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Methods of isolation of nanocellulose from wood: A review

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Abstract

Nanocellulose can be extracted from variety of lignocellulosic bio resources like jute, flax, ramie, hemp, wood and by-products of agricultural crops via various methods. Among these bio resources, wood is the most suitable source for commercial level production of nanocellulose because of its abundance, easy availability, low cost and sustainable production. Various studies have been carried out to the synthesis of highly purified cellulose Nanofibers from cellulosic materials via chemical treatments, enzymatic treatments, high pressure homogenizing, Cryocrushing, grinding; as well as a combination of two or several of the before mentioned methods. Since wood is the main raw material for industrial level production of nanocellulose, a better understanding of currently available methods may help to find out even more efficient, economically viable and environmental friendly methods for isolation of nanocellulose from wood in future. In this context the present article reviews the possible isolation methods of nanocellulose from wood.

Keywords: Wood, nanocellulose, homogenization, acid hydrolysis, tempo oxidation, sonication, microfluidizer

Introduction

Today the term “nanocellulose” is very familiar to research community. Cellulosic materials with dimension less than or equal to 100 nm at least in one dimension is defined as nanocellulose. The understanding of versatile characteristics of nanocellulose such as high specific strength and stiffness, high aspect ratio, large specific surface area, high reinforcing potential and biodegradability, attracted many researchers to carry out research on this novel material. The research on this material can be divided into three domains; first, to find out better cellulosic biomass for efficient extraction of nanocellulose; second, energy efficient, economically viable and environmental friendly methodology for production of nanocellulose; and third, its modification and advanced applications in different fields. This review is focusing on first aspect, most specifically the use of wood as a raw material for nanocellulose production.

Researchers from different parts of the world isolated nanocellulose from different plant materials like wood fibers (Abe, Iwamoto, and Yano 2007) ^[1], cotton (de Moraes *et al.* 2010) ^[13], potato tuber cells (Dufresne, Dupeyre, and Vignon 2000) ^[16], both cladodes and spines from *Opuntia ficus-indica* (Malainine *et al.* 2003) ^[29], prickly pear fruits of *O. ficus-indica* (Habibi *et al.* 2008) ^[18], lemon and maize (Rondeau-Mouro *et al.* 2003) ^[40], soybean (Wang and Sain 2007) ^[52], wheat straw and soy hulls (Alemdar and Sain 2008) ^[2], hemp fiber (Wang, Sain, and Oksman 2007) ^[51], coconut husk fibers (Rosa *et al.* 2010) ^[41], branch-barks of mulberry (Li *et al.* 2009) ^[26], pineapple leaf fibres (Cherian *et al.* 2010) ^[11], banana rachis (Zuluaga *et al.* 2009) ^[53], sisal (Moran *et al.* 2008) ^[31], pea hull fibre (Chen *et al.* 2009) ^[9] and sugar beet (Dinand, Chanzy, and Vignon 1999; Dufresne, Cavaille, and Vignon 1997) ^[14, 15] in laboratory conditions. But for commercial level production of cellulose, these raw materials except wood are not advisable because of its low availability, scattered distribution, difficulty harvesting and conversion procedure and high cost. Being the most abundant and sustainable material wood is the most suitable raw material for commercial and industrial level production of nanocellulose. About half of the wood is composed of cellulose. Many nanocellulose production units like celluforce, NAPPI, etc. are using wood as the source of cellulose. In this context the present review analysing the importance and scope of wood as a source of cellulose for the production of advanced cellulosic nanomaterials.

Isolation of nanocellulose from wood

Isolation of nanocellulose can be done mainly by three methods; 1. Mechanical methods like grinding, refining, homogenizing, cryocrushing etc.; 2. Chemical methods like

treatments etc. and 3. Bacterial cellulose production. Though mechanical methods are widely used for wood nanocellulose production sometimes chemical and a combination of chemical and mechanical methods also be used. Table 1 shows the various methods used for the extraction of nanocellulose from wood. For all kinds of extraction methods, pretreatments are necessary to remove unwanted materials like extractives, waxes, pectin, hemicellulose, and lignin from wood. A brief review on pretreatments of wood for nanocellulose isolation has given below.

