

Review Article

Study of Progress on Nanocrystalline Cellulose and Natural Fiber Reinforcement Biocomposites

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Cellulosic biomass hydrolysis yields a nanoscale substance known as nanocrystalline cellulose (NCC). Gel, liquid, or powder is adaptable to a variety of uses. Nanocrystalline cellulose has unique renewability, biodegradability, and mechanical and physicochemical qualities, and abundance boosts the material's mechanical strength by many orders of magnitude when introduced into the material matrix (polymer, ceramic, or metal). Nanocrystalline cellulose is not related with any serious environmental issues because it is a natural substance. The progress of this biomaterial as a green and renewable biomaterial for the fabrication of lightweight and biodegradable composite materials gives further impetus. The current aim of nanocrystalline cellulose research is to optimise nanocrystalline cellulose characteristics for dispersion in hydrophilic and hydrophilic media. To assess the nanocrystalline cellulose reinforcing, antibacterial, stability, hydrophilicity, and biodegradability, imaging methods and protocols in complicated matrices will need to be developed. This review includes a discussion on nanocrystalline cellulose biocomposites.

1. Introduction about Nanocrystalline Cellulose

Current interest in cellulose-based materials has increased in demand for renewable and environmental considerations [1]. Natural cellulose fibers have exceptional strength and durability benefits, making them unique in various polymer matrices for reinforcement [2]. One of these agricultural wastes is rice straw consisting of three components: cellulose, hemicellulose, and lignin. The organic fiber is cellulose and hemicellulose, whereas the cell wall is lignin. Cellulose constitutes approximately 50% to 1/4 of the plant tissues and is a sig-

nificant component of all plant materials; photosynthesis is continuously supplied [3]. It is environmentally friendly and renewable, has low density, has low surfaces, and contains hydroxyl surface bands that enable strong oxygen bonds in the single or close chains [4]. Cellulose is the world's largest natural biopolymer. Figure 1 shows hierarchical patterns for cellulose microphones, nanofibers and nanocrystals, and transmission electron micrographs of cellulose microphones.

In the natural world, an essential element is the connection of nanocellulose with hydrogen to other polymer matrices, making cells from highly organized structures that hold chains

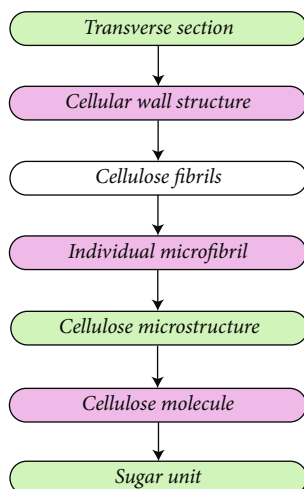


FIGURE 1: Hierarchical structures of cellulose and cellulose microfibrils, nanofibers and nanocrystals, and transmission electron micrographs [5–8].

firmly together and form highly tense microfibrils [9, 10]. Nanocellulose, its unique characteristics, has enhanced mechanical and heat properties such as a layer, mould, and latex [11, 12] by making it an exciting and safe material for polymer strengthening. Various reviews discussed the possible use of composite compounds by cellulose nanocrystals and cellulose nanofibrils [13, 14]. Cellulose has been a typical biomass with a broad spectrum of applications due to sharply growing demands of renewability and sustainability in recent years. During the last decades, particularly, nanocrystalline cellulose has deliberated high surface area, low density, and good mechanical strength, biodegradability, and nontolerable nanostructure characteristics. The nanocrystalline cellulose is now booming in numerous industries and daily applications, including drug excipients, polymers, reinforcement of adherents, and personal care products like hair conditioners and shampoos.

Figure 2 shows the amorphous cellulose chain area removed from cells of a rod structure by acid hydrolysis. Highly intensified scientific research is carried on nanometric cellulose because it is highly available and renovated. They also apply in different fields with their attractive mechanical and chemical characteristics. Both cellulose and nanometric fillers are associated with nanometric cellulose [16]. Nanocellulose is a biological material with the strength of tensile material similar to steel or Kevlar, a high specific surface area of low densities, and good biodegradability. Because of this, nanocellulose is being investigated to be used in some different equipment and sizes, including packaging materials, biomedical equipment, adhesives, electronic, and electroplating [17–25]. In the material sciences, the cellulose-nanofibers attract a considerable number. Due to their magnetic properties (for example, large areas ($100 \text{ m}^2 \text{ g}^{-1}$)), augmented volume-to-volume proportions of 100, and strong crystallinity, it has low density, lightweight mechanical characteristics, and high-porosity arrangement compared with other business fibers [26]. They are also easy to use at cheap rates, as they use less energy during combustion and can be easily recycled [27], in addition to their intrinsic properties and ecologically sodium fibers.

The chemical and mechanical processes are used to extract natural fibers of nanosizes. Hydrolysis chemical is widely used for the extraction of nanocrystalline cellulose. The nanocrystalline celluloses become tremendously interested in material science studies because of its nanometric, high crystallinity, high appearance rates, high mechanical resistance, low density, easy access, and high abundance [28, 29]. The addition of nanocrystalline celluloses has also been reported to decrease starch film permeability by water vapour. It is easy to the morphology of nitric cell fluid, which increases starch-based packaging's slow-down tortuosity and thus improves its suitability for food packing application [30]. The cellulose molecular chains have inter- and intramolecular hydrogen connecting networks as shown in Figure 3.

Students have been highly interested in nanocellulose as a new nanobiomaterial. The nanocrystalline cellulose has a high aspect ratio and a high specific surface area [32]. Furthermore, a highly crystalline area in the single molecular structure makes nanocrystalline celluloses mechanically and accessibly available in food packaging [33]. As a result of its strong hydrogen bonding and its high surface area, the nanocrystalline cellulose is integrated with the organic polymer structures as a packaging material to handle protein defects [34]. Research shows that the alginate film and water barrier [35] are greatly affected by nanocrystalline cellulose.

Cellulose is the primary renewable polymer in the world and is used as nanofiller for PBS. It is often present in plants, tunicates, algae, and bacteria. It consists of a vast molecular polymer composed of multiple β -1,4 glucose units and hydroxyl groups on the side of the chain. Acid hydrolysis is the most common nanocrystalline cellulose extraction technique that breaks down cellulose amorphous areas and crystallises them [36]. Figure 4 shows the structure of the plant cell wall.

