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Lignocellulose Derived Nanocellulose, Its Properties, and Applications - A Review

Antony V Samrot[1]*, Akasha Arif[2], Kasipandian Kasirajan[3]

[1,2]*School of Bioscience, Faculty of Medicine, Bioscience and Nursing, MAHSA University, 42610, Jenjarom, Selangor, Malaysia; E-mail:* antonysamrot@gmail.com

[3]*Faculty of Engineering, Built Environment and IT, MAHSA University, Jalan SP2, Bandar Saujana Putra, Jenjarom 42610, Selangor, Malaysia*

Abstracts: Natural fibers are abundant in natural resources. Natural fibers have been used in various applications. Natural fibers have been proved to be extremely useful in multiple fields in the world. Natural fibers possess great mechanical and optical properties. Nanocellulose fibers are obtained from plants and it has many applications. It can be used as a nanocomposite. They can be extracted by performing various techniques. It is used as a barrier due to its crystalline structure, which makes it difficult for molecules to flow through. Nanocellulose fibers are biodegradable, strong, lightweight, low density, and renewable since they have been produced from natural resources. They have immense applications in electricals, nanotechnology, medicine, drug delivery, aerospace, adsorbents, papermaking, and dental. The following review will focus on the properties of lignocellulose-derived nanocellulose, cellulose nanocrystals (CNCs), and cellulose nanofibrils (CNFs) and their applications in nanotechnology.

Keywords: Nanocellulose, CNCS, CNFS, Drug Delivery.

1. INTRODUCTION

Polysaccharides, proteins, phenolic compounds, and mineral salts make up the plant's cell wall. Plant cell walls contain about 90% polysaccharides, of which cellulose makes up 20 to 40%, hemicelluloses (15–25%), and pectins (30%). Apart from polysaccharides, the plant cell wall is also stiffened by lignin, an aromatic polymer [1]. Lignocellulose, a three-dimension polymeric composite, is the structural material of the plants [2]. The carbohydrate polymer lignocellulose consists of polysaccharides built from sugar monomers (xylose and glucose) and lignin, a highly aromatic material. Before further development into liquid fuels, chemicals, or other end products, lignocellulosic biomass must be fractionated into reactive intermediates, such as glucose, cellulose, hemicellulose, and lignin. Lignocellulose is a natural biopolymer composed of defensive inner structures that have provided plant cell walls with hydrolytic stability and structural robustness along with resistance to microbial degradation [3]. There is no limit to the amount of cellulose available on earth, which is obtained from plants, animals, and bacteria of all types, including wooden and non-woody. As the principal component of the plant cell wall polysaccharides, cellulose is a linear polymer derived from linearly connected β-d-anhydro-glucopyranose units (AGUs). A chain of cellulose polymer molecules is covalently linked by 1,4-glycosidic bonds, which lead to the aggregation of several chains, eventually forming fibrils or microfibrils as they are hydrogen-bonded together. Nanocrystals, nano whiskers, nanofibrillated cellulose, and nanofibers are other names for nanocellulose [4]. In lignocellulosic biomass from energy crops, cellulose, hemicellulose, and lignin content vary with species, plant fraction, and growth conditions [5]. Synthetic materials could be replaced by plant fibers to enhance the recyclability and biodegradability of products [6]. In general, the term "nanocellulose" is used to describe materials that have a dimension in the nanometer range, since elementary fibrils made of cellulose molecules are about 5 nm wide. According to the preparation methods used for nanocellulose (NC), several types of NC can be extracted from plants, most notably nanofibrillated cellulose (NFC) and cellulose nanocrystals (CNC) [7]. Stiffness, lightweight, low density, and recyclability are some of the properties of these fibres [8 - 10]. Plant fibers are classified based on where they are found within the plants. Straw, wood, leaf, seed, and bast fibers are the different types of plant fiber. Due to their different functions, they have different mechanical and structural properties. In the formation of composites, the mechanical and structural properties of fibers play a significant role [11]. Biocomposite is a material constructed mainly from naturally occurring fibers. The major fibers that are used for producing biocomposites are either animalderived or plant-derived fibers [12]. Plastics reinforced with natural fibers have recently attracted attention. Due to environmental issues and pollution, nontoxic reinforcing materials are needed [9]. This review will mainly focus on the properties and applications of plant-derived fibers. Chains of cellulose that are bundled together can create nano-materials that can be separated and are called nanocelluloses. According to its origin and how it was isolated, nanocellulose has a specific morphology. As nanocellulose, there are cellulose nanocrystals (CNC), cellulose nanofibrils (CNF), cellulose nanoplatelets (CNP), cellulose nanoyarn (CNY), and amorphous nanocellulose (ANP) [13]. CNCs and CNFs will be discussed in detail in future sections. Nanocellulose consists of condensed cellulose fibrils. Crystalline structures give them strength and stiffness. Nanocellulose consists of particles that are smaller than 100 nanometers [14]. Cellulose nanoparticles contain hydroxyl groups on their surfaces. cellulose nanoparticles also disperse well in water. Due to this, water is the only suitable medium that can be used in the creation of nanocomposites [15]. The plant fibers are polar, so the hydroxyl groups can react to form hydrogen bonds. Pre-treatment methods include isocyanate treatment, mercerization, acetylation, and acrylation [16, 17, 10]. The world's most renewable source is lignocellulose and its constituents. There are many applications for it, and it can be used to make composites [18]. In several fields, including biomedical science, cellulose nanofibres that can be extracted from lignocellulose have proven beneficial. Their biodegradability and sustainability make them easy to produce and there is no contribution to landfills. Further, cellulose-reinforced nanocomposites have superior properties compared to neat polymers [19, 20]. Packaging industries use a large amount of cellulose-based materials for a variety of purposes, in particular wrapping materials, containers and protective covers, as well as flexible and rigid packaging [21]. Because of its unique properties and structural advantages, nanocellulose Garcia is an attractive material in energy storage systems [22].