Pre-treatments for nanocellulose extraction

Pretreatments are carrying out mainly for two purposes; 1. for removing impurities like wax, lignin, pectin, and hemicelluloses and 2. to facilitate partial breakdown of cellulosic fibres. Lignin can be removed from fibres using bleaching agent like sodium chlorite solution. The treatment conditions like temperature and time may vary across the studies but the process should be repeated for several times for the complete removal of cellulose. Other impurities like wax, pectin, residual starch, and hemicellulose can be removed by the treatments of alkalis such as potassium hydroxide or sodium hydroxide. (Chen, Yu, Liu, Hai, *et al.* 2011) [8] explained chemical pre-treatments of wood for nanocellulose isolation. He first removed extractives and waxes present in the powdered wood samples by treating with a mixture of benzene and ethanol (2:1 v/v) for 6 h in a Soxhlet apparatus. Lignin in the samples was then removed using acidified sodium chlorite solution at 75°C for 1 h. The process was repeated five times until its colour is changed from dark brown to white. Pectin, hemicelluloses, and residual starch remaining in samples was removed by treating with 2 wt% potassium hydroxide at 90 °C for 2 h. In order to obtain highly purified cellulose, the samples were further treated with an acidified sodium chlorite solution at 75 °C for 1 h, and then treated with 5 wt% potassium hydroxide at 90 °C for 2 h. After the chemical treatments, the samples were filtered and rinsed with distilled water until the residues were neutral. According to (Rebouillat and Pla 2013) [37], the most used pretreatment processes for wood are chemical processes and steam explosion process. Chemical process was adopted from pulp and paper industry where lignocellulosic wood fibres are chemically purified to produce pure cellulosic fibres. In Paper industry, cooking process or kraft or sulphite process of wood chips will help to remove hemicelluloses and lignin partially. Further mechanical treatment like beating of cooked wood chips will separate the fibers. Bleaching of the pulp obtained from beater will result in complete removal of the residual lignin and other remaining by-products. In steam explosion pretreatment process, application of high pressure for a short period followed by explosive discharge to atmospheric pressure will result in disintegration of cellulose biomass into a fibrous dispersed solid. The obtained cellulose fibre dispersion (fiber to water ratio of ~1:10) will be first treated with water at ~80°C for ~1 hour, then with 20 wt% sodium hydroxide (fiber to liquor ratio of 1:10) at 80°C for ~1h and finally with a mixture of hydrogen peroxide and sodium hydroxide, in a stirred tank reactor, at 65°C for 2 hours. The final step resulted in bleaching of fibres. The bleached fibers will be then diluted to ~1% consistency and neutralized with sodium metabisulfite to decompose the residual hydrogen peroxide and stabilize the brightness.

Partial acid or enzymatic hydrolysis is another pre-treatment for wood. (Henriksson *et al.* 2007) [20] studied the effects of two different pretreatment methods to disintegrate MFC from

the wood fiber cell wall. He pretreated cellulosic wood fiber pulps by endoglucanases or acid hydrolysis in combination with mechanical shearing in order to disintegrate MFC from the wood. Enzyme-treatment was found to facilitate disintegration, and the MFC nanofibers produced also showed higher average molar mass and larger aspect ratio than nanofibers resulting from acidic pretreatment. (Paakko *et al.* 2007) [35] also found that endoglucanase pre-treatment facilitates disintegration of wood fiber pulp into MFC nanofibers. (Sacui *et al.* 2014) [42] also used aqueous enzymatic pretreatment at 50 °C for 2 h (0.1 mL of endoglucanase Novozyme 476 enzyme was used per 40 g of dry cellulose material suspended in 2 L) for nanocellulose extraction.