In recent years, research has been undertaken intensively on innovative materials filled with nanocellulose [38]. It is because of nanocellulose's exceptional properties. Cellulose is inherently produced from large plant natural sources, such as rice [39, 40] wood, cotton, and biomash [41]. The algae and certain bacteria of cellulose are also synthesized. Marine animal tunics are other exciting sources of cellulose. In many applications, cellulose composites may be used. The adverse effects reduce on polymer composites. For years, it is still known that cellulose has surprised scientists such as automotive, packaging, electronics, and sport [42–44]. The structural structure and cellulose reduction and nonreturn in the planer form are illustrated in Figure 5.

Cellulose is most widely discovered as an important natural material for various applications. Mainly for the production of paper, door panels, seat backs, headliners, packing trays, dashboards, mobile covers, packaging, sports cars or liner, etc., biobased materials are used [46–49].

2. Different Properties of Nanocrystalline Cellulose

The nanocrystalline cellulose meaning covers the strongest and rigid natural market materials [50], such as the resistance of high voltages, high hardness, large surfaces [51],

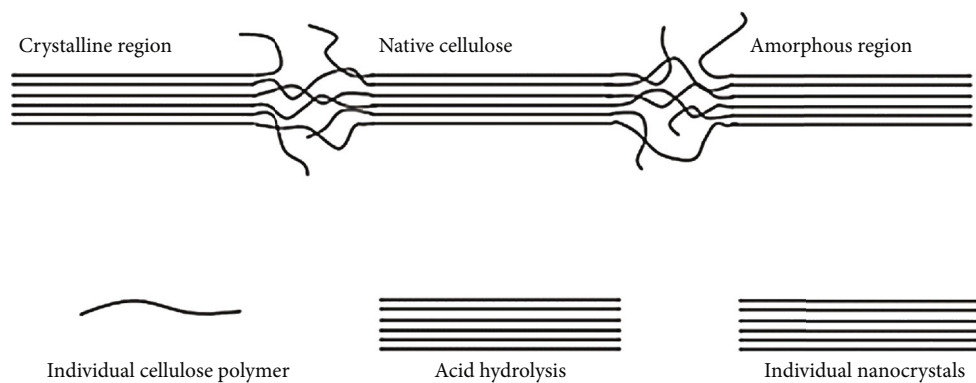


FIGURE 2: Schematic of nanocrystalline cellulose [15].

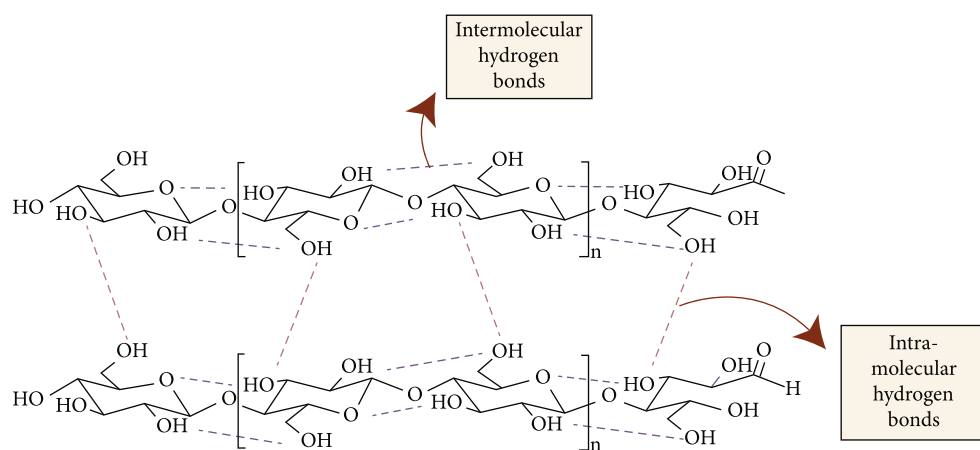


FIGURE 3: Composition of inter- and intramolecular hydrogen bond networks [31].

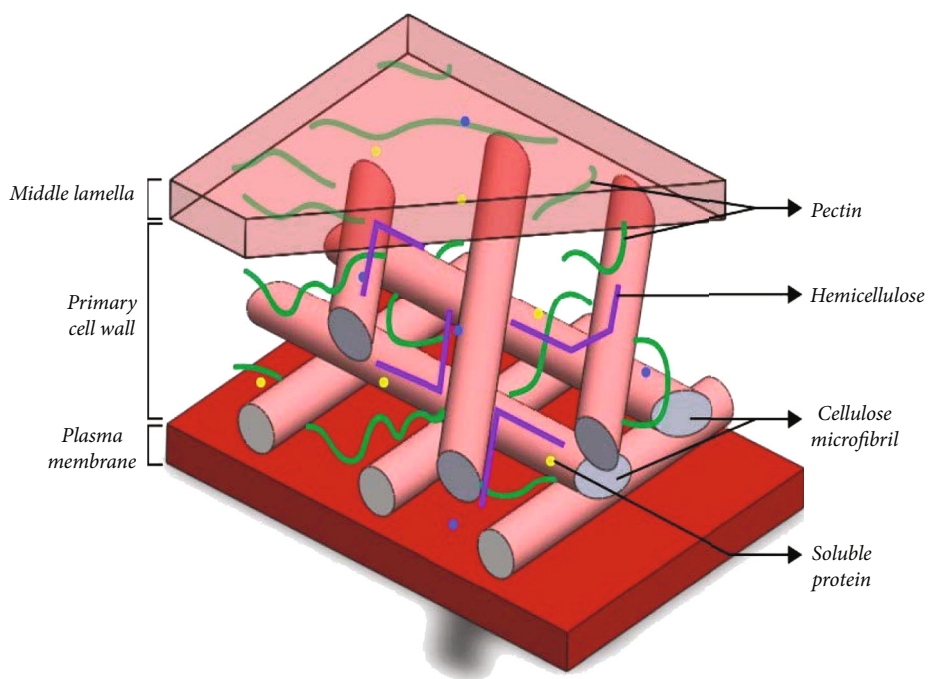


FIGURE 4: A schematic diagram of plant cell wall structure [37].