2. Properties of Nanocellulose

Nanocellulose has a variety of properties that make it useful for forming nanocomposites. In addition to its mechanical and optical properties, nanocellulose is also barrier-friendly. The stiff crystal structure of nanocellulose is responsible for its mechanical properties. Furthermore, the high reactivity of cellulose leads to strong bonds and high strength. UV-VIS spectrometers can be used to determine the optical properties of nanocellulose [15]. Usually, the problem is interfacial adhesion between hydrophobic fillers and hydrophilic matrixes. Chemistry and proper coupling agents have been studied to improve this adhesion [23]. According to Nair et al., [24] cellulose nanofibres are effective gas barriers. Because of the crystalline structure of cellulose nanofibrils, they are effective barriers. Khan et al., [25] stated that a filler can be made less permeable in order to increase the barrier properties of nanocellulose. Moreover, the dispersion into the matrix should be easier in order to increase the barrier properties of nanocellulose [26]. Thermal stability also plays an important role in composites. Thermal stability refers to the ability of a composite to maintain its elasticity and overall strength at a specific temperature. Thus, many researchers are trying to develop composites that can be used at high temperatures [20]. In order for nanocellulose to be useful in biocomposite technology, where processing temperatures for biopolymers exceed 200C, their thermal stability is crucial. In nanocomposites, nanocellulose acts as a nucleating agent, promoting polymer crystallization. Due to nanocellulose's high aspect ratio, stiffness, and strength, it has been used as a reinforcement in polymer nanocomposites with enhanced mechanical properties [27]. Nanocellulose has been widely used in supercapacitors, conductive films, sensors, substrates in electrical devices, and separators in energy storage devices due to its large surface area, high aspect ratio, flexibility, and optical properties. Nanocellulose's large surface area and high water-holding capacity make it an ideal rheology modifier, mainly for paints and personal care products [28]. This biodegradable nanofiber exhibits high strength characteristics, lightweight, and low density (around 1.6 grams per cubic centimeter). Nanocellulose is transparent and contains reactive surfaces of hydroxyl groups that can be functionalized in a variety of ways [29]. In higher plants, cellulose acts as a reinforcing element in the cell wall [30]. Various raw materials, extraction processes, and raw material nature affect the fundamental properties of obtained nanocellulose, such as crystallinity, morphology, aspect ratio, and surface chemistry [4]. Lignocellulosic fibers protect plants by providing hydrolytic stability, structural strength, and preventing enzymatic and microbial decay, known as biomass recalcitrance [5]. Plant-derived cellulose nanofibers have one of the highest specific strengths and moduli among natural materials, higher than plastics, metals, and ceramics [31]. During CNC synthesis by sulfuric acid, amorphous cellulose regions are selectively hydrolyzed, producing highly crystalline particles. Due to electrostatic repulsion, CNC particles are attached to sulfate groups with negative charges, which inhibits aggression by the particles in aqueous suspension. Nanocellulose varies from three main categories based on the synthesis technique and conditions, which determine its properties, dimensions, and composition: 1. cellulose