(Saito *et al.* 2006) [43] introduced 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO) oxidation, an efficient pretreatment for mechanical isolation of nanofibres. In his study, softwood and hardwood celluloses were oxidized by 2,2,6,6-tetramethylpiperidine-1-oxyl radicals (TEMPO) and then those fibres were converted to transparent dispersions in water, which consisted of individual nanofibers of 3 - 4 nm in width. Though chemical pre-treatment is widely accepted, mechanical pre-treatment also used in few studies. For the production of CNF, (Vartiainen *et al.* 2015) [50] adopted mechanical pretreatment of the wood pulp suspension in the grinder. This pretreatment resulted in more homogeneous and finer input material for the microfluidizer, as well as lower total energy consumption. Since the pretreatment caused disintegration of fibre agglomerates and initiated fibrillation, the clogging tendency of the microfluidizer was decreased significantly.

Methods of Nanocellulose extraction

Nanocellulose materials is divided into two categories based on its structure, morphology and crystalline nature; Cellulose nanofibres and Cellulose nanocrystals. Cellulose nanocrystals are highly crystalline and usually have a length less than 500 nm, while nanofibres are made up of amorphous and crystalline cellulose chains and have a length of up to several microns. Nanocrystals are usually obtained through chemical methods *i.e.* by acid hydrolysis or enzymatic hydrolysis of cellulose pulp whereas nanofibres are produced mainly through mechanical methods like homogenization, cryocrushing, and so on. Table 1 shows the studies conducted by various researchers on isolation of nanocellulose from wood.

Chemical methods

Acid hydrolysis is widely used chemical method for the isolation of cellulose nanocrystals. Cellulose nanocrystals generally have a diameter of about 2–30 nm and could be several hundreds of nanometers in length. The first successful preparation of cellulose nanocrystals was done in 1947 through hydrolysing cellulose with hydrochloric acid and sulfuric acid by (Nickerson and Habrle 1947) [34]. Later in 1951, Ranby prepared the stable CNCs colloidal suspensions though sulfuric acid hydrolysis of wood fiber (Ranby 1951) [36]. In acid hydrolysis, the amorphous regions of cellulose are more easily affected by acid compared to the crystalline regions, leading to first degradation of amorphous regions, while the crystalline regions remain intact. The hydrogen ions from acid can easily break the 1,4-β-glycoside bonds present in amorphous regions of cellulose. Finally, whisker-like nanocrystals are obtained. (Beck-Candanedo, Roman, and Gray 2005) [3] evaluated the effect of the acid/pulp ratio and

H₂SO₄ hydrolysis time on the properties of wood nanocrystal suspensions. They found that shorter CNCs with a lower dispersity index can be obtained for a longer time of hydrolysis. Also, their results showed that by increasing the acid/pulp ratio, the dimensions of the nanocrystal decreased.

A single step process for CNC isolation using ammonium persulfate (APS), an oxidant with low long-term toxicity, high water solubility and low cost, was developed by (Leung *et al.* 2011)^[25]. He prepared CNC by heating cellulosic materials at 60 °C in 1 M APS for 16 h with vigorous stirring. The reaction time was substrate-dependent, ranging from 3 h for bacterial cellulose and 16 h for complex substrates such as hemp, flax, and wood. CNCs obtained from wood were significantly smaller in diameter, (≈6 nm) as compared to those obtained by acid hydrolysis (16–28 nm and 20–40 nm respectively). Moreover, APS treatment resulted a total CNC yield of 65% as compared to 21% yield obtained from acid hydrolysis. High uniformity of CNCs greatly facilitated their subsequent recovery and purification so that the resulting liquid was easily processed using centrifugation or ultrafiltration with a 50 kDa cut-off membrane filter.