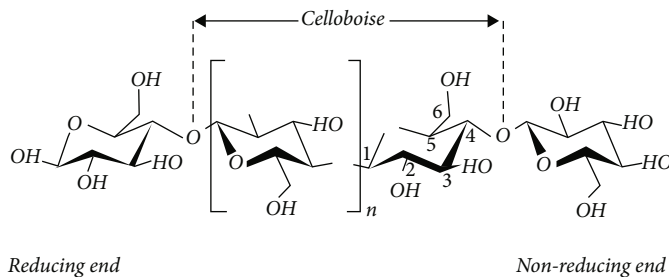


FIGURE 5: Structural organization of cellulose in planner form showing reducing and nonreducing end [45].

low densities, high-load ratio, hydroxyl reactive clusters' variable surface characteristics, and other chemicals, with electrical, mechanical, thermal, and optical characteristics.

2.1. Chemical Properties. Under climatic conditions, age, and degradation process, the natural fiber is structured and chemical. The chemical components spreading across cell walls are the primary and secondary wall layers. Each chemical plant varies from one plant to the next and is presented in Table 1 [52]. Each plant cell wall is primarily charging cellulose. The polymerization of 30-36 β -1 chains and 4 correlated glucose units is a rigid and insoluble crystalline material around cell walls. Hemicelluloses also include plant polymers and acids such as xyloglucans, xylenes, glucomanans, and galactoglucans. Therefore, hydrogen uses to coordinate the cellulose fibrils and gravel them into a matrix of hemicelluloses and lignin's with high molecular weight pectin molecules. In between cellulose and lignin in some walls, the hemicelluloses act as a clamp [53]. Lignin is also a connecting agent that enhances cellulose strength [54].

Cellulose is a biomass-derived biopolymer that is sustainable, abundant, and natural. The cellulose structure is arranged in fibrils with a lignin and hemicellulose matrix surrounding it [56]. It is the classic example for the plant of polymer plants of a renewable and biodegradable fabric polymer [57]. According to researchers, the overall production of the biopolymer is forecast to exceed € 7.5/1010 tonnes per year. However, only about 6 to 109 tonnes are processed in the paper chemical, fabric, material, and chemicals [58]. Figure 6 shows the biodegradable polymer matrices. Table 2 shows the chemical compositions of some natural fibers.

2.2. Thermal Properties. As regards nanocrystalline cellulose, its thermal property is one of the main restrictive factors in the application of nanocrystalline cellulose(NCC) mechanical characteristics at high temperatures [50]; however, the nanocrystalline cellulose is excellent for the treatment of heat thermoplastics ($n200^{\circ}\text{C}$) [61] (NCC degradation, usual at 0 temperature). For example, in the paper industry, paper with extra durability, strength, and flexibility is produced using nanocrystalline cellulose. In addition, nanocrystalline cellulose has unique papers with optical characteristics [62], in some cases.

2.3. Optical Properties. Researchers initially found liquid crystalline nanocrystalline cellulose, which resulted in an

TABLE 1: Chemical composition of standard lignocellulosic fibers [52, 55].

Type of fiber	Source	Composition (wt %)		
		Cellulose	Hemicellulose	Lignin
Wood	Hardwood	31-64	25-40	14-34
	Softwood	30-60	20-30	21-37
Nonwood	Bagasse	32-55.2	16.8	19-25.3
	Coir	32-43.8	0.15-20	40-45
	Corn cobs	26.1	45.9	11.3
	Corn stalks	35	25	35
	Cotton	82.7	5.7	<2
	EFB	43-65	30	19
	Oil palm frond	56.03	27.51	20.48
	Flax	62-72	18.6-20.6	2-5
	Hemp	68-74.4	15-22.4	3.7-10
	Jute	59-71.5	13.6-20.4	11.8-13
	Kenaf	31-72	20.3-21.5	8-19
	Ramie	68.6-85	13-16.7	0.5-0.7
	Sisal	60-78	10-14.2	8-14
	Sunn	80	10	6
	Wheat straw	43.2	34.1	22
	Curua	70.7-73.6	9.9	7.5-11.1
	Abaca	56-63	20-25	7-13
Alfa	45.4	38.5	14.9	
Bamboo	26-65	30	5-31	
Banana	63-67.6	10-19	5	
Coconut	36-43	0.15-0.25	41-45	
Soy hulls	56.4	12.5	18	
Rice husk	25-35	18-21	26-31	
Rice straw	59.1	18.4	5.3	

interesting observation of the nanocrystalline cellulose in 1959, in birefringence suspension. Most of the studies focused on nanocrystalline cellulose observations of this phenomenon. Li et al. produced a solid, cellulose iridescent film with a unique NCC feature to create safety documents such as banknotes, passports, and flat-water supplies [61] concerning the optical qualities of nanocrystalline cellulose.

2.4. Mechanical Properties. Table 3 shows the cellulose nanocrystals and other strengthening materials mechanical



FIGURE 6: Biodegradable polymer matrices [59].

TABLE 2: Chemical compositions of some natural fibers [60].

Fiber	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Waxes (%)
Sugarcane bagasse	45	30	24	1
Bamboo	26-43	30	21-31	—
Flax	71	18.6-20.6	22	1.5
Kenaf	72	20.3	9	—
Jute	61-71	14-20	12-13	0.5
Hemp	68	15	10	0.8
Ramie	68.6-76.2	13-16	0.6-0.7	0.3
Sisal	65	12	9.9	2
Coir	32-43	0.15-0.25	40-45	—
Pineapple leaf fiber	81	—	12.7	—
Curaua	73.6	9.9	7.5	—

properties. Nanocrystalline cellulose characterizations are calculated through atomic force microscopy (atomic force microscope), analysis of radiation diffraction, inelastic radi-

TABLE 3: Cellulose nanocrystals and other strengthening material mechanical properties [10, 64–66, 50].

Material	σ (MPa)	E (GPa)	ρ (g cm ⁻³)
CNC	7500 - 7700	110 - 220	1.6
Glass fiber	4800	86	2.5
302 stainless steels	1280	210	7.8
Softwood kraft pulp	700	20	1.5
Carbon fiber	4100	210	1.8
Boron nanowhiskers	2000 - 8000	250 - 360	—
Aluminum	330	71	2.7
Carbon nanotubes	11000 - 63000	270 - 950	—
Kevlar KM2 fiber	3880	88	1.4

σ = tensile strength; E = elastic modulus in axial direction; ρ = density.

ation dispersion, and Raman effect. It carries theoretical and indirect experimental measures [63].