nanocrystals (CNCs), also called cellulose whiskers 2. Cellulose nanofibrils (CNFs), also called nanofibrillated cellulose (NFC), microfibrillated cellulose (MFC), or cellulose nanofibers 3. Electrospun cellulose nanofibers (ECNFs) and bacterial cellulose (BC) [32]. Using atomic force microscopy (AFM), it has been possible to evaluate the adhesion properties of cellulose surfaces [33]. Using negatively charged colloidal silica particles, Borkovek et al. [34] studied cellulose layers with colloidal silica particles. As a result of the overlap of diffuse layers formed by negatively charged carboxylic groups on the surface of the cellulose, the researchers determined that there was an attractive force between the silica particles and cellulose surfaces. According to the authors, nonelectrostatic forces, most likely originating from hydrogen bonding, dominate the adsorption of cellulose onto probe surfaces. Zhang and Young [35] investigated the adhesive characteristics of cellulose films extracted with acetone and are high in –OH groups. During the deconstruction of the source and its conversion into lignocellulose nanocrystals, particular attention has been paid to understanding the chemical and structural changes occurring during organosolv pretreatment and acid hydrolysis undertaken under different operating conditions. Using Fourier transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), field emission scanning electron microscopy (FE-SEM), atomic force microscopy (AFM), and X-ray diffraction (XRD), a complete characterization of the LCNCs was performed [36]. Biomedical, cosmetic, environmental remediation and electronics are a few of the many applications of cellulose nanofibres (CNF) [37]. Nanocomposites are advantageous because of their low cost, low density, and their wide availability. In order to provide better stability and strength to biodegradable films, the application of nanocellulose and nanofibers, referred to as green nanocomposites, is intended to enhance their resistance and stability [38]. Structural, Physicochemical and morphological tests can be used to assess the properties of CNF [39].

3. APPLICATIONS OF NANOCELLULOSE IN NANOTECHNOLOGY

Nanocomposites with fiber reinforced in them can be produced and have several applications. Nanofibres can be utilized for reinforcing the composite matrices. The nanofiber’s reinforced composites have useful applications in biomedical and construction [40]. Madsen and Gamstedt [41] stated that nanofiber composites are better to use. For example, using cellulose nanofibres is better than using carbon nanotubes. The reason behind it is that cellulose nanofibres are able to bond to one another through hydrogen bonding. The main problem that arises is the manufacture of cellulose nanofibres. But other than that, they are stronger and the point to be considered is that they can be extracted from biodegradable material. A study showed how reinforcement of nanoclay in sisal fiber affected the mechanical strength of the fiber. The incorporation of nanoclay increased the tensile modulus and tensile strength of the fiber [42]. Nanocomposites can also be used in the aerospace industry. They have many applications due to their mechanical and thermal properties. The nanocomposites also provide chemical stability. All this is advantageous because obtaining fiber is not expensive compared to traditionally used composites. Limitations such as less thermal conductivity, high electrical resistance and moisture absorption can be overcome by using nano-reinforced composites [43].

