in a water pool to control heat transfer. This is done because a large amount of heat is generated. Essential parameters not dependent on other parameters are ultrasonication power, concentration, and processing time [38]. Generally, in the pretreatment stage of Lignocellulosic feedstock ultrasonication method is used. Physical and chemical changes experienced by lignocellulose are cell wall structural disorientation, increase in surface area, and reduce the degree of polymerization of cell wall constituents [39]. Drawbacks of ultrasonic treatment are high energy consumption, environment friendly, and cost-effectiveness. Despite this, ultrasonication treatment is proved to be one of the most highly efficient production technologies for nanocellulose production [22].

High-pressure homogenization (HPH)

High-pressure homogenization (HPH) is mostly used for Carbon Nano Fiber creation (CNF). This method was initially used for the extraction of CNF from the pulp of wood. The cellulosic pulp. The cellulosic pulp is subjected to high pressure and velocity when passed through the tiny nozzle, which eventually results in the nanometer range production of fibers [22, 40]. Using the response surface methodology, parameters like diameter of CNF, pressure, and crystallinity was evaluated. The response surface methodology was used to assess crucial parameters like the number of cycles, yield, pressure, the diameter of CNF, and crystallinity drawn out from kenaf bast. The CNF yield was increased by pressure and homogenization cycles, while the CNF crystallinity was raised by the interrelation between the pressure and homogenization cycles [41].

The HPH was responsible for disrupting the cellulose hydrogen bond network, which resulted in isolating nanocellulose from the eucalyptus pulp. It was observed that the optimal circumstances to process nanocellulose were 50 MPa of homogenization pressure and 10 HPH cycles. The produced nanocellulose was found to have the least average molecular weight, which could have been because of extensional solid flow at the homogenizing valve entrance, and frictional forces experienced by the fluids during HPHinduced mechanical breakdown of long molecules [22, 42]. Some drawbacks of this process are high operating cost, extensive mechanical damage to the crystalline structure of CNF, clogging because of the small orifice plate, high energy requirement and big size distribution. The HPH has many advantages, like being simple to set up, having no solvent requirement and wastewater generation, and producing largescale CNF in the industry [39, 11, 43].

Cyrocrushing

Micro-fibrillated cellulose was prepared from wheat straw and soy hulls with the help of cyrocrushing. The diameter range of the 60% nanofibers obtained by the cyrocrushing method was 30-40 nm. While hemp, flax, rutabaga fibers with chemical treatment and cyrocrushing got diameters of 5-80 nm. Nanofibers obtained from soybean stock with the help of cyrocrushing had diameters of 50-100 nm [4]. After refining, Kraft fibers underwent treatment consisting of immersing water-swollen cellulose in liquid nitrogen and cyrocrushing [44-46].

Nanocellulose was extracted from a raw kapok husk by isolating its cellulose before undergoing mechanical methods like cyrocrushing and ultrasonication. Thus, this experiment showed that as ultrasonication time increases, the sample size becomes smaller and almost invisible. It was also proved that 80 mins of ultrasonication is more thermally stable and has more engineering applications than 20 mins of ultrasonication and frozen 24 and 48 hours of cryocrushing [37]. Dissolving cellulose was used as a raw material further ground in a knife mill and passed a fraction of it through the 20-mesh screen. Then pulp obtained was frozen with liquid nitrogen and was milled again [47].

Micro fluidization

The Empty Palm Fruit Bunch Fibers (EPFBF) were subjected to Sulphur free chemical treatment to produce different cellulose pulps, a by-product of palm oil processing. The pulp was deconstructed into Nano Fibrillated Cellulose (NFC) with the help of micro fluidization. On the other hand, an overpressure device produced nano paper. Morphological and structural features of NFCs were studied with the help of atomic force and a scanning electron microscope. It was also found that it had high tensile strength, lower water absorption, and elastic modules [48]. High-pressure micro fluidization was used to break microcrystalline cellulose and to expose its surface groups and mechanoradicals. This experiment was used to study the structural, morphological, mechanical, and rheological properties and interaction with Hydroxypropyl methylcellulose (HPMC). It was observed that there was an increase in its colloidal stability, lessened particle aggregation, and better dispersion in the film matrix [49]. Scattered cellulose nanocrystal strengthened chitosan-based nanocomposite was developed with the help of the micro fluidization technique.

