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Review Article

Waste-Derived Cellulosic Fibers and Their Applications

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The use of bio-based materials has become a focus of research nowadays. For the development of new generations of advanced resources, renewable and available resources must be combined with advanced technologies. Researchers have looked into biomass and waste cellulosic materials as sustainable sources for nano-crystalline cellulose extraction. Besides the different treatment methods suitable for various applications, this review aims to provide integrated details on the extraction methods and applications of cellulosic fibers and cellulose nanocrystals derived from wastes of different sources. There are numerous applications including building materials, electronics, furniture, automobiles, medical applications, sports goods, filtrations, water purification, and delivery systems of drugs which have been discussed.

1. Introduction

Food waste can never be defined in one-dimensional terms because the standard of what is edible and inedible varies from individual to individual [1]. Depending on ethnicity and geographical location, dietary habits differ [2]. In the food system, food wastes are placed into four categories: at the postharvest level, during manufacturing, during retail and distribution services, and finally at the household level (Figure 1) [3].

Other important factors that may determine the extent of food waste include pest control efforts, storage, and transportation [4, 5], consumer demand [1], as well as whether or not the country is developed.

The physicochemical properties that usually determine the reutilization of plant-based organic waste are their carbohydrate, lipid, protein and ash content, pH, chemical oxygen demand, and total solids [6]. Fruit and vegetable waste has an abundance of cellulose, carbohydrates, flavors, colorants, minerals, and antioxidants [7]. All these substances are useful and can be used to enhance the quality of other foodstuffs or be added into animal feed [8]. In addition, fruit and vegetable waste contains other extranutritional compounds that can be added to foodstuffs [9]. The most wasted food products are

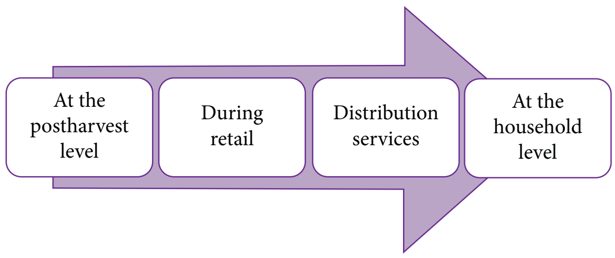

Figure 1: Four categories of food waste: at the postharvest level, during manufacturing, during retail and distribution services, and finally at the household level inspired from [3].

fruits and vegetables [1]. All these substances are useful and can be used to enhance the quality of other foodstuffs or be added into animal feed [10]. In addition, fruit and vegetable waste contains other extranutritional compounds that can be added to foodstuffs; the most wasted food products are fruits and vegetables. This is usually a consequence of damage to the fruit which renders it unsellable or postprocessing waste such as stalks, peels, leaves, seeds, stems, and husks [1]. In general, discarded cotton fabric has been largely neglected as a potential source of cellulose nanofibers. Recycling textile waste and reusing it in solar steam generation is of tremendous interest [11].

In the previous two years, the amount of cotton consumed in the United States has outpaced production, and the US Department of Agriculture predicts that trend is still continuing. As a result, cotton waste generation increased, wherethere are two types of waste generated: preconsumer waste during the yarn, fabric, and garment manufacturing process and postconsumer waste at the end of the product's life cycle (Figure 2) [12].

Cotton fibers can be reclaimed to make low-grade yarn and nonwoven products for uses in automotive parts, building insulation, and furniture [13]. Approximately, 75% of the preconsumer waste is recycled in this way. Fibers from waste materials to reuse them in future production is commonly referred to as fiber reclamation [14]. As a result of impurities left on used products and their varying tear and wear conditions, postconsumer waste is more difficult to recycle than preconsumer waste. Impurities on fibers are removed by treating with alkali [15]. Cellulose can be converted into useful products rather disposed off or burned [16]. Cotton contains 95% cellulose, and its production is agrochemical and energy-intensive. Regenerating fibers from postconsumer cotton waste is an innovative solution for recycling cotton waste. Cellulose, in particular, has the potential to play a significant role in the replacement of fossil oil-based fibres and cotton with innovative ecological man-made fibres [17]. Despite this, cotton fibers are difficult to dissolve in common solvents as hydrogen bonds between cellulose macromolecules are strong. The viscose process in rayon production uses carbon disulfide (CS_2), and the cuprammonium process employs a complex solution of cuprammonium hydroxide and heavy metals [15]. In a study, the alkali/urea aqueous system was applied for the first time to the recycling of postconsumer cotton products and the regeneration of value-added cellulose fibers through wet spinning [18]. This method is very promising for industry adoption as it uses nontoxic solvents at a low cost. The molecular weight of cotton was reduced by a mild hydrolysis process before dissolution, and impurities were removed [19]. In another work, data were compared between two solvents for dissolving cotton waste and synthesizing cellulose fibers [20]. Some studied on recycling conditions for used white, post-consumer cotton t-shirts [21], where some researchers investigated the possibility of conserving dyes of colorful t-shirts during recycling in order to produce regenerated fibers with intrinsic colors [22].