(Liu *et al.* 2014)^[27] reported isolation of cellulose nanocrystals from bleached hardwood pulp by phosphotungstic acid (HPW) catalyzed-hydrolysis method. CNCs with the diameter of 15–40 nm were given, which had high thermal stability and stable dispersion in aqueous phase. The process is shown in Figure 3. The reaction was carried out with 75 wt.% phosphotungstic acid at 90°C for 30 h; the yield of CNCs was up to 60%. Phosphotungstic acid could be recovered through extraction with available ethyl ether. Because this method is a solid/liquid/solid three-phase reaction, the reaction efficiency is low and the reaction time is relatively long compared with the mineral acid hydrolysis method.

Several researchers isolated individualized CNFs with width of 3–4 nm and length of at least a few microns from wood were prepared completely by 2,2,6,6-tetramethylpiperidine-1-oxyl radical (TEMPO-) mediated oxidation under moderate aqueous conditions (Saito *et al.* 2006; Fukuzumi *et al.* 2009)^[17, 43]. (Sacui *et al.* 2014)^[42] isolated nanocellulose from wood pulp 2,2,6,6-tetramethylpiperidiny-1-oxyl (TEMPO) oxidation. The oxidation was carried out by adding 2 mol/L NaClO (10 mmol per gram of cellulose) to the suspension. The pH of the suspension was maintained at 10 by adding 0.5 mol/L NaOH with a pH stat for 5 h. The reaction was then quenched by adding ethanol (ca. 0.2 L). The resulting suspensions were then washed with water and isothermally centrifuged.

Mechanical Methods

A purely mechanical process can produce fine fibrils of several micrometres in length and less than 100 nm in diameter. Cellulosic fibres can be disintegrated into fine fragments of nanometre scale by mechanical refining methods. (Herrick *et al.* 1983)^[21] and (Turbak, Snyder, and Sandberg 1983)^[49] first reported this method for producing microfibrillated cellulose. In this method, dilute cellulosic wood pulp fiber/water suspension is passed through a mechanical homogenizer at high pressure and fed through a spring high-pressure loaded valve assembly. As this valve opens and closes in rapid succession, the fibers are subjected to a large pressure drop with high shearing and impact forces which facilitates microfibrillation of fibre and ultimately the progressive release of CNFs.

The function of mechanical homogenizer was well explained by (Rees 1974)^[39]. During this process the cellulosic pulp fiber suspension was allowed to pass through a small outlet of several millimetres diameter under higher pressure. This procedure is often repeated for several passes in order to increase the degree of fibrillation. The number of passes required to produce nanofibres may vary depend upon the raw material. Higher number of passes increases the energy required for disintegration. In order to facilitate disintegration and to reduce the energy consumption, pretreatments like mechanical cutting or the enzymatic treatments or chemical treatments (acids, alkalis, ionic liquids etc.) would be adopted. These pre-treatments may lower processing cost by lowering the number of passes through the homogenizer. (Stenstad *et al.* 2008)^[45] prepared microfibrillated cellulose (MFC) from fully bleached spruce sulphite pulp through mechanical homogenization. The wet pulp sheets collected were cut by repeated shredding in an ordinary office shredder, which reduced the fibre length to approximately 1 mm. The resulting pulp was diluted to 2% consistency and subjected to 20 passes through a Gaulin M12 homogenizer (from APV), with a pressure drop of 600 bars at each pass. (Stelte and Sanadi 2009)^[44] prepared cellulose nanofibers of 10–25 nm diameter from two commercial hard- and softwood cellulose pulps through two steps mechanical process; initial refining and subsequent high-pressure homogenization. This method has several disadvantages like reduction in the degree of crystallinity of nanofibre due to high shear force applied during refining, reduction in degree of polymerization and fiber blockage problems caused by fiber agglomeration (Henriksson *et al.* 2007; Herrick *et al.* 1983; Turbak, Snyder, and Sandberg 1983)^[20, 21, 49]. It was also noticed that this method may cause damage to the microfibril structure by reducing molar mass and fail to sufficiently disintegrate the pulp fiber. In order to avoid thermal degradation of fibres due to high temperature generated during homogenization cooling facilities has to be provided to maintain the product temperature in the range 70–80°C.