This study found that there was a 10-15 turn over decrease in the size of aggregates because of the use of micro fluidization. This technique helped to enhance the CNC spread in the chitosan matrix and enhanced its mechanical properties [50]. Kombucha membranes are produced as a secondary product by fermenting tea broth with symbiotic cultures of bacteria and yeast. Thus, cellulose nanofibrils were produced from these kombucha membranes by purification, separation, and mechanical treatment. The mechanical treatment used in this production of nanofibrils was micro fluidization. Results obtained after micro fluidization suggest a crystallinity decrease of about 46%, which also decreased the size of the fibrils. An increased concentration of chemicals used for chemical treatment resulted in increased purification and removal of impurities [51].

Grinding

Using modified commercial grinders, a cellulose sludge is generally moved between static and rotating grindstone, operating at roughly 1500 rpm. With grinding, mechanisms characteristics like cell wall structure comprising of nanofibers and hydrogen bond breakage because of grinding are studied. Nanofibers produced by super grinding technologies have the diameter in the range of around 90 nm. The homogenized cellulosic pulp was ground with approximately ten iterations and produced fibers of diameter 50-100 nm [52, 53]. Also, during the grinding process, the shearing stress needs to be optimum; otherwise, it will degrade the pulp fibers and could affect their characteristics and properties [53, 4]. A cell wall with a constant width of about 15 nm can be achieved by removing lignin and hemicellulose and putting the material in a swollen water state. This process helps to avoid strong hydrogen bond formation between cellulosic bundles [54].

The bagasse kraft pulp was given endoglucanase pretreatment, which consisted of a variation in the range of enzyme dosage before it was sent for the grinding process to obtain Cellulose Nanofibers (CNF's). Structural characteristics, size distribution, energy consumption, etc., were studied for the effect of enzyme dosage on the CNFs. The results revealed that CNFs had good thermal stability, a length of 298-4500 nm, a 9-26 nm diameter, and improved energy efficiency [55]. Pinecones were used to produce Nanocellulose fibers with the help of mechanical grinding and chemical treatment. Thus, the effects of these treatment processes were studied for tensile strength, grinding conditions, and high-strength fibers. After the treatment process, samples were tested, and it was found that they had optimum chemical concentrations and diameters in the range of 5-25 nm. 70% crystalline index and high thermal stability showed that pinecone nanofibers are a good candidate for nanocellulose production [56]. Cellulose Nanofibers were extracted by dissolving Linter into an eco-friendly pretreatment method with an ultrafine grinder. It was found that extracted nanofiber had a diameter of around 30-70 nm, a crystallinity index of approximately 62%, and high thermal stability [57].

Ball milling

The dry pulp of length and height about 5 cm and width around 9 cm was soaked in water which contained a solid content of 10 wt.% overnight at room temperature to form water swollen fibrils. These fibrils were broken apart with the help of a kitchen blender for around 10 mins and were later diluted in 1wt% solution. Then, 25 grams of this mixture was then taken into a 70ml volume of the plastic specimen container. Before the ball milling process zirconia balls were added into the container. The ball milling process mixed swollen fibrils and balls in the container. Various milling conditions were observed during this process to study its effects on fibers