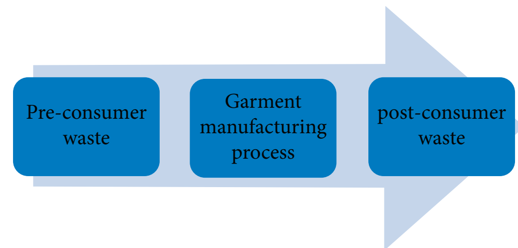

Figure 2: Illustration of the generation of cotton waste.

Plant-based organic waste is comprised of cellulose, which is being used for many applications, including paper and textiles, building, electronics, biomedicine, and many more [23]. Scientists and researchers are currently trying to investigate the potential use of this cellulose derived of waste as a substitute for other environmentally hazardous man-made fibers [24]. Because of its low cost, extensive availability, and low content in non-fibrous components, cellulose is a raw material for fuels, chemicals, paper industry, building board, and food sectors. Not only are these cellulose fibers safe for human intervention but also are also considered a potential source of clean energy [25]. There are many applications for biomass derived from natural fibers: biocomposites, biomedicine, and automotive components. By using waste materials as cellulose fibers, micro and nanoparticles, microfibers, and nanowhiskers can also be produced. Agricultural waste is one of the major sources of cellulosic organic waste. Agricultural waste arises usually as a result of low-quality production and also obtained from post processing of foods [26, 27]. Distribution waste refers to food loss happening in the market, and domestic waste is food loss at the consumer level [3]. Cellulosic waste from food loss and agricultural activities contains approximately 31–60% cellulose, with pentosans accounting for 11–38% and lignin 12–28% [28].

The extent of cellulose polymerization has been a source of debate over the years, with several researchers proposing various structural models [29–31]. Lignins are heterogeneous, branched, three-dimensional structures containing both phenolic and enolic precursors. Hemicellulose on the other hand is a polymer made up of sugars such as cellulitis [32–34]. Fibers are made up of three main components, cellulose, hemicellulose, and lignin, which are arranged in microfibrils. These cellulose fibers are especially important and have many applications in industry owing to their unique properties that include tensile strength, high biodegradability, low weight, and relatively cheap cost [35–38]. Cellulose fibers use get minimized if integrated with other substances such as hemicellulose, lignin, and pectin [39]. Cellulose has a high molecular weight, making the biopolymer extremely stable and very resistant to degradation by chemicals and enzymes; therefore, to isolate the natural cellulose, intensive pretreatment processes are required [40–44]. These treatment methods varied and range from mechanical, chemical, and chemomechanical [45–49].

2. Pretreatment Methods of Cellulose Extraction

The underlying principle for all cellulose extraction methods is their ability to rid of the noncellulosic parts that are present in the green waste, such as lignin and hemicellulose as previously mentioned (Figure 3). Cellulosic fibers can be extracted from all plant materials, and the choice of cellulosic source is dependent on the availability of the plant source, the application for which the cellulose will be used as well as the associated costs, and they can be used as an alternative to glass fibers [50]. The methods of natural fibers isolation are categorized into chemical, physical, physicochemical, and biological methods.

2.1. Chemical Pretreatment Methods. Chemical pretreatment methods rely on the chemical interactions between cellulosic green waste and the chemical compounds such as acid or alkaline solutions. An acid concentration of 10–30% is effective in degrading both lignin and hemicellulose as well as depolymerizing cellulose. The efficacy of dilute acid of 1- 2% has been proven to be useful in extracting cellulose. It wasmanaged to attain a hemicellulose degradation rate as high as 81% when they treated the perennial grass *Phalaris aquatica*.

Pretreatment with alkaline solutions depends on the process of saponification, and the alkaline compounds cause the lignocellulosic biomass to swell [51–52]. A 4-fold increase was in the total volume of reducing sugars when treated switchgrass with 1% of sodium hydroxide for 12 h at 50°C. In addition to this, it was achieved a delignification rate of up to the maximum lignin reductions were 85.8% at 121°C, 77.8% at 50°C, and 62.9% at 21°C [53].

Organic solvents work by hydrolyzing the internal bonds that compose both lignin and hemicellulose. They also break down the bonds that hold these two structures together [51]. Using organosolvents is a promising pretreatment to solubilize lignin. Coproduction of materials from cellulose fibres and added-value chemicals from hemicelluloses and lignin is an efficient strategy in a biorefinery. Recent researches are focused on employing biphasic systems to fractionate biomass into three separate phases (cellulose, hemicelluloses, and lignin) in a single pot reactor [54].

An alternative to ionic liquids is utilization of deep eutectic solvents (DES). Utilization of DES selectively degrades the biomass, but without damaging any of the carbohydrate structures [55]. As stated, a number of oxidation methods can also be used for biomass delignification; examples include ozonation, cavitation, photocatalysis, and Fenton oxidation [56].