Nanocrystalline cellulose has been extensively studied in several areas, including polymer electrical electrolytes, packaging, antireflective, and solid iridescent movies for its excellent mechanical properties [67]. Finally, nanocrystalline cellulose natural cellulose characteristics are not only

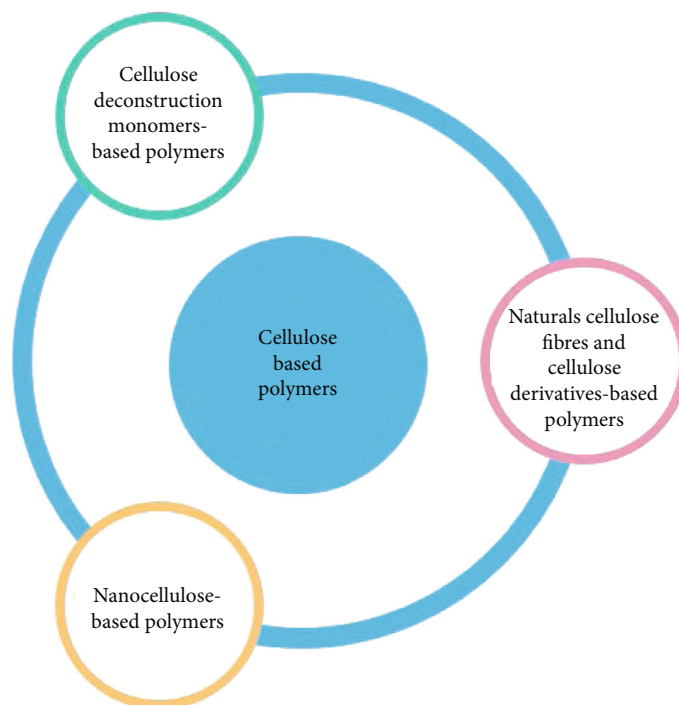


FIGURE 7: Main routes for the production of biopolymeric materials from various forms of cellulose [45].

inherent but have unique features like high crystallinity index (N70 per cent), large surface area ($\sim 150 \text{ m}^2/\text{g}$), and high tensile strength aspect ratios (~ 70) (7500 MPa). NCC has been taken into account in specific sectors in recent years, for example, regenerative medicine, printing, optical applications, and composites [68].

3. Extraction Methods of Nanocrystalline Cellulose

In order to reach nanostructured cellulose molecules of high crystalline and surface areas, the hierarchical structure of natural fibers must be separated. Many extraction methods for glycosidic strips have been reported to break the cellulose nanofibril domain. It includes and combines two or more such techniques and mechanical, chemical, and biological treatment. Furthermore, all such methods lead to the development and disintegration of nanostructured cellulose molecules. Generally, nanofibrillar cellulose, called cellulose nanofiber, is produced by mechanical cellulosic decomposition. Cellulose's nanofibers such as homogenising, cry-crushing, microfluidisation, grinding, and high-intensity ultrasonic have mechanical approaches available [69]. An essential approach to the alignment process is enzymatic pretreatment for lignocellulosic fiber. We know that pretreatment in mild and chemical processing conditions is economical, energy-free, environmental, productive, and biological [70].

In biological pretreatment, lignin and hemicellulose decay with the help of lignocellulosic materials such as brown, white, and spongy red champagne and bacteria. The natural treatment may include an enzyme from microbes. Brown red and soft fungi attack mainly cellulose,

while white red hits both cellulose and lignin. Compared to other pretreatment procedures, there are also inherent disadvantages, such as long pretreatment times and high rates [71, 72]. Cellulose-nanocrystalline, alkaline pretreatment, acid hydrolysis, oxidants, and ionic fluids are the most promising methods in chemical pretreatment. Acid hydrolysis is the standard method used to prepare nanocrystalline cellulose because of moderate working conditions and excellent suspended stability. The amorphous regions around the cellulose fiber are destroyed in controlled conditions to maintain crystalline areas under acid hydrolysis. Nonetheless, to separate lignin from its cellulose biopolymers must be energetically pretreated. Then, biopolymers formed and required deconstruction, derivation, and nanoparticles. Three main routes are manufactured with cellulose-based polymers. The principal routes for biopolymer production in different forms of cellulose are exhibited in Figure 7.

Natural fillers based on cellulose nanofibrils and cellulose microfibrillated, essential particle size factors affect the stability, durability, and strength of lignocellulose-based biocomposite materials [73–75].

3.1. Plasma Processing Technology. The formation of cellulosic nanomaterials is derived from biomass residues. In the last few years, however, several attempts have been made during production on the bench scale to improve the process' acceptance in an industrial context. In this light, the heterogeneous solid acid catalyst of the cotton linter microcrystalline cellulose with amberlite IR 120 was one step of forming nanocrystalline cellulose in this regard. The first-order kinetics of $42.8 \text{ per } 10^{-2} \text{ min}^{-1}$ and a response rate of $10.1 \text{ per } 10^{-5} \text{ mol/minute}$ were followed in the production method.

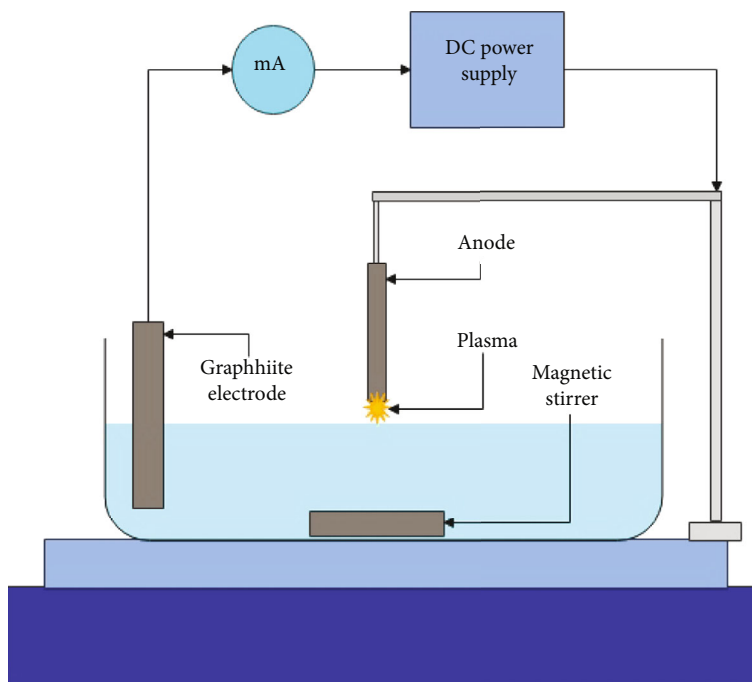


FIGURE 8: Schematic representation of the nanocrystalline cellulose preparation experimental using plasma processing technology [76].