[57]. Ball milling greatly impacts the structural, morphological, thermal stability, etc., properties of the nanocellulose [58]. Microcrystalline cellulose was obtained when cotton Linters were subjected to 200 rpm rotations in ball mills for 4-8 hours with water, toluene, and 1-butanol. Thus, a difference in morphology, polymorphism, crystallinity, the difference in hydrogen bonding of cellulose particles, etc., was observed [59]. A nanocellulose was extracted from sugar cane bagasse with the help of chemical treatment and ball milling. This research observed that nanocellulose obtained from acid hydrolysis with ball milling had higher crystallinity than nanocellulose obtained by ball milling [60]. Nanocellulose obtained from cellulose powder and paper with mild acid hydrolysis and ball milling. Thus, ball-milled cellulose had lower crystallinity and crystal size than mild acid hydrolysis ball-milled cellulose. Nanocellulose produced from mild acid hydrolysis and ball milling had excellent thermal stability and high crystallinity at high temperatures without much interchange in its chemical structure. Thus, it was proved that mild acid hydrolysis and ball milling methods could produce high-quality nanocellulose [61].

Applications of nanocellulose

Application Nanocellulose has received particular interest recently because of its distinctive mechanical properties, low toxicity, biodegradability, and potential versatility for chemical modifications.

Significant research has been conducted on the uses of nanocellulose in different fields like drug delivery, environmental protection, electronic sensors, and batteries.

Figure 2: Applications of nanocellulose.

Tissue Engineering

Cellulose is an important constituent in the cell wall of all plants and is made up of complex polysaccharides. The cellulosic polymers are produced by chemically modifying the Cellulose, which is used for various uses. Cellulose ethers like carboxymethyl cellulose and hydroxyethyl cellulose are used to produce pharmaceuticals, paints, food, personal care, and hygiene. Regenerated Cellulose is used to produce textiles, disposable hygienic products, and home fabrics. It is also used in mining, adhesives, paints, and gas recovery [62]. Also, various studies have shown that Bacterial Cellulose-based bio scaffolds are used for supporting proliferation and cellular adhesions. Bacterial Cellulose is also used as a hydrogel scaffold for culturing the equine-derived bone marrow mesenchymal cells [63]. The cytotoxicity of cellulose nanocrystals was studied against the human brain microvascular endothelial cells, breast and prostate cancer cells, and stem cells, and no cytotoxicity effect was observed. Also, several polymer nanocomposites reinforced with polyurethanes and polylactic acid have shown favorable biocompatible properties with good and revamped cell adhesion and proliferation [64]. Nanocellulose is also used for Cartilage replacement and soft tissue implants because it enhances characteristics of biomedical materials like life span, durability, biocompatibility, and better processability for efficient manufacturing. These materials are biocompatible, provide better chemical stability and mechanical durability, and are non-degradable under physical conditions. All these characteristics make it suitable for blood vessels and articular cartilage tissue engineering. Interconnected porosity is a necessary condition in scaffold applications where chondrocytes are allowed to penetrate and migrate through the biomaterial [65]. Microbial cellulose membrane is used for wound-healing of gravely damaged skin and replacement of small diameter blood vessels. Also, microbial cellulose membrane having a unique nanostructure is used to develop regenerative medicines like guided tissue regeneration (GTR), renewal of dura mater, and periodontal treatments [66]. An important application of nanocellulose is that chitosan-based scaffolds are used for bone tissue engineering. Bone defects that require graft are helpful to heal, but it is a regularly occurring issue and costly problem for health care systems.