2.2. Physical Pretreatment Methods. The principle goal of physical pretreatment processes is to decrease the size of the cellulosic biomass, thereby increasing its surface area. As surface area increases, the effectiveness of the enzymatic hydrolysis also increases. There is a substantial quantity of literature on the enzymatic hydrolysis of lignocellulosic woods based on the effects of various pretreatment procedures on the enzymatic hydrolysis reaction. Therefore, mechanical disintegration methods such as cutting, grinding, milling, and shredding are usually the methods of choice. The obvious advantage of these kinds of pretreatment methods is that they are environmentally benign, in comparison to chemical pretreatment processes. In contrast, physical disintegration consumes a lot more energy than chemical pretreatment [57–59]. Other than reducing size, physical pretreatment methods also aim to minimize the crystallinity of cellulose, so that it is more accessible for further processing.

2.3. Physicochemical Pretreatment Methods. These pretreatment methods, as the name implies, combine the application of both physical forces and chemical compounds. Using the process of steam explosion, ability is to liberate acetyl residues from cellulosic biomass. The resulting acetic acid facilitated further hydrolysis of the green waste [60]. A process known as ammonia fiber expansion also reduces cellulosic crystallinity while increasing surface area, and this is done by using anhydrous ammonia suspension [59]. In a related procedure known as the ammonia recovery process or ARP, aqueous ammonia is passed through the biomass, allowing for the solubilization and delignification of hemicellulose [61].

In an attempt to determine the extent of degradability of switchgrass, the comparison of two methods such as cellulose solvent and organic solvent-based lignocellulose fractionation (COLSIF) and immersion of the switchgrass in aqueous ammonia was compared. It was found that COLSIF-treated cellulose was 16 times more accessible to cellulase in comparison to the aqueous ammonia immersion method, which mainly got rid of lignin. This led to the conclusion that cellulose accessibility to cellulases is of greater importance than the elimination of lignin [62] which can be done by applying an effective physiochemical method.

Liquid hot water treatment can cause the degradation of hemicellulose, and at temperatures which exceeds 180°C, lignin is also degraded leaving just cellulose [51]. Microwave irradiation is another thermal pretreatment method that works by interfering with the lignocellulosic structures of the green waste. To increase its efficacy, it is often used in combination with chemical methods [63]. Figure 4 shows the pretreatment procedure for lignocellulosic biomass for fermentative utilization.

2.4. Biological Pretreatment Methods. Biological pretreatment is a method which uses microorganisms such as lactic acid bacteria and enzymes to treat the biomass. The two main underlying principles include saccharification and delignification. Variation of microorganisms to pretreat lignocellulosic biomass was used [65]. More specifically, biological delignification uses both fungi and fungal-isolated enzymes. Wood-rot fungi have been proven to degrade both cellulose and lignin [66]. White-rot fungi was used to assess the rate of delignification of Bermuda grass stems which discovered that the white-rot fungi had achieved a 41% removal of all aromatic

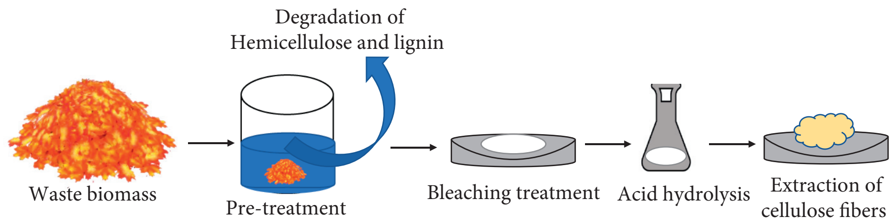

Figure 3: Illustration about methods of extraction of cellulose fiber from waste.