It has shown that in ultrastructural morphological analysis, the average particulate diameter is 36 nm. Furthermore, they investigate four distinct types of lignocelluloses: feedstocks, a rapid and effective grinding method, liquefaction, centrifugation, and washing for nanocrystalline cellulose isolation [77]. Liquefaction of glycol and methane sulfonic acid shows efficacy during isolation. However, in terms of implementation, it takes a lot of time to respond to multistage processes and increases the total cost. In addition, a pot-oxidant method for hydrolysis has been developed as a biomaterial for the manufacture of cellulose tools with plain electroprocess. The mean nanostructure material fiber diameter was 51.6 ± 15.4 nm. In addition to conventional procedure, a 6.5 per cent added to crystallinity for the product acquired with the pot response. A further study used microcrystalline cellulose empty fruits to isolate nanocrystalline cellulose with ultrasound TEMPO oxidation as lignocellulosic feedback. Sonic treatment was observed when the yield increased by about 39 per cent compared to the nonsonic condition, with a significant effect on the insulation process. Structural analysis shows a rod similar to crystalline morphology for extracted nanocrystalline cellulose biomass, with an average length of 122 nm, respectively, and a width of 6 nm [78]. A new plasma solution method helps develop the nanocrystalline cellulose [79], microcrystalline cellulose, and FP as the source material in an electrolytic solution. Figure 8 shows the scheme for the experimental system used in plasma therapy for nanocrystalline cellulose development. The graphic anode placed under atmospheric pressure transmits direct current into the surface area of the electrolytic solution as a cathode. As a consequence, the redox reaction occurs when the glow discharge appears. Cellulose

oxidation causes the hydroxyl surface to occur during the reaction when plasma processing is carried out with distilled water due to subsequent hydrolysis.

3.2. Acid Hydrolysis. Concentrate the desired acid and deionized water in combination with the purified initial product. It is the best technique used to separate cellulose nanocrystals from cellulose fibers [38, 78, 80]. The procedure involves acid-induced deconstruction, including the spread of acid molecules through heterogeneous acid hydrolysis to cellulosic microfibrils. Glycosidic bonds are cleaved into the amorphous cellulose fibrils which cause the hierarchy of fibril bundles to break down into cellulose nanocrystals [39, 81].

There was a selective splitting in the cellulosic chains [20] in the difference in kinetic hydrolysis from paracrystalline to crystalline areas. These acids' most common chemical function consists of the release of a glycosidic cellulosic ion, which causes oxygen elements to spread and amorphous glycosidic bond hydrolytic splits [16] to react to glycosidic bonds between the two oxygen moieties 103, 102, 103, 103, and 102. The acidic therapy hydrolyzes pectin, and hemicellulose residues break polysaccharides into simple sucre. Thanks to their large freedom of motor after the hydrolytic division, these crystallites can grow in size and thus in dimensions greater than the original microfibrils [20]. Cellulose nanocrystals have quickly reduced their polymerization due to acid hydrolysis. Dialysis with deionized water separates and rinses the mixture at the end of the procedure to remove residual acid and neutralised salt as in Figure 9.

Sonic treatment is generally applied [16, 38, 78, 84, 85] to improve and homogeneously disperse cellulose nanocrystals in aqueous media.

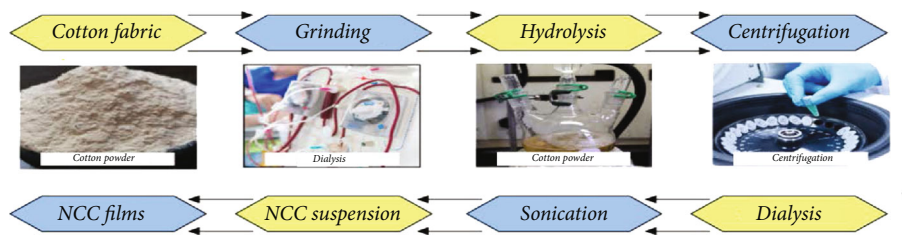


FIGURE 9: Schematic representation of the different steps used to produce CNCs using acid hydrolysis [10, 82, 83].

3.3. Ionic Liquids. Cellulose is a potent solvent ionic liquid. It consists of liquid molten salts and is thus commonly referred to as “green” solvents at environmental temperatures. The first ionic liquid used to isolate NCC from the sugarcane bagasse was 1-butyl-3-methylimidazolium chloride. Studies show that cellulose dissolution in 1-ethyl-3-methylimidazolium acetate results in no substantial 85°C degradations of the polymer cellulose chain. Cellulose dissolving potentially of this sort of ionic liquid is not decided to the same degree by the ionic liquid presence of water [86]. The cellulose has been dissolved and blocked by the homogenizer. Consequently, 100% NCC crystalline structure is one of the effective uses of ionic liquid. Cellulose was dissolved and passed by an ionic fluid without obstruction. Then, by adding water, cellulose was taken in, and by freezing, NCC regenerated. The reaction temperature, microwave power, and weight relationship between cellulose and ionic liquid are soluble in cellulose. The best solubilization found was also demonstrated when the 400 W microwave response temperature was 130°C and 1% ionic liquid ratio [82]. Thus, cellulose insolventy retains 1-ethyl-3-methylimidazolium acetate with just 15-16 wt % of its water content. Some reports describe prepared NCCs, including totally amorphous and partially crystalline NCC, by regenerating lignocellulosic ionic liquid [87]. The crystallinity observed seems to depend on the time of dissolution, cinematic recovery, and solvent-free choice. Therefore, the ionic liquid offers a new route for the disintegration and restoration of lignocellulosic substances.