Therefore, to overcome this issue, chitosan, a biodegradable and naturally occurring material, is used as a scaffolding matter for bone tissue engineering and regenerative medication. Chitosan supports the fitting and addition of osteoblasts and the generation of mineralized bone matrix. Thus, the addition of suitable polymers and ceramic components helps to enhance structural integrity, bone regeneration, and strength [67]. Bacterial Nano cellulose (BNC) is a favorable biomaterial for producing an artificial blood vessel. However, BNC cannot reach all the required properties of the original blood vessel. So, for this purpose, polyvinyl alcohol (PVA) was introduced in BNC tubes to improve its mechanical properties and water permeability. Thus PVA-BNC would be a suitable choice for vascular grafts [68]. Biocompatible Chitosan Poly Nanocellulose (CPN) composites were produced with the help of the solution casting method. The characterization of bio nanocomposites was done with Thermo gravity analysis (TGA), X-ray diffraction (XRD), Transmission electron microscopy (TEM), and reduced total reflectance-Fourier transform infrared spectroscopy (ATR-FTIR) spectra. TGA showed that the thermal stability of bio nanocomposites decreased when the concentration of nanocellulose improved. Water and oxygen permeability assessments showed that it was possible for CPN to maintain a damp conditions over the wound. They also revealed blood compatibility, enhanced swelling, and antibacterial activity. The outcome of the experiments and research also showed that the CPN 3% composites showed an effective antibacterial characteristic in contrast to the other composites. Thus CPN 3% can be a likely contender as an injury curing matter for biomedical applications [69]. Naturally occurring polymers like fibrinogen, elastin, and collagens comprise most of the body's extracellular matrix (ECM). ECM is responsible for providing mechanical and structural integrity to tissues to help adjust day-to-day cellular activities and injury healing. A perfect tissue engineering scaffold would recreate the structure and task performed by the ECM.

The electrospinning process uses a line-up of natural and synthetic polymers to make the non-woven ECM analog scaffolds of micro-nano diameter fibers. This production approach will help the natural polymers develop tissue engineering scaffolds to achieve excellent outcomes, both in vitro and in vivo, because of enhancing the bioactivity supplied by the material present in the human body. E.g., Silk fibroin-based biomaterials can be used for ligament, bone, or vascular applications [70]. The increasing demand for dressing acute and diabetic wounds has resulted in large-scale research for techniques to develop suitable methods to heal the wounds. An environment-friendly in situ 3-step approach was used to grow nanocomposite dressings by impregnating silver nanoparticles onto a matrix of cellulose nanocrystals isolated from Syzygium cumini leaves. This approach resulted in tissue repair, decrease in inflammation, increase in angiogenesis, and deposition of collagen that leads to aesthetically sound skin formation in less time. The research outcome has proved the potential for the development of anti-microbial, cytocompatibility, and nanoporous nanocrystals by improving the anti-microbial agent concentration to create better effective wound management [71].

Water Purification

Nanocellulose has been picked out as the one to improve the efficiency of water purification and prevention as well as reduce costs. In water purification and treatment, nanocellulose has been used either as a sorbent or as a layer for removing impurity. It offers high-capacity retention, high specific surface area, aspect ratio, and environment inertness, and for all these reasons, it is chosen for water purification and treatment. Active sites present on the nanocellulose increase the tying up capability of pollutants on its surface. Nanocellulose affects the surface assimilation behavior of heavy metal ions, dyes, microbes, and organic molecules [72]. Nanocellulose-based composites with add-on materials like Platinum and silver have formed thin film composite membranes, which are further used for water purification. These membranes were evaluated for performance in forwarding feed mode with feed solutions like urea, pure nano water, and wastewater samples. These membranes showed enhanced selectivity, high water flux, and solute rejection rate [73]. Nanocellulose-based adsorbents are used for wastewater purification and are used as an alternative to energy-consuming and costly technologies based on activated carbon-based adsorption. Crystalline nature, increased surface area, and others have enhanced the adsorption removal efficiency of nanocellulose-based adsorbents. Nanocellulose has been used as an adsorbent for removing residual antibiotics, commonly found in aquaculture and industrial discharge [74]. Electrospun nanofibrous filters have shown increased capability rates in applications like air and water cleaning process in contrast to conventional methods. According to the newest research, nanocellulose filters are found to have removed harmful viruses from water, and the efficiency of these filters is found to have matched with some of the finest industrial filters. Biofouling and increasing membranes life span are the two biggest challenges wastewater treatment which can be overcome by using AgNPs to the strain membrane layer, inhibiting the biofilm's development and increasing the membrane's life span [75]. Scanning electron microscopy (SEM) research have disclosed that nanocellulose has a membrane porous structure in the microfiltration range (5.0-6.1μm) that provides a high-water permeability (900-4000 Lhm2).