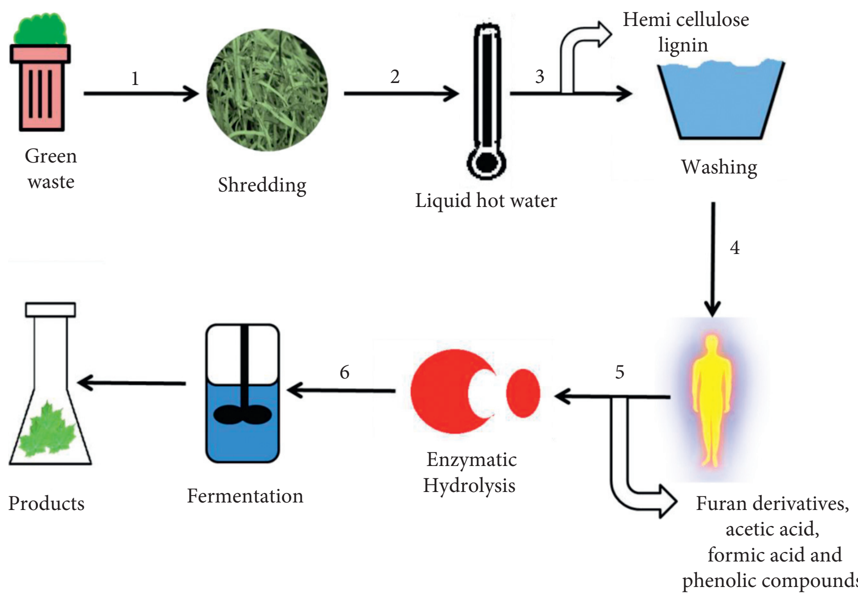

Figure 4: The pretreatment procedure for lignocellulosic biomass for fermentative utilization. (1) Shredding. (2) Use of high temperature and pressure to remove both lignin and hemicellulose. (3) Washing of the hydrolysate. (4) Detoxification. (5) Isolation of the monosaccharides, the samples undergoing enzymatic hydrolysis. (6) Microbial fermentations [64] (Figure 4).

compounds, while also achieving a biodegradability rate of 77%. However, an obvious disadvantage of this method, as with any biological method, is the fact that it is time consuming, and therefore, researchers often have to resort to other more efficient chemical or physical methods. Isolated enzymes offer faster delignification rates in comparison to whole organisms [67]. The phenomenon using the enzyme multicopper oxidase laccase on both eucalyptus and elephant grass [68]. Multicopper oxidase laccase is an enzyme that hydrolyses lignin by altering its three phenolic molecules. Using this enzyme, they achieved delignification rates of 35% for elephant grass and 85% for eucalyptus [68]. *Clostridia* are one of the best-known microorganisms that can undergo biological saccharification. This is made possible because *Clostridia* has a specialized collection of enzymes known as cellulosome which includes chitinases, cellulases, endo and exoglucanases, pectate lyases, xylanases, and hemicellulases. *Clostridium thermocellum* is especially a good candidate because of its ability to tolerate very high temperatures [69]. A disadvantage of utilizing enzymes instead of whole microorganisms is the risk of further metabolizing the generated sugars into unwanted by-products [65]. Another problem arising from the use of enzymes is product inhibition, where after a while, the products made by the enzymes work by negative feedback and bind to the enzyme's active site, thereby, preventing the enzyme from carrying out any further catalytic processes. Prawitwong and their colleagues managed to circumvent the inhibition brought about by *C. thermocellum* with the addition of β-glucosidase, a thermostable enzyme [70]. They coupled this with an alkali pretreatment, and in the end, they were able to achieve saccharification of 72% of all glucan. Another upside of biological pretreatment is the fact that of all the by-products formed, none compromises the success of subsequent enzymatic and microbial hydrolysis reactions [71]. This is not the case with physicochemical methods because there is almost always a detoxification step is required. The overall mechanism of pretreatment is shown in Figure 5.

3. Extraction of Nanocellulosic/Cellulosic Fibers

Cellulosic fibers can be extracted from cellulosic materials using several techniques either prefers pretreatment or not, it depends on the method preferred by the researcher [72]. There are mainly three categories of isolation methods: mechanical extraction, enzymatic hydrolysis, and acid hydrolysis [73]. In general, there are three main extraction techniques: acid hydrolysis, enzymatic hydrolysis, and mechanical process as mentioned in above pretreatment process. Nanocellulose is most commonly

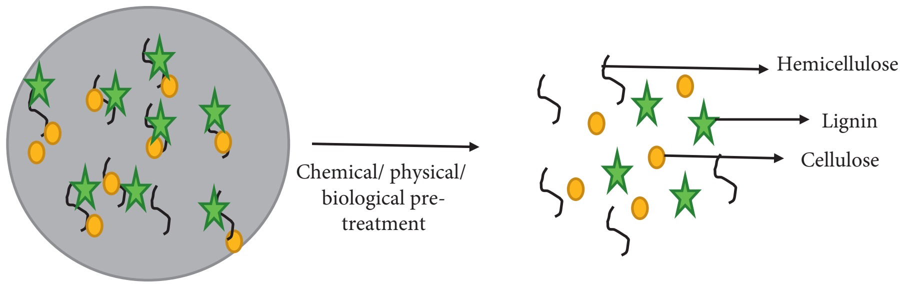

Figure 5: Mechanism of pretreatment.