3.4. Mechanical Treatment. In the process of production with hydrolytic acid, oxidative and enzyme treatment combinations, or directly [14, 88, 89], the mechanical methods of producing nanoscale cellulose particles have also been extensively studied. They include microfluidisation, ultrasound, homogenization at high pressure, and ball milling.

The methods are often used to make cellulose nanofibers with nanometers or decades of nano-thermometers and up to several meters in length [10, 90]. Some researchers have used high energy bead framing (HEBM) [89] to develop a scalable mechanical method in recent years. Applications of commercially available microcrystalline cellulose (MCC) have been isolated from and aqueously dispersed or diluted acid (phosphoric acid) by the authors in the course of a HEBM process. The morphology and the dimension ratio values of acid hydrolysis are very similar to the cellulose nanocrystals. The cellulose nanocrystal output rate was between 57% and 76%. The resulting rod, similar to cellulose nanocrystals, is a high thermal stability crystallinity index

between 85 and 95%, which is used to melt the most common thermoplastics. The isolation of cellulose nanocrystals by ultrasonic use was also mentioned by another mechanical method [61, 89]. Rod-shaped cellulose nanocrystals were made using a purely physical high-intensity ultrasound method from an aqueous dispersion of microcrystalline cellulose. The cellulose nanocrystal was 10-20 nm in diameter and 50-250 nm in length.

However, the output of this method of cellulose nanocrystals does not exceed 10%. The ultrasound effect was not selective, meaning that amorphous cellulose and crystalline cellulose can be eliminated. Water is known to have the ability to hydrolyze polysaccharides [91]. The main features of a prevailing hydrolysis rate are water molecules and the accessibility of H_3O^+ and water species. In sub- and supercritical water, lower and higher species levels are present [92]. Their use for hydrolysis reactions could therefore be efficient. In some studies, water has previously been used to produce lignocellulosic material at high temperatures and pressure. Very few studies on subcritical water hydrolysis method cellulose nanocrystals production have been reported [93]. Not only because of its greener characteristics but also because of the low and cleaner waste, low corrosion, and low reactant costs, it is the sole use of water as a reagent promising. [94] used this procedure for the production of commercial microcrystalline cellulose nanocrystals. The authors reported that optimising reaction conditions certainly means high-quality cellulose nanocrystals [93]. Hydrolyzed cellulose joins with subscriptive water (120°C and 20.3 MPa for 60 minutes). The states of the experiment permit for more water, activity, and ionization diffusion. Partial cellulose hydrolysis with a yield of 21.9% has therefore been achieved. The cellulose nanocrystals obtained showed a high index of crystallinity (79.0 per cent) and rod-like form with the same aspect of cellulose nanocrystal as those reported. Moreover, the thermal firmness of these cellulose nanocrystals was better than the source of cellulose (approximately 300°C).

4. Modification of Nanocrystalline Cellulose

Table 4 shows the effect of structural modifications on nano-based crystalline cellulose. Change of the nanosurface cellulose is the essential process to ensure homogenous distribution and enhanced polymer matrix compatibility. Some techniques for this purpose have also been registered, including esterification, siltation, polymer grafting, and mediate oxidation of 2,2,6,6-tetramethylpiperidine-1-oxyl (tempo).

TABLE 4: Effect of structural modifications on nanobased crystalline cellulose [95–102].

Methods of modification	Process followed	Key results
Chemical modification	Partial oxidation of cellulose which was immediately followed by interaction of aldehyde groups with amino group of polyglutamic acid	The modified cellulose exhibited enhanced compatibility with hydrophobic polylactic acid when composite materials were prepared
Surfactant-aided modification	Suspension of NCC was mixed with various surfactants of different concentrations using orbital shaker at 200 rpm for 24 hours	The modified NCCs were observed as potent drug carrier for paclitaxel
Surface modification	1% (<i>w/v</i>) of NCC suspension was mixed with TA and DA using 1 and 40 mg/mL of concentrations, respectively. The mixture was stirred for 3 hours at room temperature prior to obtain the final product	The modified NCC obtained from OPEFB was observed with improved curcumin binding efficiency in the ranges of 95–99%
Hexadecyltrimethylammonium bromide- (CTA-) assisted hydrophobic modification	Spin coating technique was used to prepare CTA-based NCC film	Surface plasmon resonance technique revealed the ability of the film to sense copper ions more efficiently
Chemical modification	Alkaline hydrolysis of Eichhornia crassipes using 10% (<i>w/v</i>) of NaOH at 100°C for 3 hours followed by acidic oxidation using peracetic acid (CH ₃ CO ₃ H) at 80°C for 2 hours	NCC obtained from chemical modification of the biomass was observed to remove an anionic dye (reactive blue 21) and basic dye (crystal violet) efficiently
Cationic surfactant cetyltrimethylammonium bromide- (CTAB-) mediated surface modification	100 mL 0.4% (<i>w/w</i>) of NCC suspension prepared from Citrus limetta albedo (by alkali treatment, bleaching, and acid hydrolysis) was added into 100 mL 4 mM of CTAB solution, and the mixture was heated at 60°C for 3 hours	After the modification, NCC was observed with enhanced surface area and also investigated as sustained release drug delivery system for NSAID
Chemical modification	A derivative compound of nanocrystalline cellulose was synthesized, namely, cationic dialdehyde cellulose (CDAC), by sequential oxidative reductive amination process	Nanocrystalline cellulose was observed as promising nanofiller with improved strength and antismwelling properties for reinforcing chitosan (CTS) film when 1% of CDAC was well mixed with 1% solution of chitosan
Chemical modification	The surface modification is anticipated in aqueous organic media through aromatic nucleophilic substitution in the presence of an alkaline reagent	The modification explored the chemistry of postmodification for the applications of grafting molecules onto cellulose

4.1. Acetylation. The esterification reaction has become a famous method of hydrophobic cellulose surface treatment. Cellulose pretreatment groups replace the surface cellulose groups with acetic nanoparticles with cellulose function groups (COCH₃). Acetylic anhydride is used in homogeneous and heterogeneous forms with acetylating cellulose nanoparticles in the presence of acetic acid and small amounts of catalysts such as sulfuric acid or perchloric acid. When the partially acetylated molecules are sufficiently soluble during a consistent acetylation process, on the other hand, precipitate isolation is not necessary during the heterogeneous reaction. In homogeneous reaction conditions, a replacement time, temperature, and molar cellulose derivative ratio can be easily managed. Natural polymer degradation is negligible during the response and degrading, and additional routes are available to replace or implement new working groups in full. The state of acetylation plays an essential role in altering the physical properties of cellulose while maintaining the microfiller morphology. Research shows a high degree of transparency and decreased hygroscopicity of acetylated composites and improved thermal resistance to cellulose acetylation and increased natural resistance to acetylated plant fiber/polyester composites [103].