Nanocellulose was found to have high metal ion removal rate against metals like Ag+, Cu2+, Fe2+, and Fe+. The metal ions were removed because of the interactivity between positively charged metal ions and negatively charged nanocellulose [76]. Biobased composite membranes were combined with nanocellulose crystals in a chitosan matrix with freeze drying and compacting. It was found that following the contact time of around 24 hours, and these membranes successfully removed the positively charged dyes like Methyl Violet 2B, Victoria Blue 2B, and Rhodamine 6G [77]. A Thin Film nanocomposite layer was made by implanting Cellulose Nanocrystals (CNCs) on an active polyamide layer. The membrane was made in situ by interfacial polymerization of m-phenylenediamine (MDP) and trimethyl chloride (TMC), accommodating various quantities of CNCs. TFNs were tested for seawater desalination and found that by doubling the flux, the salt rejection rate remained the same, i.e., 97.8%. The advantages of TFN membranes are that they are inexpensive, abundantly available, and environmentally friendly [78].

A new supramolecular polysaccharide composite from cellulose, chitosan, and benzo-15-crown5 was developed with the help of Butyl methylimidazolium chloride [BMIm+Cl−], which is an ionic liquid and sole solvent utilized for dissolution and made of composite. This composite had superior mechanical strength and fantastic adsorption ability for heavy metals and organic pollutants. Cellulose chitosan was found to have good adsorption capability for Cd2+ and Zn2+, but adding benzo-15-crown5 enhanced its adsorption capability and can adsorb more amounts of metal ions than before. Pollutants soaked up on the composites considerably desorb which allows the core components, like cellulose, chitosan to be recovered with the same adsorption capabilities [79]. The addition of phosphate groups on nanocellulose has increased the metal sorption capacity and velocity. The high elimination rate of metal ions was because of the high surface area, nature, and density of the functional group on the surface of nanocellulose. This nanocellulose was found to remove 99% of metal ions like Cu2+ and Fe3+ from the effluents coming from the mirror-making industry. Thus, studies and research have shown that adding phosphate groups to nanocellulose has increased the efficiency of removing multiple metal ions simultaneously from the effluents [80]. Another study has revealed that Graphene oxide (GO) nanosheets, including hydroxyl and carboxyl groups, were inserted on the layer of cellulose hydrogel in order to retain gel structure and nanoporous property. This resulted in excellent strength with good adsorption rates. GO / cellulose hydrogel showed high effective recreation, metal ion retrieval, and high surface assimilation capacity for Zn2+, Fe3+, and Pb2+ [81]. According to the newest research, removing heavy metal ions in aqueous solutions has been possible with the help of nanocellulose, which contains cationic and anionic surface groups. While ionic and non-ionic surface groups appeared to remove organic pollutants like dyes, fertilizer, oils, and pesticides. Electrospinning, vacuum filtration, and coating techniques are nowadays utilized to manufacture nanocellulose base layers [82].

Coconut husk consisting of coconut pith and coconut fibers is used to remove metal ions like elemental mercury and is found to have excellent adsorption rates. Also, the coconut husk is cheap and easily available throughout the year. Thus, implementing coconut husk for water purification can reduce cost and energy requirements [83].

Food Packaging

A method was devised in which cellulose nanocrystals (CNCs) were surfactant altered and the addition of silver nanoparticles in polylactic acid (PLA) matrix utilizing melt extrusion along with film generation procedure was used for the production nanocomposite films. It was found that these films had high tensile young modulus, increased crystallinity, and also increased antimicrobial activity next to Staphylococcus aureus and Escherichia coli cells. This indicates, these nanocomposites can be used for food packaging and its various applications that require a constant antimicrobial consequence [84]. Polysaccharide-lipid or protein-lipid amalgamation has formed emulsion films that have enhanced the tensile strength and thermal stability barrier effects. The inclusion of lipids to hydrophilic films resulting in formulations is captivating research that can be used for food packaging applications where food requires low water vapor permeability [85]. Chitosan-xylan/cellulose nano whiskers nanocomposite films were conveniently produced by introducing cellulose nanowhiskers into the chitosan-xylan matrix. This nanocomposite had fantastic antioxidant and antimicrobial activity. It was also found that these composites had good tensile strength, and elongation at the break was considerably enhanced. The stability of nanocomposite films was increased in aqueous solutions as their swelling percentage decreased. Thus, good antimicrobial, antioxidant, and mechanical property makes this nanocellulose composite a suitable candidate for food packaging and concerning health areas [86].