extracted from biomass fibers by acid hydrolysis [74]. It can be easily hydrolyzed into cellulose as this process uses sulfuric acid for acid hydrolysis. As a result of the esterification of the hydroxyl group by sulfate ions, it is able to isolate nanocrystalline cellulose and disperse it as a stable colloid system [75]. The major problem with acid hydrolysis is the acid wastewater that is generated when the nanocellulose suspension is washed to neutralize the pH value. Usually, cold water is added followed by centrifugation to neutralize the pH of the water [76]. The resulting products can also be washed by washing them in alkaline substance such as sodium hydroxide to neutralize pH levels [77]. The acid hydrolysis of four different types of biomass by Maiti et al. [78] resulted in the extraction of nanocellulose from them. In this reaction, the acid is washed with deionized water and centrifuged, followed by 0.5 N sodium hydroxide for neutralizing the suspension, followed by distilled water for washing again. It is possible to use TEMPO (2,2,6,6-tetramethylpiperidine-1-oxyl radical) as the catalyst to oxidize the carboxylate group of cellulose with the primary oxidant hypochlorite [79]. The process of enzyme hydrolysis refers to the process of digesting or modifying cellulose fibers by enzymes [80]. It was demonstrated by Moniruzzaman et al. [80] that cellulose fibers could be separated from wood chips by pretreatment with ionic liquid for increasing the accessible surface area, followed by enzymatic hydrolysis with laccase. Nanocellulose obtained from wood fibers has a higher crystallinity and thermal stability than native wood fibers. The mechanical process involves applying high shear forces to fibers in longitudinal direction, which cleaves them, resulting in nanofibrillated cellulose [81]. The most prevalent mechanical methods include homogenization under high pressure, ultrasounding, and ball milling. High-pressure homogenization (HPH) involves passing cellulose slurry at high pressure and high velocity through a vessel [82]. Defibrillation of cellulose fibers also done using ultrasonication [83]. The ball milling process is another mechanical method that can defibrillate cellulose fibers. A rotating jar creates shear forces between and among the balls due to its centrifugal force [84]. One of the main disadvantages of mechanical processes is their high energy consumption. In order to decrease energy consumption, the mechanical process is usually combined with other pretreatment methods [85].

4. Applications of Cellulosic Fibers

Natural fiber composites extracted from jute and the fibrous husk of coconuts are used to make building materials (panels, roofing goods, door shutters, door frames, and many other materials) (Figure 6) [86]. In many countries across the world, these cellulosic fibers are used either alone or as composites where they are combined with other materials. Some countries have even used these natural fibers as replacements for wood. In India, agricultural green waste such as bagasse fibers have been used to synthesize insulation boards [87]. In China, the same method has been used to synthesize chipboards [88]. Similar products have also been developed both in Thailand and Japan [89]. In the Philippines, these chipboards were produced mainly from the stalks of bananas and coconut husks [90]. Papua New Guinea, Indonesia, and Malaysia on the other hand have resorted to using fibers isolated from oil palm trees [91–93].

4.1. Furniture. As with all green waste utilization, the use of cellulosic waste fibers in the furniture industry greatly minimizes waste. Fibers isolated from fruit and vegetable waste can be used to create medium density fiber board (MDF) [94]. Similarly, the use of flax fibers in furniture production was described by Van de Velde and Kiekens [95]. Considerable research has been made into the use of cellulosic fibers such as fruit peel waste in manufacturing products such as furniture padding and plastic fencing [96].

4.2. Automobile Industry. For decades now, cellulosic waste fibers have been used in the automobile industry. The use of natural fibers in car manufacture can greatly decrease the car's weight, thereby, also minimizing its fuel consumption. These biocomposite fibers can be used both on the exterior and in the interior of cars. Headliner panel, door panel, dashboard, and seat back are examples of some of the automotive parts that have been created from fiber biocomposites in the past [97]. A study was carried out where the use of palm kernel fibers in the production of brake pads was examined [98]. Popularly known car brands such as Audi, Volvo, Ford, Volkswagen, and many more have all used natural fibers in manufacturing their automotive components [99, 100].

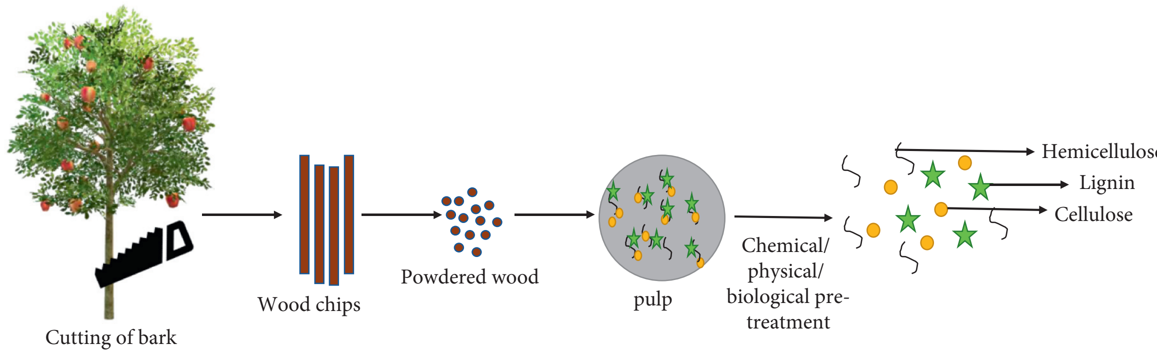

Figure 6: Illustration about the utilization of cellulosic fibres from wood of plant.