Nanocomposites have also been used in 3D printing. The utilization of fibers in 3D printing allows high strength to weight fabrication. These products are useful in the automotive and aerospace industries as mentioned earlier [44]. Cellulose nanocrystals (CNCs) are crystalline materials that are extracted from microcrystals of cellulose. The extraction is done by a strong hydrolysis process. The sources of these nanocrystals are cellulose fibers [45]. Cellulose fibers comprise of single fibers. The single fibers are interconnected with the middle lamella. The middle lamella does not contain cellulose and comprises of 90% lignin. The single fibers are surrounded by a cell wall and have a lumen at the center. Figure 1 shows the structure of cellulose fibers [46]. The size of CNCs is smaller compared to cellulose nanofibrils (CNFs). They can be extracted from cotton from different plant sources by acid hydrolysis. This hydrolysis procedure leads to the cleavage of cellulose fibers. The crystalline part is left intact [47-49]. One of the notable properties of the CNCs as stated by Eichhorn et al., [50] is to stabilize Pickering emulsions. This is worth noting because then cellulose nanocrystals can be used in inks and paints. Cellulose nanocrystals have been used as rheological modifiers in ink. According to Parveen et al., [51] nanocellulose can also be used to make cementitious composites. Cement composites are considered to possess good compressive properties but they do not have adequate tensile strength. For this reason, glass, vinyl alcohol or carbon has been reinforced. Sometimes, steel is also used for reinforcing that increases the chances of corrosion. Due to this, research has been going on to find a fiber that can be a better choice for reinforcement and for increasing the tensile strength. As is already discussed, fibers possess good thermal and mechanical properties. So, reinforcement of fibers in cement composites is quite useful.

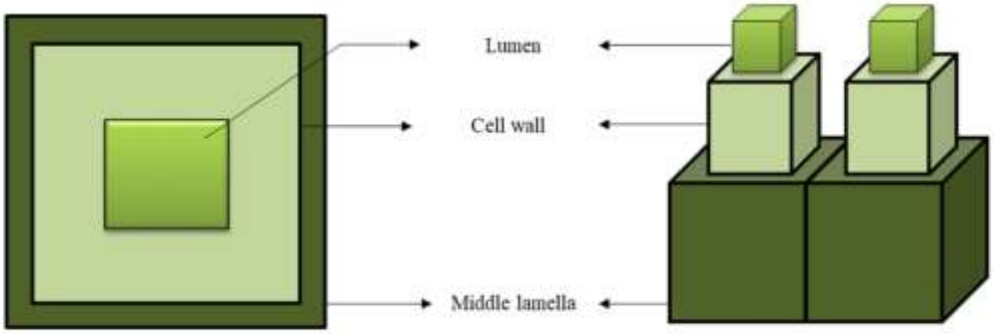

Figure 1. Cellulose fibers [87].

Fibers are used because they are recyclable and are available abundantly. They also replace petroleum-based polymers. The need to decrease the organic volatile emission is crucial now more than ever because of all the environmental issues. For this reason, waterborne polyurethanes (WBPU) are used. They have the ability to stabilize particles in water dispersions. The stabilization occurs by the emulsifiers that are covalently bonded. The addition of nanocellulose to WBPU increases their strength. CNCs possess a modulus that is almost equal to crystal. So, reinforcing CNCs is advantageous [52-54]. Similarly, CNCs are very useful in the food industry for stabilizing food. It is a good stabilizing and emulsifying agent. Cellulose can be used to replace xanthan gum. Products like xanthan gum can be very expensive and hence using cellulose-based products is affordable and convenient [55].

Softwood is one of the sources of cellulose nanofibrils. The process followed for the preparation of CNFs is referred to as high-pressure homogenization. They have gel-like properties [28]. There are other sources of CNFs as well. Raw plant materials can also be used for extracting CNFs. They may include bamboo fibers, raw cotton, raw cotton linter, sugarcane bagasse, wheat straws, etc. Waste paper can also act as a source of CNFs [56]. Cellulose nanocomposites have also been used for wastewater treatment. This is because they possess good adsorption properties. CNFs have been shown to be efficient membranes. The membranes that are based on cellulose act as good adsorbents and absorb pollutants from contaminated water [57]. Cellulose nanomaterials are useful adsorptive components that can adsorb heavy metals from contaminated water. Nanocellulose possesses rigidity and mechanical strength that aids in high pressure. The use of nanoparticle-based membranes decreases the carbon footprint [45].

