

Electrospun Cellulose Fibres and Applications (Serabut dan Aplikasi Selulosa Elektropusing)

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ABSTRACT

Cellulose fibres and nanofibres have gained interest because of the high strength and firmness, biodegradability and renewability. The enthusiasm in cellulose and its modification as cellulose-derivative has been exponentially expanding. This paper discuss on cellulose and its derivatives, and methods to produce cellulose fibres and nanofibres. Emphasis is given on electrospinning technique, the most utilised technique to produce cellulose fibres and cellulose nanofibres with ranging from nanometer to millimeter in diameter. It also summarises cellulose in terms of a matrix of cellulose, solvent, parameter electrospinning, fibre diameter and their perspective applications.

Keywords: Cellulose; cellulose nanofibre; electrospinning; electrospun

ABSTRAK

Serabut selulosa dan serabut nano mendapat perhatian kerana kekuatan yang tinggi dan keteguhan, keterbiodegradan dan keterbaharuan. Keghairahan dalam selulosa dan pengubahsuaianya sebagai selulosa-terbitan telah berkembang pesat. Kertas ini membincangkan tentang selulosa dan terbitannya serta kaedah untuk menghasilkan serabut selulosa dan serabut nano. Penekanan diberikan pada teknik elektropemusingan, teknik yang paling kerap digunakan untuk menghasilkan serabut selulosa dan selulosa serabut nano dengan diameter antara nanometer hingga milimeter. Ia juga merumuskan selulosa daripada segi matriks selulosa, pelarut, parameter elektropemusingan, diameter serabut dan perspektif aplikasinya.

Kata kunci: Elektropemusingan; elektropusing; selulosa; selulosa serabut nano

INTRODUCTION

As a renewable bio-based material on the earth, cellulose has become an extensive interest in producing novel polymers and materials (Prasanth et al. 2015; Rosenau et al. 2006; Young-Mook Lim 2010). Cellulose with biodegradable properties makes its fibre to be utilised in many applications such as biomedical areas, protective clothing, mechanical areas and filtration (Cucolo & Aminuddin 2001; Muhammad Johan Iskandar et al. 2018; Razali et al. 2018). This homopolysaccharide is produced through $\beta(1-4)$ glycosidic bonds condensed from linearly connecting D-glucose units as shown in Figure 1. Researchers believed that intermolecular hydrogen bonds in cellulose chain can give the linear polymer molecules to unite in sheet-like structures while intramolecular hydrogen bonds bring cellulose chain stiffness character (Klemm et al. 2005). Nonetheless, dissolution of cellulose has become a challenging issue due to its properties of limited solubility and incapability to melt in common aqueous and organic solvents (Fauzee & Othaman 2013; Krässig 1993; Marsh & Wood 1942). This is caused by the numerous intermolecular and intramolecular hydrogen bond networks exist in cellulose structure (Zhou & Zhang 2000). Besides, other interactions involved among cellulose structures have been mostly omitted. Currently, this complication has been already discussed and reanalysed

as an accepted description (Medronho et al. 2012). It has been decided that biopolymeric cellulose network has a clear amphiphilic character and that cellulose solubility has the highest impact of hydrophobic interactions in the cellulose structure (Medronho & Lindman 2015). Thus, it is crucial to promote 'green' cellulose extraction technique and suitable cellulose dissolution path to make full use of cellulose resources in the world.