4.3. Medical Applications. For natural fibers to be deemed suitable for medical applications, they need to exhibit long-term usage within the body, but without inducing any toxic or allergic reactions [37]. Possible uses of natural fibers in biomedicine include the following: for skin grafting, as drug delivery systems, in dental procedures, bone reconstruction, and as scaffolds for tissue engineering [101–104].

Cellulose nanofibrils have the potencyto enhance cell proliferation additionally as reinforce polymer matrices, making them a great candidate for use in tissue engineering [105]. This includes tissue scaffolding, vascular grafts, and tissue regeneration. A test was carried out about the properties of hydrogels containing modified cellulose nanocrystals (CNC) compared to hydrogels without cellulose nanocrystals [106]; this research proved that the CNC-containing hydrogels were more elastic and showed significant structural stability. The absence of any cytotoxicity made them even more suitable for use in tissue scaffolding. In a study, cellulose nanocrystals were used as fortifying agents for tissue scaffolds in alginate matrices, and though cell proliferation was at the start diminished as a result of the nanocellulose's hydrophobic nature, the CNC's maintained cell growth over a longer period of time, promoting cell proliferation in the long run [107]. The incorporation of the CNCs in the hydrogels also decreased the enzymatic degradation of the hydrogels by the proteolytic enzyme trypsin. The potential use of nanocellulose in bone tissue engineering [108] created hybrid materials that contained both cellulose nanocrystals and hydroxyapatite, where it was examined about the link between hydroxyapatite growth and the surface chemistry of CNC's. A study discovered that the addition of CNCs was an excellent scaffold as they promoted the nucleation of hydroxyapatite. The CNCs also appeared to enhance the viability of fibroblast cells. They studied the efficacy of CNC-coated bioactive glass as a substitute material in the promotion of bone regeneration [25]. The mixture of the two materials would imitate fibrous collagen and hydroxyapatite similar to what is seen in the bone matrix.

In a study, it was observed that the addition of the CNC coating to bioactive glass improved the proliferative and adhesive properties of MC3T3-E1 cells, which can be a useful application in bone implantation. An experiment supporting that nanocellulose can be used in vascular graft therapy [109]. The oxidized cellulose nanocrystals (OCNC) exhibited great tensile strength, likened to that of pig arteries. This showed that the OCNC/fibrin composites are excellent candidates for vascular grafting as their strength and elasticity could be modified.

The utilization of nanocellulose in drug delivery systems is another current area of interest. Drug delivery systems are used to deliver biomolecules including chemical compounds and genes to target tissues or organs. The idea is that once nanocellulose is incorporated, the bioavailability of the drug is enhanced due to slower release rates, which increases the residence time of the drug as well as reducing systemic toxicity.

The use of nanocellulose in drug delivery is by combining curcumin-loaded cellulose nanocrystals with chitosan in alternating layers [110], where thedrug release was sustained at acidic pH which led to the conclusion that if the drug delivery systems can maintain release in acid environments, then the same drug delivery system can be used to treat tumours that thrive in the same acidic surroundings. By integrating cellulose nanocrystals with poly(ethyl ethylene phosphate) , it can be used in delivering antitumor drug doxorubicin to cancer cells. Faster drug release was exhibited at pH 5.0, which demonstrated that at the normal physiological pH of 7.35–7.45, this drug delivery system should be able to successfully evade degradation until it reaches its target site [111].

Incorporation of cellulose nanocrystals and sodium alginate is an attempt to demonstrate the possibility of controlling the release of two separate drugs to the same target site [112]. They created a drug delivery system with an outer membrane that would degenerate to release one drug (ceftazidime), while an inner membrane (consisting of alginate and cellulose nanocrystals) housed an epidermal human growth factor that would later get released at a slower rate. To target folate receptor-positive cancer cells, conjugation of cellulose with folic acid and fluorescein isothiocyanate was obtained. The findings indicated that in both human and rat brain tumour cells, uptake of the drug was greater in cellulose nanocrystals incorporated drug delivery system than drug delivery systems that did not incorporate cellulose nanocrystals with folic acid [113].

The efficacy of gene delivery was enhanced when cellulose nanocrystals were combined with gold nanoparticles. The same cellulose nanocrystals were grafted with methacrylate derivatives and intertwined with plasmid DNA. CT imagingshowed that the plasmid DNA became condensed and found the interaction with anionic cell membranes to be reduced. Thus, nanocellulose is found to be a promising candidate for potential employment in gene delivery [114]. A multi-layer chitosan-based electrospun mat containing Semellil extract and cross connected by genipin can be used for wound dressing. Due to its better wound healing function, this type of dressing could be an excellent substitute for ANGIPARS™ ointment.[115].

4.4. Sporting Goods. In addition to all these, natural fiber biocomposites may also be used in the production of sporting equipment. The flax-based tennis rackets and bicycles among some of the known sporting goods containing cellulosic fibers were reported. In addition to its high specific stiffness, flax fibre has an inherent vibration absorption property. Hybrid materials, composed of cellulose and other fibers, have already been utilized as replacements for wood and metal in products such as golf clubs, ski equipment, fishing rods, spars, and tennis rackets [116].