In addition to homogenizer, other instruments such as microfluidizer and ultrafine grinder or disc refiner also used to extract CNFs. In microfluidizer the fiber suspension is pumped through thin z-shaped chambers under high pressure up to 30,000 psi allows the defibrillation of cellulosic pulps. Rotor and stator discs are the main parts of a disk refiner in which rotor disc is mobile but the stator disc is fixed type. During refining, the dilute fiber suspension is forced through a gap between the rotor and stator disks, which have surfaces fitted with bars and grooves against which the fibers are subjected to repeated cyclic stresses. Continuous stress on the fibre will release micro/nanofibrils from the fibre surface. According to (Jonoobi *et al.* 2015)^[24], the grinder blocking can be avoided by increasing the rotor speed to 1,440–1,500 rpm immediately after feeding. The procedure of isolation of CNFs from wood cells using an ultrafine grinder was first explained by (Taniguchi and Okamura 1998)^[46]. They isolated CNFs having diameters in the range of 20–90 nm.

Ultrasonication in combination with chemical pretreatment was another method used to extract nanofibres from wood (Chen, Yu, Liu, Chen, *et al.* 2011)^[7]. At first, poplar wood fibers were subjected to a chemical pretreatment to eliminate impurities like lignin and hemicellulose. The obtained chemically purified cellulose fibers were then mechanically separated into nanofibers using a common ultrasonic generator of 20–25 kHz in frequency equipped with a cylindrical titanium alloy probe tip of 1.5 cm in diameter. The

ultrasonication was conducted for 30 minutes to isolate the nanofibers. Ultrasound energy is transferred to cellulose chains through a process called cavitation, which refers to the formation, growth, and violent collapse of cavities in water. The energy provided by cavitation is approximately 10–100 kJ/mol, which resulted in breaking of the hydrogen bond between cellulose chains (Tischer *et al.* 2010) [47]. Thus, the ultrasonic impact can gradually disintegrate the micron-sized cellulose fibers into nanofibers. Random and irregular fragmentation of cellulose chains may produce aggregated nanofibers having wide distribution in diameter (Cheng, Wang, and Rials 2009) [10]. Similar to this (Chen, Yu, Liu, Hai, *et al.* 2011) [7] also extracted nanofibres from wood powder (sieved under 60 mesh) of needle fir (*Abies nephrolepis*). Chemically purified cellulose fibers soaked in distilled water (*1% by mass) were sonicated for 30 min using an ultrasonic processor (JY98-IIID, Ningbo Scientz Biotechnology Co., Ltd, China) at 20–25 kHz and an output power of 1000 W to isolate the nanofibers. Obtained nanofibers displayed a classical web-like network structure with lateral size of 10–20 nm. Nanocellulose was prepared from TEMPO (2,2,6,6-tetramethylpiperidine-1-oxyl) oxidized bleached hardwood kraft pulp by using ultrasound assisted process. Nanocellulose obtained was thinner with higher degree of fibrillation, more carboxylic functionality, and higher yield (Loranger, Piché, and Daneault 2012; Mishra *et al.* 2012; Mueller *et al.* 2013) [28, 30, 33]. (Vartiainen *et al.* 2015) [50] studied the properties of cellulose nanofibrils extracted from softwood and hardwood pulps by mechanical method. The pulp slurry having 2 wt% cellulose and 98 wt% water was first dispersed using a high shear Diaf dissolver 100WH N for 10 minutes at 700 rpm. Suspensions were then fed into supermasscolloider (Company: Masuko Sangyo's MKZA10-15J), which was used for pre-refining. Grinding stone type was MKE10-46 made of silicon carbide and resins with a diameter of 10". The fibre slurries were forced through a gap between rotary and stator grinding stones at 1500 rpm. The quality of fibril cellulose was controlled by moving the lower stone to set the clearance between the grinding stones. The pre-refined material was further fibrillated by high-pressure homogenization through a microfluidizer (Microfluidics M7115). The machine was equipped with a pair of ceramic 500 µm and diamond 100 µm interaction chambers. The operating pressure of the fluidizer was 1850 bar and fibrillation was done using five passes. Microfluidization process caused fibre delamination and separation of macrofibrils into micro or nanofibrils. Also fibre shortening occurred during processing when the amount of fibrillation energy was further increased. As a result, a relatively uniform fibril size distribution was obtained. Similarly, the enzyme pretreated partially purified commercial wood pulp (13.80% hemicellulose and 0.70%