There are many applications of plant-based fibers. Cellulose-based fibers have been utilized as reinforcements for biomedical purposes as well. For instance, for tissue repair use of aerogel is increasing. In order to develop aerogel, nanomaterials are used that are biopolymers. Biopolymers are used because they are available easily and there is less toxicity associated with them [46]. According to Du et al., [58] hydrogels are heterogeneous mixtures with two phases. The solid phase is a 3D network and the dispersed phase is water. They prepared cellulose nanofibril-based hydrogels and observed that the hydrogels have good mechanical properties. The hydrogels have many biomedical applications and are used as food additives, in hygiene products, and as soil conditioners.

Electrospun nanofibrils are also used in the biomedical industry. Electrospinning is considered the most dependable method for producing nanofibrils or any nanoparticle for that matter. The advantages of the electrospun nanofibrils are that they can be used for vascular tissue engineering, bone tissue engineering and tendon or ligament tissue engineering [59]. Tissue engineering involves tissue regeneration and repair. In this process there is restoration and proliferation of the damaged or diseased cells. Nanocellulose is a non-toxic source that can be utilized for tissue engineering [60]. Scaffolds are crucial in all types of tissue engineering. The scaffolds should be able to provide adequate volume for vascularization along with the formation of new tissue. Moreover, the scaffold should be stable enough so that shape does not change in case of tissue defects. This is where nanocellulose comes in. The hydrogels are used to make calcium sulfate. The calcium sulfate increases the adhesion tendency of the scaffolds. Furthermore, the nanocellulose also enhances the formation of neural networks. There are studies going on for growing nerve cells of humans on nanocellulose in order to treat Parkinson’s and Alzheimer’s disease [61].

Using cellulose alone is not practical because the solubility and mechanical property is not enough. In order to avoid this problem, zinc oxide nanoparticles can be used. They have antibacterial properties that can be helpful in wound healing [62]. Pestalotiopsis is a fungus that is able to grow and decolorize dyes. This is possible due to its laccase enzyme activity. This property of the fungus can be considered for wound dressing applications. The immobilization of laccase on cellulose may be utilized as an antimicrobial membrane that can be useful for wound dressing [13].

Cellulose nanofibres are also used to make nanocellulose papers. These papers have suitable optical transparency that makes it easier to observe any changes. These papers can be used for eardrum membrane regeneration and for wound healing. It also provides benefits for quality control in tissue engineering. For designing the artificial cornea optical transparency is extremely important [63].

3.1 Application as Barriers

Both CNFs and CNCs are considered remarkable oxygen barriers. However, the paths for the diffusion of gases vary because of the morphological differences between CNCs and CNFs. The CNFs have an entangled structure. The CNCs have a rigid uniform structure. Figure 2 illustrates the behavior of oxygen in CNFs and CNCs. [64]. Increasing the thickness of the barrier the oxygen permeability can be decreased. The range of transmission of oxygen of cellulose nanofibers is 17-18 mL/m² in a day. This is when the relative humidity is 0%. The transmission can vary depending on the relative humidity [65].

The types of cellulose fibers also affect the permeability of oxygen. The CNFs that are acetylated are used for modified atmosphere packaging. The permeability of this type of CNFs is about 10-20 mL/m^{-2} in a day. On the contrary, the CNFs that are carboxymethylated have less permeability compared to acetylated CNFs [66]. Wu et al. [67]. used tetramethylpiperidine oxidized cellulose nanofibres and checked their oxygen barrier properties. It was found out that the barriers worked best in dry conditions. While in humidity the permeability decreased.