A ginger fiber produced thin nanocellulose film with ultrasonication and chemicals. This thin layer transferred 83.3% of the light and exhibited antimicrobial activity. Ginger fiber produced thin nanocellulose layer had excellent high thermal stability, maximum temperature of decomposition (353°C), and lower moisture resistance. Thus, ginger fiber could be used as a material for food packaging as it is abundantly available and cheap [87]. A ternary bio-composite was prepared from chitosan (CS), βcyclodextrin citrate (β-CDcit), and oxidized nanocellulose (ONC) biopolymers. To increase the antimicrobial and antioxidant characteristics of the membrane, the clove essential oil (CEO) was incorporated. By using the different concentrations of ONC, different results could be obtained. It could be seen from the results that the CEO inclusion complex of CS bio-composite the along with β-CDcit with or without ONCs showed higher activity to gram-negative bacteria as compared to gram-positive bacteria. Similar results could be seen in better anti-fungus activity in contrast to yeast [88]. The silver nanoparticles (AgNPs) based antimicrobial food packaging has been used because of their high-temperature stability, extensive range of the antimicrobial spectrum, and processability. However, the toxicity of AgNPs has been a topic of debate as it was found that silver easily let go of its nanocomposites to ethanol at 10%, which exceeded the specific migration limits set by rules and regulations [89].

According to the latest study, paperboard packaging is of great interest because it recyclable and biodegradable. The research was carried out for the effects of (2,2,6,6-Tetramethylpiperidin-1-yl) oxyl, called TEMPO, which was utilized to oxidize the cellulose nanofibers and polypyrrole covering on paperboard. It was observed that mechanical properties and reduced gas permeabilities were significantly enhanced. Thus, studies have revealed that this improved paperboard can be used for food packaging as it reduces waste generated by conventional plastics [90]. The cellulose derivatives like cellulose acetate, ethyl cellulose, methylcellulose, and carboxymethyl cellulose. They are utilized for the devising of cellulosebased films. Cellulose acetate is known for rigid wrapping film, while its triacetate is famous for its moisture barrier as well as low gas attributes. Also, it was found that the cellulose-based composites and nanocomposites have increased the shelf life, heat seal range, gas barrier properties and find its uses for storage of fresh fruits and dried fruits, meats, vegetables, dairy products, confectionaries, tea etc [91]. Polylactic acid (PLA)-Cellulose nanocrystals (CNCs) nanocomposite film and PLA-CNC oregano essential oil nanocomposite layer was utilized for the storage and packing of cooked ham and mixed vegetables. It was found that Listeria monocytogenes growth was slowed down to 14 days [92, 93].

Drug Delivery

Application Nanocellulose provided limitless opportunities for a variety of industrial applications, including drug delivery and tissue engineering in biomedicine. This paper examines recent advances in the use of controlled drug delivery. To improve product safety and patient health compliance, drug delivery technologies alter drug profiles, absorption, distribution, and elimination. This study aimed to enhance the requirements above by synthesizing and testing a drug delivery medium made of calcium carbonate and nanocellulose. 3d-printed nanocellulose and $CaCO_3$ profiles were created using the correct layer-by-layer films. The 3-D printed double laminated

$CaCO_3$-nanocellulose released 5-fluorouracil as a single effective composition over time [94]. CNCs were also identified using fluorophores to detect different analytes in drug delivery.