4.5. Electronics. In the electrical industry, nanocellulose is used to supplement the conductive power of related composites. Researchers exploit nanocellulose in the production of electrical materials due to its renewability, biodegradability, low cost, light weight, and most importantly because it is environmentally benign [117]. An example of this is the use of nanocellulose-based hybrid materials in the biosensing devices to detect analytes such as pathogens, drugs, gases, and biomarkers that may help in diagnosing various diseases. TEMPO-oxidized cellulose nanocrystals was utilized to determine the presence of the amino acids such as phenylalanine, leucine, and valine. The prevalence of these three amino acids is indicative of type 2 diabetes, and by using this specially designed sensor, it was able to examine the serums of both healthy individuals and those with the disease [118]. Cellulose nanocrystals were conjugated with fluorescent dyes and used as biomarkers in mice. Fluorescent dye conjugated CNCs moved to the bones as a result of electrostatic attraction to the calcium ions that make up the bone matrix. This demonstrated that these modified CNCs could potentially be used in therapy that treats bone-related disorders [119].

4.6. Biodegradable Nutritive Pots. In recent years, many consumers have been searching for greener alternatives to obtain biodegradable, eventually recyclable, and derived from renewable resources with minimal pollution for soils and plants due to reports of the detrimental effects of plastic pots used in agriculture on the environment in recent years.[120]. Plastic pots, containers, trays, and containers are widely used in greenhouses and private gardens. These containers are discarded in landfills, where they degrade very slowly [121]. Accordingly, biodegradable pots are an effective substitute for plastics [122]. Plastic pots tend to be light, inexpensive, and durable, and their walls are relatively impermeable [123]. Biocontainers are considerably more expensive as their prices range from 10% to 40% higher than plastic containers [124]. Cellulose fibers are considered to be the raw materials with the greatest availability among existing plants and renewable resources, offering significant advantages over synthetic, inorganic, or mineral fibers [125]. Cellulose-based biodegradable pots were prepared from peat and cellulose fiber preparations done with wire or vacuum dewatering using special molds [126]. Vegetables, flowers, medicinal plants, ornamental shrubs, or various forest species, nutritive and biodegradable pots are used in seedling manufacture in various ways until vine cuttings are produced [127]. In biodegradable pots, high levels of peat provide an optimal medium for seedling root development and provide a nutritional reserve at the same time. This fibrous component ensures oxygen flow by allowing air and water to circulate. The availability of nutrients from peat is not reliable over the long term. In this regard, the methods for keeping nitrogen from urea or ammonium phosphates, as well as pH, are important [126].

4.7. Separation. Nanofibers can be used as filters to trap particulates [128]. In general, filter effectiveness improves linearly when the thickness of the filter membrane is reduced, and the applied pressure rises. The electrospinning method can reduce filter diameters to less than $0.5\,\mu$m, resulting in improved filter efficiency when pressure is increased [129]. An affinity membrane out of regenerated cellulose nanofibers was created. This membrane was functionalized with protein A/G and showed significant immunoglobulin G (IgG) binding capacity, making it suitable for IgG purification [130]. Cellulosic nanofibers have a lot of potential for separation technology in food and beverage plants, but they have not been fully investigated yet [131].

4.8. Water Purification. Cellulose nanofibers (CNFs) of biological origin have been employed to convert waste water into reusable form and for efficient heavy metal cleanup [111]. They are good candidates for application as water purifying biomembranes because of properties such as high specific surface area, nanosize, nontoxicity, hydrophilicity, bioadsorption ability, and so on [132]. Oil and organic pollutants were also separated from water using CNFs. CNFs produced from bacteria were employed as oil adsorbents from water sources was reported by Sai et al. [133]. Incorporation of nanoparticles to the cellulose might also influence the better removal of contaminants (Figure 7).