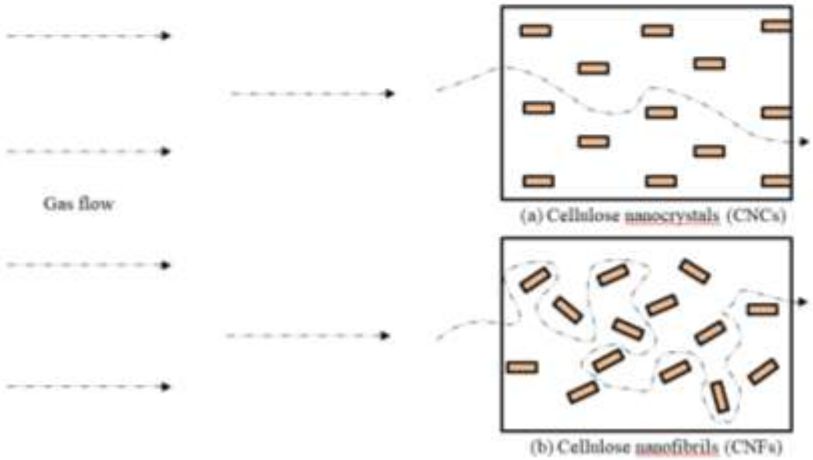

Figure 2. Gas (arrows) passing through CNCs (a) and CNFs (b) (Inspired from Wang *et al.,* 2020) [64].

3.2 Drug Delivery

Nanocrystalline cellulose has received attention for drug delivery in biomedical research. Studies have shown that nanocellulose is not toxic to human cells and it can be useful as a carrier for drug delivery. Furthermore, there are no threats to the environment which is also one of the advantages [68]. Another study by Tong et al., [69] tested the drug delivery in rats by using curcumin-loaded cellulose nanocrystal film. It was observed that the wound healing was significantly improved in diabetic rats. This study proved that cellulose nanocrystal can be useful for healing wounds in the case of diabetes. According to Karimian et al., [70] the nanocrystals can be administered orally. This can be done for the drugs that are less water-soluble. Nanocrystalline cellulose can be used for anchoring different types of compounds in order to change their hydrophilicity. The study mentioned that there were no observed side effects and that this can be used for multiple biomedical applications.

Cancer is characterized by the uncontrollable multiplication of cells. Anticancer treatments have disadvantages such as low availability, less water solubility, and less efficiency. These are the main problems associated with chemotherapy. Due to this reason, studies have been performed to incorporate nanoparticles and to test if they are a more efficient way to deliver the drugs. According to a study, nanocrystals were prepared that efficiently encapsulated curcumin. These nanocrystals had a good drug delivery. The nanocrystals had increased cytotoxic activity against the cancer cells [71]. Cellulose nanocrystals have been used with chitosan for the delivery of cancer drugs such as doxorubicin. The doxorubicin was loaded by forming thin films of nanocellulose. The study concluded by saying that nanocellulose can be used for stable drug delivery [72, 73]. Nanocellulose can be used for different types of drug delivery as well. For example, it can be used for oral drug delivery. Different pharmaceutical agents can be mixed with nanocellulose to make a carrier that can be administered orally [74-75]. Jackson et al., [75] wrote that nanocrystalline cellulose has many advantages when used as an excipient for drug delivery. Nanocrystalline clays are also being used for drug delivery. They also mentioned that the drug can be released with control through ion exchange.

The nanoparticle-based carriers are better for drug delivery because they have specified morphology and have stability. Moreover, surface modification is easier and they have sufficient biocompatibility. Rod-shaped nanocarriers are internalized faster compared to spherical nanocarriers [45]. Pinho and Soares [76] stated that cellulose from cotton can be used to make hydrogels that can be used for drug delivery. The network of hydrogel is in such a way that it allows the entrapment of molecules for bioactivation.

3.3. Nanocellulose Products for Dental Procedures

Nanocellulose has been used for making dental products in order to use fewer chemical products. There are products that have been developed for periodontal tissue recovery using nanocellulose. The number of surgical steps for the whole procedure has also been decreased using nanocellulose products. The nanocellulose scaffolds have fewer chances of interaction with blood cells and more importantly rejection by the host body [77]. Nanocomposites are also used for dental filling procedures. The fabrication of the core is done by using nanocomposites materials and then they are used for application. For instance, veneers, on-lays, in-lays, and crowns [78]. As mentioned earlier, scaffold materials can also be produced using nanofibrils. The scaffolds can be applied for regenerative treatment for periodontal and teeth. Barrier materials are used that are placed between the teeth and mucoperiosteal flap. These barriers are semipermeable that avoids the invasion of gum tissue to the regenerative area. In this way, graft rejection is avoided [79].