lignin) was passed through a M110EH microfluidizer for eight times at maximum pressure 1100 bar (Microfluidics Ind., USA) to produce nanocellulose (Sacui *et al.* 2014) [42]. (Bufalino *et al.* 2015) [5] produced highly crystalline and thermally stable microfibrillated cellulose (MFC) from *Cordia goeldiana* veneer wastes. The veneers were powdered and then passed through 60 mesh for further chemical modification. The chemical pre-treatment adopted by him was given in section xx. The chemically modified fibers were subjected to intense refining in Supercollider (opening between disks of 0.01 mm) to produce MFC. (Tonoli *et al.* 2012) [48] isolated cellulose micro/nanofibres by three different processes, namely: refining, sonication and acid hydrolysis of the eucalyptus kraft pulp. Refining process was found to be less efficient because the quantity of nanofibres with diameter less than 100nm obtained was very low. The action of hydrodynamic forces associated with ultrasound during sonication was effective to open the structure of the milled fibres, releasing the micro/nanofibrils that form the fibre cell wall. However, the crystallinity of the micro/nanofibrils was reduced because of the strong mechanical oscillating power imparted during the sonication conditions which resulted substantial damage to the cellulose structure. Acid hydrolysis resulted in nanowhiskers with lower diameter and length, and high crystallinity. Similar to the previous studies, the Increasing hydrolysis reaction time led to narrower and shorter whiskers, but increased the crystallinity index.

Chemo-mechanical methods

Steam explosion is found to be an effective method for the separation of nanofibrils from biomass (Cherian *et al.* 2008) [12]. High pressure steaming followed by rapid decompression is called the steam explosion. Cellulosic fibres are treated with mild acids like oxalic acid under elevated pressure and temperature. A sudden release of pressure results in flash evaporation of water which exerts a thermomechanical force causing the material to rupture. By this method, the nanofibrils are liberated from the bundles as individual entities. (Bhatnagar and Sain 2005) [4] and (Chakraborty, Sain, and Kortschot 2005) [6], had successfully isolated the cellulosic nanofibres from wood using a combination of chemomechanical treatments. Hettrich *et al.* reported a combined chemical and mechanical method for the preparation nanocellulose from different cellulosic materials such as bleached pulp, cotton linters and microcrystalline cellulose. Prior to the mechanical treatment, pretreatments such as grinding, acid hydrolysis, decrystallization and derivatization are used for the preparation of nanocellulosic materials. Extracted cellulose has spherical shape with diameter of less than 200 nm (Hettrich *et al.* 2014) [22].