Environmental protection field

Due to its biodegradability, ease of availability and related issues properties as an example substantial surface-to-volume ratio and superior mechanical properties structures, nanocellulose has attracted the interest of numerous scientists as a source of materials with nanometer dimensions. The potential applications of nanocellulose, particularly in environmental protection [95].

Electronic Sensors

NC has been combined with various materials to create a wide range of sensors for detecting analytes such as gas, chemicals, enzymes, ions, and glucose. Many of the sensor technologies discussed in this review have high sensitivity, selectivity, and low cost, which is critical for commercialization [96]. Significantly, much research on the fabrication of functional electrode materials in various electrochemical methods is advancing the widespread use of electrochemical devices [97]. The simple and safe electron transfer between CNTs (Carbon Nanotubes) and a variety of protein redox cofactors, in conjunction with conductive polymers and metallic or semiconductor nanoparticles, allows for the implementation of vulnerable electrochemical biosensing protocols [98].

CNT-based electrochemical transducers significantly enhance the performance of amperometry enzymatic sensors, biosensors, and biological molecules sensing devices. Hydrogen peroxide and NADH have significantly increased electrochemical reactivity at CNT-modified electrodes, making these nanomaterials appealing for various oxidase- and dehydrogenase-based amperometry biosensors [99].

Batteries

Nanocellulose-based elements have recently been widely used to create high-performance Sulphur electrodes. CNCs are frequently made using sulfuric acid hydrolysis, followed by mechanical exfoliation. This strategy is not only inefficient and dangerous, but it also falls short of controlling CNCs dimensions [100].

Graphene-cellulose composites were developed and studied as potential donor composites for Sulphur impregnation and Li-S battery applications. They show that a low surface area graphene/cellulose composite can be designed to achieve high electrochemical performance and good cyclability. Composites of graphene and cellulose have been developed and tested as a matrix material for Sulphur impregnation in Li-S batteries. The outcomes show that a simple host matrix can successfully be used for Sulphur impregnation [101].

Carbon nanofibers (CNFs) were also explored as porous additives22 to carbon/sulfur composite materials or, more importantly [102]. The use of nanocellulose-based separators in lithium-metal, lithium-sulfur, and sodium-ion batteries Because of Li metal has been regarded as the most promising harmful electrode material for extremely electricity batteries due to its high theoretical specific capacity and low standard potential [103].

Nanocellulose in the paper industry

One significant use for nanocellulose is in the paper industry, where it is primarily employed as a nanofiller and nanocoating. After using inorganic nanofillers, nanocellulose is primarily employed to recover its energy-giving capabilities. The main benefit of using nanocellulose is that it aids in resolving issues with various inorganic fillers. Because nanocellulose uses much energy, raising the cost of production, various technologies can be used to reduce this cost. Utilizing cellulose nanofiber will increase the utilization of various pulp types, including hardwood and softwood. The cost of drying cellulose nanofibers is the critical issue facing the paper industry today [104] There are many challenges, such as environmental, economical in the production of paper and different products related to the paper industry, which has issues in terms of different specifications such as qualities, and specialties related to paper, so one of the critical functionality of nanocellulose is the use of additives in the production of the paper industry and to increase the competitiveness in the paper production and also to make use of nanocellulose fibers and to overcome the different challenges related to it [105]. The critical feature of nanocellulose is that the utilization of cellulose nanofibers the nanocellulose can be made by using a variety of techniques such as chemical and mechanical. It has a crucial role in the making of paper as it increases the critical physical strength of paper, but they have a disadvantage of high cost and are also dangerous to nature, so the production should have a cleaner process [106].

Nanocellulose in the medical industry

The medical sector, which includes public health, pharmaceuticals, hospitals, and many other related domains, is one of the essential industries, and nanocellulose contributes significantly to this industry. In addition to being used for cell interaction, nanocellulose can be used in the field of biomedicine along with other materials such as metals, ceramics, and different composites for healing. 3D printing is also used, much like the process of additive manufacturing, which has been applied in a variety of ways and with various technologies [107].