3.4. Food Industry

Nanocellulose from plants has been used as a food additive. However, it was found out that it is expensive to obtain. Recently, studies have shown more reliable processes for producing it which reduced the cost [80, 81]. Moreover, it can also be used as a stabilizer for fats and oils in food. Nanocellulose is able to form dispersions and emulsions which is why it can be used as a thickener [82]. Gomez et al., [80] wrote how nanocellulose has been used as a stabilizer. Nanocellulose was used to check if a frozen dessert will keep its shape. However, the problem that was faced was the taste and texture of the dessert were altered. This happened because a high quantity of nanocellulose was used. When balanced quantities were used then it was noticed that the shape did not change and the taste remained the same. Another advantage in the food industry is the food packaging by using nanocellulose. Nanocellulose is used in food wraps that provide safety [81]. The wraps that are made from nanocellulose are inexpensive, biodegradable, and non-toxic. Moreover, the packaging paper possesses good mechanical properties [82]. Packaging in the form of coating is quite common. The item that is to be packaged is coated with thin layers of nanocellulose [84, 21]. Studies have been tested to see the oxygen permeability of paper by coating with nanocellulose. The studies concluded that the oxygen permeability decreased with the coating of nanocellulose [21]. Cellulose nanofibrils are also used to preserve blueberries. The CNFs with calcium carbonate are used for this. The shelf-life of several fruits can be increased by using nanocellulose. Strawberries have also been coated with nanocellulose to preserve them. Cellulose nanocrystals are used in order to delay the ripening of mangoes. This also maintains the quality of fruits [85].

3.5. Applications in Papermaking

Recently, studies have started leaning more towards the applications of nanocellulose in papermaking. Nanocellulose has been observed to improve filler retention in addition to the strength of the paper [86 – 91]. The recycling of paper is considered crucial in the papermaking industry. However, it is important to maintain the quality of paper after using recycled products. So, for this reason, nanocellulose can be used because it can act as a strengthening agent. When nanocellulose was first used in papermaking, it was extracted from wood [83]. Nanocellulose is used in papermaking in order to increase the tensile strength of paper. The mechanical strength of the paper is also influenced by nanocellulose [90-91]. A study conducted by Kasmani and Samaria reported that by adding nanofibrillated cellulose in the pulp for making paper, the clarity and brightness of the paper increased. Moreover, the burst strength and tensile strength also improved. The roughness of the paper was also observed to decrease. The overview of the effects of nanocellulose on paper is given in figure 3.