4.2. Silylation. Another efficient mechanism to stabilise the spread of nanocellulose particles into a suspension is the partial nanocellulose situation. On the nanocellulose surface, a random distribution of alkyl molecules such as n-butyl, N-octyle, N-dodecyle, and isopropyl defines its content by surface substitution (DS). Cellulose might disperse with DS value 0.61–1, resulting in a colloiddally stable dispersion, with intact morphological properties, in a solvent that has low polarity (tetrahydrofuran). But since the chains in the centre of crystals are linked with high sialylation (DS over 1), crystals are disintegrated and original morphology is lost. After the surfaces were altered by the partial sialylation of various alkyl moieties [104], Goussé et al. received a stable suspension of tetrahydrofuran tunicate whiskers (THF).

4.3. Polymer Grafting. An alternative way to improve the fiber-surface hydrophilicity is polymer grafting on the nanocellulose surface. Two main strategies are used for polymer grafting. Connector components are used in the “grafting on” approach to attach the presynthesized polymer chain to the hydroxyl cellulose surface groups. On the other hand, the “graft of” approach-initiated polymerization on location constitutes polymer chains onto the substratum by the immobilized initiator. The first approach to the “grafting

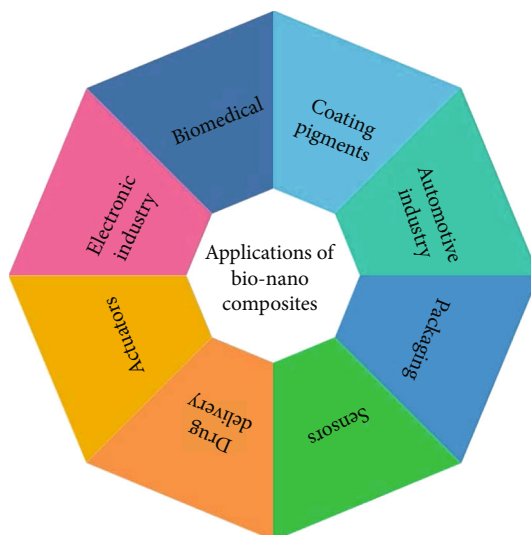


FIGURE 10: Applications of cellulose nanoparticle-reinforced biocomposites in various fields.

on” approach was [105] to take the grafting of DNA oligomers on the cellulose surface [74], while Habibi et al. first reported the “grafting from” approach. This work involved the modification of the area by the grafting of poly (ϵ -caprolactone) using stannous octoate ($\text{Sn}(\text{Oct})_2$) [7] through the ring-opening polymerization.

4.4. Active Agent/Surfactant Surface Area. By interacting with the subfactor and/or active surface agents, the hydrophilic cellulose suspension adhesive can also be increased to a nonpolar hydrophobic polymer matrix. Tensile is generally defined as an agent to lower water surface tension. Thus, the use of cellulose modified by surfactant would alter the dynamic of nanocomposites’ surface tension relative to their interface. The interfacial tensional value generally lies between the two immiscible phases of the surface tension values. Therefore, if two-stage molecules have similar surface tensions, interfacial tension will be zero [106].

For this reason, literature uses stresses such as alkenyl succinic anhydride, isocyanate, polypropylenes malleated, or chlorosilane. Noncovalent surface modification typically takes place by adsorption of the surface of nanocellulose. Surface modification by nanocellulose surfactant made of mono and phosphoric acid diester and alkyl-phenolic tails was introduced by [107]. Cellulose-modified particles have been dispersed in nonpolar solvents. Furthermore, in nanocomposites, [64] reported the polystyrene nanocellulose-coated surfactant. In addition, improve the dispersion of ionic surfactant modification cellulose in poly(lactic acid (PLA) polymer matrix [108].

5. Applications of Cellulose Nanoparticle-Reinforced Biocomposites

The potential for various applications for cellulose nanoparticles is present, and their use in nanocomposites is widely studied. With the integration of biofibers, biofibers, based

on renewable energy resources such as cellulose plastics, starch plastic, polyhydroxyalkanoates, and polylactides, will become green biocomposites soon. Nanocellulose is primarily considered for applications on paper and packaging and construction, automotive and furniture, electronics, pharmaceuticals, and cosmetics as in Figure 10.

For companies producing electro-electro acoustical devices, nanocellulose is used as a high-quality sound membrane. Nanocellulose has been used in various applications, including first-rate electronic paper additives (e-paper), ultrafiltration refining membranes, oils for mineral oil regeneration, and membranes. The high strength, rigidity, and small dimensions of nanocellulose can convey special features to the use of fiber-reinforced composites and may later in different applications, and it is shown in Table 5 [109].

5.1. Biomedical Applications of NCC. Since the toxicity of nanocrystalline cellulose has not been implemented, NCC has been introduced to biomedical applications by several research groups. [116] suggested modified nanocrystalline cellulose, especially chemotherapy agents, for the targeted delivery of medicines [113]. For example, NCC successfully targets and controls the supply of folic acid in the mammalian brain to cancerous tumours. Nanocrystalline cellulose also has numerous biomedical applications, such as the diagnosis and stagnation of NCC (e.g., the use of human elastase enzyme at a damaged site) [117] and also has cardiovascular graft replacements [8], enzyme/protein [118] immobilization, and viral inhibitors (alphaviruses and perhaps also herpes simplex viruses). The fluorescent labelling of nanocrystalline cellulose provides potential applications in biomedical questions such as biosamples, bioassays, and applications in bioimaging [63].

5.2. Other Potential Applications. Tissue engineering, wastewater packaging, structural and efficient characteristics of

TABLE 5: Applications of NCC derivatives in different fields [110–115].