Table 1: Characteristics of nanocellulose extracted from wood by various methods

Sl. No.	Raw material used	Method	Width of nanocellulose	Length of nanocellulose	Reference & Remarks
1	Softwood pulp of Norway spruce	Homogenization	5-15 nm (Strong acid pre-treatment), 15-30 nm (enzymatic pre-treatment)	-	(Henriksson <i>et al.</i> 1999) [19] Enzymatic pre-treatment is better than acid-pretreatment
2	Wood	APS method	6.0 ± 0.2 nm	124 ± 6 nm	(Leung <i>et al.</i> 2011) [25] Yield- 36% & CI- 81%
3	Powdered poplar wood	Ultrasonication	Nanofibers was found to be 13.0 and 12.8 nm respectively after 1000 W and 1200 W ultrasonic treatments	-	(Chen, Yu, Liu, Chen, <i>et al.</i> 2011) [7] Chemical pre-treatment
4	Wood	Ultrasonication	10-20 nm	-	(Chen, Yu, Liu, Hai, <i>et al.</i> 2011) [8] Relative crystallinity- 71%

5	Hardwood (eucalyptus) and softwood (black spruce)	H ₂ SO ₄ hydrolysis	4-5 nm width for both soft wood pulp and hard wood pulp	100-150 nm for softwood and 140-150 nm for hardwood	(Beck-Candanedo, Roman, and Gray 2005) ^[3] L/D - ~ 29 L/D - 21 to 28
6	Wood CNC	H ₂ SO ₄ hydrolysis	7.5 ± 2.9 nm	176 ± 68 nm	(Morelli <i>et al.</i> 2012) ^[32]
7	Micro/nanofibres and nanowhiskers	Sonication Acid hydrolysis for 30 min and 60 min	The diameter of the micro/nanofibrils generally varied between 20 and 50 nm. 15 ± 6 nm (30 minutes) 11 ± 4 nm (60 minutes)	The length ranged between 200 nm and 2.5 μm, 175 ± 38 nm, 142 ± 49 nm	(Tonoli <i>et al.</i> 2012) ^[48] Aspect ratios (L/D) between 10 and 50. Aspect ratio-12. Aspect ratio-14.
8	Nanowhiskers	Acid hydrolysis with H ₂ SO ₄	5.9 ± 1.8 nm	130 ± 67 nm	(Sacui <i>et al.</i> 2014) ^[42] L/D- 23 ± 12
9	Paper-mulberry (Broussonetia kazinoki Siebold) bast pulp	Sulfuric acid hydrolysis	Fibrous and spherical or elliptic granules of nano-cellulose with sizes of 50-60 nm	-	(Reddy and Rhim 2014) ^[38]
10	Commercial hard- and softwood cellulose pulps	Initial refining and subsequent high pressure homogenization.	Nanofibers of 10-25 nm diameter	-	(Stelte and Sanadi 2009) ^[44]
11	Softwood pulp	Homogenization	-	-	(Stenstad <i>et al.</i> 2008) ^[45]
12	Rubber wood	Alkaline pre-treatment + Homogenization	10-90 nm	-	(Jonoobi <i>et al.</i> 2011) ^[23]

Conclusion

Being a novel multifunctional material, nanocellulose has attracted many researchers in the last few decades. Nowadays nanocellulose is used for wide range of applications such as thermo-reversible and tenable hydrogels, paper making, coating additives, food packaging, flexible screens, optically transparent films, lightweight materials for ballistic protection, automobile windows and drug delivery because of its special characteristics like renewability, eco-friendliness, low thermal expansion coefficient, high aspect ratio, better tensile strength, good mechanical and optical properties. Due to the increasing demand for nanocellulose researchers developed different methods for the isolation of nanocellulose from diverse cellulosic materials especially wood. Pilot plants established in different countries for commercial level production nanocellulose are using wood as the source of cellulose. However wood is low cost, easily available and renewable in nature, the energy consumption and production costs of nanocellulose from wood have limited their wide spread applications. A detailed analysis on currently available methods of nanocellulose isolation from wood might give a breakthrough for researchers for finding more efficient, economically viable and environmental friendly methods of nanocellulose isolation from wood. In this way the present review would be helpful for research community. Growing interest in nanocellulose research, establishment of new pilot plants for nanocellulose production, new applications of nanocellulose and large-scale development of nanocellulose based technical products clearly suggest that the impressive rate of development in the nanocellulose field will continue in the future.

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