The manufactures of polymer nanofibres via electrospinning technique have been perceived as a persuasive system for producing fibres with submicron diameters by electrostatic forces (Bognitzki et al. 2001; Muhammad Hariz et al. 2014; Razali et al. 2018). Many polymers have been effectively electrospun into ultrafine filaments generally in dissolvable arrangement and some in melt structure (Faten Ermala et al. 2017; Huang et al. 2003; Hutmacher & Dalton 2011). Electrospinning is used for producing nanofibres when colloidal suspension of solid nanoparticles or solution is spun (Jaworek et al. 2009; Leach et al. 2011). The reason for choosing electrospinning is that it requires a single step, low energy and low-cost material processing technology that can operate in atmospheric conditions (Yu 2007). Electric charge draws liquid from a nozzle in fine jet and disperses it into highly charged droplets. The free charge generates electric stress, which make the solution to fly over from

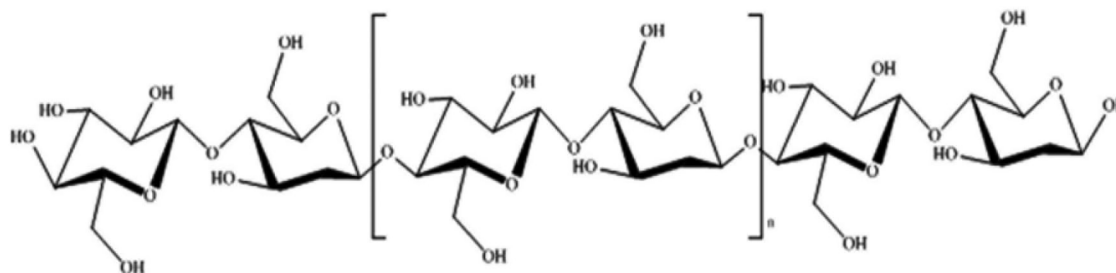


FIGURE 1. Structure of cellulose

the needle and form a conical shape commonly known as the Taylor cone. The injection of liquid can be controlled by adjusting the flow rate, voltage applied to nozzle, speed of drum controller, distance between tips of needle to drum controller and diameter of the syringe (Javadian et al. 2012; Quan et al. 2010; Zeng et al. 2003). There is a minimum viscosity for every polymer solution termed the critical entanglement concentration, beneath which a steady fly cannot be accomplished and no nanofiber will be framed in spite of the fact that particles may be accomplished, which are beads from electrospinning method (Leach et al. 2011; Reneker & Yarin 2008; Wang et al. 2009). The principle process of electrospinning as shown in Figure 2.

This paper attempts to assess the background of cellulose fibres and cellulose nanofibres followed by electrospun cellulose fibres and nanofibres and lastly the applications of cellulose fibres and nanofibres. To date, most of the review papers on cellulose electrospinning either focusing on derivatives or the effect of the electrospinning parameter on the characteristic of the nanofiber (Ohkawa 2015; Prasanth et al. 2015; Young-Mook 2010). The objective of this current study was to discuss on cellulose and its derivatives and how to produce cellulose fibres and nanofibres. However, emphasis is given on electrospinning technique with their perspective applications.

CELLULOSE

Cellulose Fibres The cellulose fibres have multiscale criteria where their average widths are 10 to 50 μm and normal lengths of strands from 1 to 3 mm (Figure 3). The fibre divider thickness is generally somewhere around 1 and 5 μm . Cellulosic parts of a wood fibre divider structure are the basic fibril, macrofibril, microfibril, cellulose molecule and the lamellar layer (Meier 1962). As indicated by Meier (1962), the expression ‘basic fibril’ was accounted for a breadth of 3.5 nm and connected after the phrasing of Frey-Wyssling (1954). Cellulose strands are utilised as potential fortifying materials for various favourable characteristics such as biodegradable, plentifully accessible, less expensive, low weight, renewable, intriguing particular properties and low rough nature as these are waste biomass with great mechanical properties (Bledzki et al. 1996; Hornsby et al. 1997). On the other hand, cellulose fibres have a few disservices; for example, dampness retention, quality varieties, low warm steadiness and poor similarity with the hydrophobic polymer network (Georgopoulos et al. 2005; Saheb & Jog 1999).