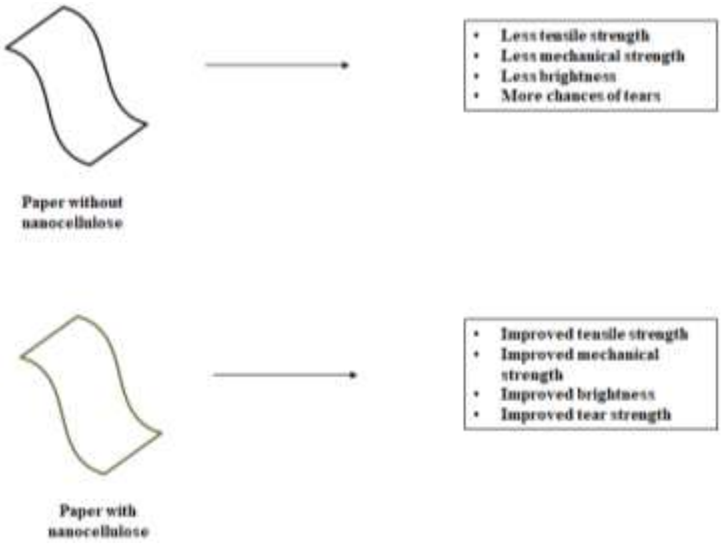

Figure 3. Effects of nanocellulose on paper

The consumption of energy in the papermaking industry has been studied in many types of research and they have tried to find ways to reduce it. One of the common processes that have been followed is lessening the mechanical beating. Mechanical beating is applied to the pulps used for the production of paper. This takes approximately 30% of electricity which is necessary in order to produce paper [86, 92]. So, in order to decrease energy consumption, CNFs can be used. They are the alternative to mechanical beating and can be added in the pulp slurries. Studies have shown that if cellulose nanofibres are added to the pulp slurries then the rigidity and strength of paper tend to increase. The only issue that may arise is the cost of CNFs [86, 93, 94, 95, 96]. According to Brodin, Gregersen, and Syverud [94], the density of the paper is observed to increase when cellulose nanofibres are added to the pulp. Due to the addition of CNF, there are hydrogen bonds formed that add to the rigidity and density of the paper. This also strengthens the paper. According to the study conducted by Sehaqui, Zhou, and Berlung [97], the addition of nanofibrillated cellulose (NFC) increased the density of the paper. The reinforcement effect of NFC was observed to be strong. Das et al., [98] stated in their article that if a little number of cellulose nanofibrils are added then the tensile strength of the paper is affected significantly. The properties of cellulose are influenced by the addition of CNFs. Dewatering can be avoided by using CNF in papermaking. In this way, CNFs are utilized as coating material. CNFs act as good packing films that also possess reliable barrier properties. Several types of coatings can be done, for instance, roll coating, bar coating, size press, and spray coating. The recycling of paper becomes easier when CNFs are utilized. This is because in traditional mechanical beating the structure of the fibers is damaged. But when nanofibres are used then the fibers stay in their original morphology possessing the same properties [87].

3.6. Applications as Adsorbents

Nanocellulose can also be used for the purification of water. Many chemicals have been removed using a membrane-coupled filter. Nanocellulose has been proved to be a reliable adsorbent to remove organic contaminants. These contaminants include natural oils, dyes, and chemical pesticides. Nanocellulose possesses a surface that has ionic as well as non-ionic groups. Due to this it is able to absorb the contaminants [65]. A study synthesized sulphonated nanofibrils in order to use them as adsorbents for lead (Pb^{+2}). The nanocellulose was prepared using a peropdate-sulphonation reaction. This reaction is environmentally friendly because no halogen waste products are produced. Furthermore, the periodate that is used can be recycled. The adsorption capacity was observed to increase at optimum pH. It was also observed that at low pH, the adsorption of metals was less. For heavy metals, the optimum pH range for adsorption is between 4-6 [99]. Another study used nanocellulose to adsorb heavy metals. The nanocellulose was colored and then it was suspended in three separate containers. Each of the containers had iron, copper, and silver respectively. Rapid adsorption was observed initially and then it was constant for up to 48 hours. The CNCs and CNFs used showed approximately 100% adsorption at equilibrium [100]. Nanocellulose materials are used for air purification, dye removal, and for decontamination of microorganisms. The adsorption rate for heavy metals can be increased up to 465.1 mg/g by using cellulose nanocrystals with succinic anhydride. It has been reported that nanocellulose is a safe, eco-friendly, and most reliable material for membrane-related applications. Furthermore, different types of filtration methods can be carried out using nanocellulose. For instance, nanofiltration, microfiltration, reverse osmosis and ultrafiltration. The only point to note here is the cost because it can be expensive. So, there is a need for more studies in order to reduce expenses on the processing [13].

CONCLUSION

Based on the above discussion, it can be inferred that plant-based nanocellulose has multiple applications. One of the most important points to be noted is that nanocellulose is biodegradable, strong, non-toxic, renewable, environment friendly and easily available. Plastics can be replaced with products made of cellulose. Several products can be made from nanocellulose. As discussed in the review, nanocellulose can also be used to manufacture electrical products and biomedical products. It can be used in aerospace, drug delivery and papermaking etc. As a result, the use of nanocellulose is immense and environment friendly and much needed to use in the place of toxic materials.

DATA AVAILABILITY

The data used to support the findings of this study are included within the article.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

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