Cellulose nanocrystals have been employed as a carrier of various drugs, including hydrophobic drugs and many other types of drugs in the pharmaceutical sector, where nanocellulose also plays a crucial part in the development and supply of life-saving medications [108] Hydrogels and nanogels are two different forms of nanocellulose components. While nanogels assist in the delivery of drugs, hydrogels are used in areas such as wound healing, artificial kidney transplantation, contact lenses, and others. Nanogels also play a role in the treatment of cancer, the development of vaccines, problems with tissue engineering, biocatalysts, and other conditions [109].

As Nanocellulose has its natural occurrence on the planet, different features which are optically feasible and its use for modifications of surface chemicals and its functional ability and other many domains are in the research domain, bioelectronics and bioprinting, and proper chemical modifications in the nanocellulose is required to get the properties in the different criteria in the mixed and challenging field of nanomedicine [110].

Applications of nanocellulose tend to play a more vital role in the field of the biomedical sector because it tends to reduce the low toxicity and increase biodegradability, so the use of different types of polymers is made, and due to this, the biocompatibility increases, and the reflection on advancements in the design and fabrication of advanced nanocellulose-based biomaterials which are used for different biomedical applications that the use of nanocellulose has an essential use in the field of the biomedical sector [65].

Adsorption, separation, disinfection, and nanofiltration using nanocellulose

Nanocellulose can be used for adsorption, separation, wastewater treatment, and nanofiltration processes, among other things. Essentially, it serves as a bio adsorbent. When it comes to the separation process, the separation of water and oil mixtures has become crucial to reduce industrial pollution from various industries. The use of oil/water separation membranes is used with the help of different types of modifications of anions, which are used to increase the energy of the adsorption to remove harmful ions. Adsorption methods comprise different types of adsorbents, which are parts of nanocellulose [111]. As previously indicated, several adsorptions and biosorption techniques are utilized to disinfect the wastewater and the filtration process to clean up polluted water. Disinfection of wastewater in the industry is also accomplished with the aid of nanocellulose [82].

Wastewater from industry comprises varying levels of active hydrocarbons, pollutants, and other elements. The oil is extracted from the wastewater using a cellulose filtration membrane, which lowers the percentage increase in degradants from the water and increases its purifying capacity [112].

Nanocellulose in the Polymer industry

Nanocellulose now plays a critical role in the operation of the polymer industry. There has been an increase in the order of production of plastics and different polymeric products, and maintaining the sustainability of this product is the most challenging thing today nanocellulose helps in reducing the impact of nondegradable materials in the polymer industry; it also helps in yielding a good quality material which has a great outcome, so nanocellulose is a good option for the production of composites with starch which is natural and matrix which is synthetic. Need for development is required for the manufacturing of biomaterials to replace them with petroleum-based synthetic polymers [113].

Nanocellulose is a form of green technology which aids in creating a double bond with many environmental and different technological factors for developing renewable products different forms of matrixes of polymers such as thermoplastics are used for the formation of different resources which are organic in the environment and different types nanocellulose based polymer nanocomposites are produced and offer a variety of valuable features [114].

Nanocellulose in the Food processing industry

Cellulose nanostructures are utilized in the food industry in a variety of food additives. Nanocellulose is employed in the food processing industries in the form of biopolymers. Because biopolymers have some mechanical constraints, CNCs, nanofibrils, microbial cellulose are employed in the packaging process in the food business. Cellulose nanocrystalline is used to create nanocomposite components with adequate water barriers feature [115].

Conclusion

The main motive of the paper was to discuss the information about the importance of nanocellulose and its use in the manufacturing process and the reasons behind it are distinct mechanical characteristics, less harmfulness, biodegradability, and potential adaptability for chemical alterations and so it has got special interest in the recent years and has various virtues in the sectors of water purification, food packaging, drug delivery etc. were also studied. The authors feel that applying these technologies into the development of approach having less price, are beneficial to nature, have a less maintenance will trend in the recent times for the production of nanocellulose.

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