Type of cellulosic derivatives	Field of applications	Key findings
NCC (nanocrystalline cellulose)	Biomedical	3D printable with cartilage regeneration once NCC aerogel structure was crosslinked with polyamide epichlorohydrin
NCC (nanocrystalline cellulose)	Waste water treatment	Starch-based hydrogel nanocomposite reinforced with magnetic functionalized NCCs for the application as a novel nanoadsorbent in the removal of cationic dye from aqueous solution
NCC (nanocrystalline cellulose)	Food packaging	Incorporation of 8% NCC resulted into the improvement in food preservation characteristics both in gelatin and starch-based composite films
MCC (microcrystalline cellulose)	Pharmaceutical	MCC was well observed as an efficient adsorbent for peppermint oil (PO), a multicomponent liquid drug
MCC (microcrystalline cellulose)	Pharmaceutical	MCC-based hydrogels were observed in vitro to load and deliver cephalexin in various simulated body fluids
MCC (microcrystalline cellulose)	Polymer composite	Surface-modified MCC using urea was filled with chitosan for the preparation of polymeric composite materials with improved stability and function
MCC (microcrystalline cellulose)	Adsorption	Pyridonedi acid functionalized (PDA) was synthesized for the removal of lead and cobalt with maximum adsorption capacities of 177.7 and 122.7 mg/g, respectively

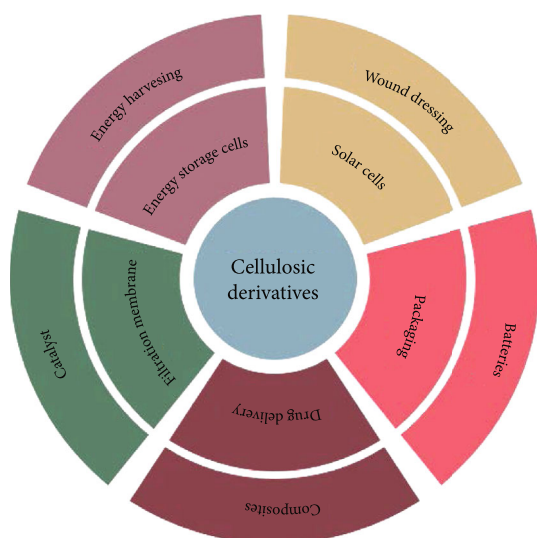


FIGURE 11: Promising applications of cellulosic derivatives.

cellulosic products, and significant applications in the pharmaceutical sectors are also being utilised in several areas: alternative materials, the recognition of metal ions, and the production of electronic goods and parts. In polyvinyl alcohol, nanocrystalline cellulose is widely used and distributed to enhance mechanical properties (PVA). The main ingredient in nanocrystalline cellulose modification as a binding agent was 1-hydroxymethyl-5-dimethylhydantoin with cyanuric chloride (cych) (HDH). The synthesiser NCC cych-HDH-Cl has been discharged into PVA or chitosan for antibacterial film preparation after chlorination. Effects on *Staphylococcus aureus* (ATCC 6538) and *Escherichia coli* O157:H7 (ATCC 43895) [119] were significantly detrimental to the latter. Membranes of cellulose acetate (CA) are also used for food packaging. Nanocrystalline cellulose particles are, however, well integrated with these membranes to enhance their industrial usefulness, using N-halamine pre-

cursors for polymethacrylamide (NCC PMAMs). Thus, for *Staphylococcus aureus* and *Escherichia coli*, the composite membranes had good antibacterial properties within 10 and 5 minutes, respectively [83].

In the recent successful cellulosic derivatives study, Figures 11 and 12 shows a variety of applications. In preparation of biocomposite materials, nanocrystalline cellulose is widely used as possible nanofiller. But poor addition between the matrix and the filler causes nanoparticles to autoaggregate and reduces adhesion of the polymer matrix. Tempo-mediated oxidation was performed for PLA- and PHBV-strengthened polymer composites to overcome these constraints by the nanocrystalline cellulose suspension resulting from OPEFB [120].

The biocomposites are developed to offer full potential as packaging materials through the increased oxygen obstacle and mechanical stability. In addition, nanocrystalline cellulose helps maintain structural integrity in the production of sensors due to its structural description of a high surface area, an important aspect ratio and considerable rigidity. Nanocrystalline cellulose quantum point-assisted tyrosinase [122, 123], an integrated biosensor for aqueous system phenol detection, has been developed.

The NCC was amended during CTAB architecture to improve the conductivity of samples by decreasing the hydrophilicity of the cellulose derivative. In the end, a sensor has urbanized reasonable phenol detection limits with 0.0008 mg/L LODs of 0.5 to 3.8 mg/L. In research, NCC modified by CTAB and GO was produced to permeate the nickel ions selectively. SPR has been used to determine the nanocomposite material's binding affinity constant. A nickel ion of a broad range of 0.01 to 0.1 mg/L is the 1.6/103 binding affinity constant [98]. In addition, for possible use in fuel cells as conducting membrane, a single proton-driving nanocomposite was prepared with NCC imidazole-doped molecule. The maximum electrical conductivity showed at 140 B/C with 1 imidazole per 1.7 units of glucose was 2.7 10⁻² s/m, which is an improvement of 5 times that of non-doping performance [110, 124].



FIGURE 12: Various applications of nanocellulose (NCC) [121].

6. Conclusions

The exploration of new materials for advanced applications has been fascinating for environmentally sound biorenewable materials from various natural resources.

- (i) Among the several renewable resources, cellulose is the most common and significant polymer in nature. Several types of cellulose may be processed, including fiber, cellulose microphones, and nanos
- (ii) Recently, cellulose nanocrystals (CNC), especially for their crystalline structure and crystalline structure, were investigated in several advanced applications. Despite the great advantages of cellulose nanocrystals, their broad application was limited in terms of energy consumption and production costs
- (iii) Thus, the first portion of this study concentrated on cellulose supplies and CNC manufacturing processes. They also spoke about cellulose structural organization and cellulose nanomaterial nomenclature for beginners
- (iv) We consider that the research presented in this paper increases researchers' interest in nanomaterials based on cellulose and a fundamental understanding of nanocrystals from cellulose

Data Availability

The data used to support the findings of this study are included within the article. Further data or information is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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