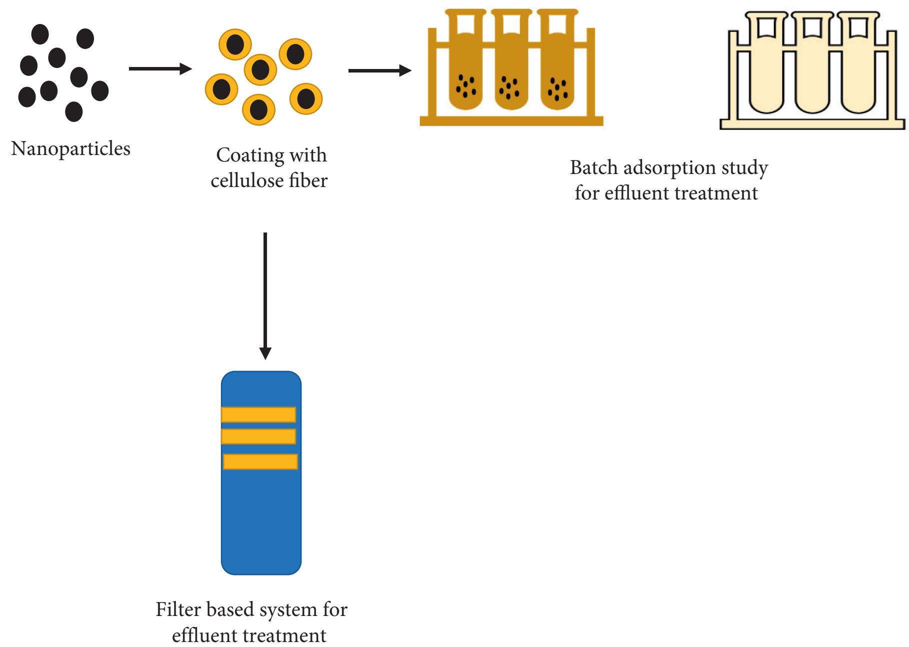

Figure 7: Water purification [134].

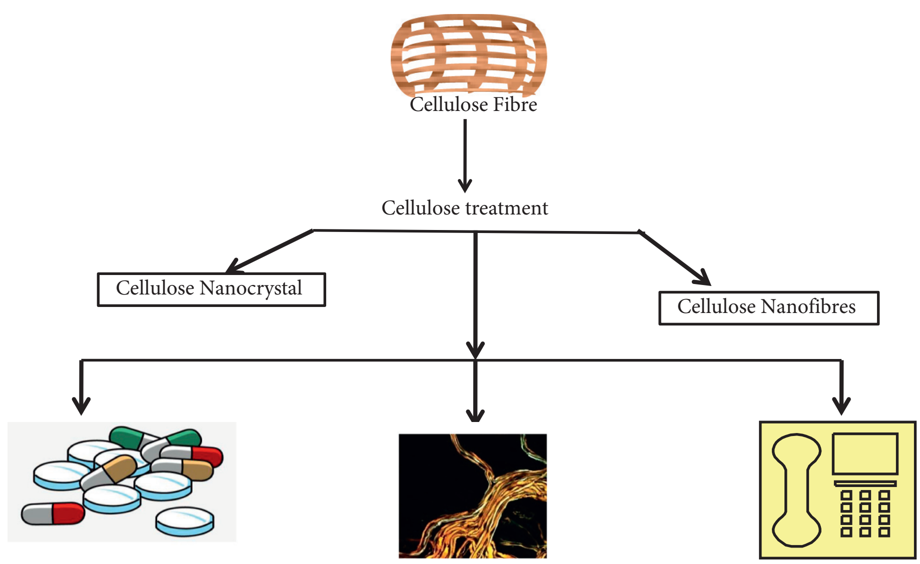

Figure 8: Flowchart of utilization of cellulosic fibres in different fields.

4.9. Food Packaging. Using electrospinning, nanofibers are produced with antimicrobial, antioxidant, oxygen scavenger, moisture absorbent, odor absorbent, and many other bioactive elements embedded [135]. Moreover, nanofibers are highly sensitive to changes in environment and can be modified to contain heat-sensitive molecules [136]. Cellulose offers appealing properties such as hydrophilicity and water insolubility, which can be used as reinforcing agents in packing materials or films [137]. CNFs are utilized as edible coatings on a variety of fruits and vegetables to extend their shelf life. They accomplish this by limiting microbial development, oxidation, and moisture transfer, all of which help to maintain product quality [138]. The presence of cellulose fibers is said to improve the mechanical properties of the fabricated film, such as tensile strength and elastic modulus. The cellulose fibers also lowered water vapor permeability, resulting in a composite edible film with good stability [139].

4.10. Delivery Systems. Nanoencapsulation is a useful technology for disguising unpalatable flavors, protecting nutrients from unfavorable processing and storage conditions, and enhancing the use of low-soluble compounds [140]. Nanolipid carrier (NLC) was used to encapsulate astaxanthin potential application in transparent beverages

[141]. Light, oxygen, and heat are all adversaries of food additives like volatile or unstable flavors and antioxidants. As a result, for the stabilization of functional additives, nanofibers with a greater thermal stability are used [142] (Figure 8). The cellulose can be made into nanoparticle after carboxymethylation and can be used for drug delivery [143–144].

5. Conclusion

Cellulose can be obtained from most plant sources and can also derived from plant-based wastes. It has enormous applications as it is easy to extract, nontoxic, biodegradable, and ecofriendly. Many polyesters and plastics can be replaced by cellulose. In this review, various methods of cellulose extraction and applications of cellulose in various fields like biomedical, environmental, pharmaceuticals, drug delivery, and several nanotechnological applications are discussed. It can be used as a best alternative for commercial products.

Data Availability

No data is used in this review article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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