Cellulose Nanofibres Nanotechnology is a unique phenomenon below 100 nm, enabling a novel application. In nanotechnology field, nanomaterials from cellulose play a large role. Recently, interest in cellulose nanofibres has significantly increased as cellulose nanofibres have a high potential to be used in wide different areas particularly as

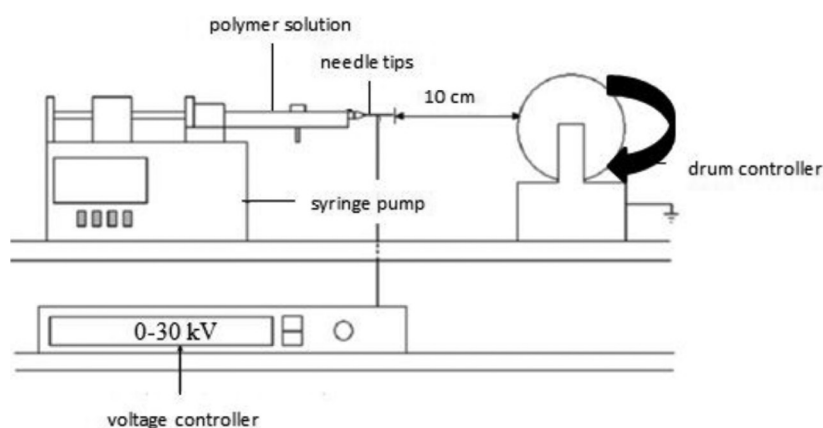


FIGURE 2. Schematic diagram of electrospinning process

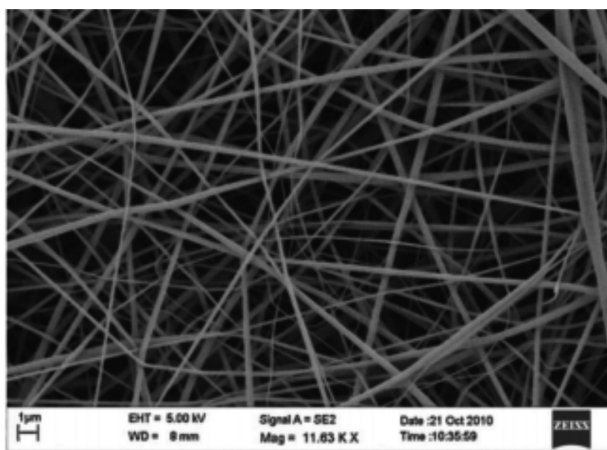


FIGURE 3. SEM image of electrospun cellulose acetate fibres regenerated into cellulose, $D = 1 \mu\text{m}$ (Rezaei et al. 2015)

the reinforcement in evolution of nanocomposites. Many studies have been done on isolation and characterisation of cellulose nanofibres from various sources (Saurabh et al. 2016). Extraction of cellulose nanofibres can be obtained from the cell walls by simple mechanical methods or a combination of mechanical and chemical methods.

PRODUCTION OF CELLULOSE NANOFIBRES

Chemomechanical Treatment To obtain purified cellulose, Alemdar and Sain (2008a) used wheat straw by a chemical treatment to extract cellulose nanofibres. A mechanical treatment was applied to the chemically treated fibres to diagnose the nanofibres from the cell walls. By a chemomechanical technique, cellulose nanofibres were extracted from the agricultural residues, wheat straw and soy hulls (Alemdar & Sain 2008b). Moreover, the diameters and lengths of wheat straw nanofibres have been determined ranging from 10-80 nm and a few thousand nm, respectively. In a proportion of soy hull nanofibres, the diameter is 20-120 nm with a length shorter than that of wheat straw nanofibres. By applying chemomechanical treatments, Wang and Sain (2007) extracted the cellulose nanofibres from soybean stock. These are an assortment of cellulose nanofibres with 50-100 nm of diameter range and thousands nm in length. After that, wheat straw was extracted to obtain the cellulose nanofibrils using steam explosion, acidic treatment and high shear mechanical treatment.

Homogenisation Process At numerous desirable lengths and diameters below 100 nm from particular starting cellulose materials, Zimmermann et al. (2010) tried to separate nanofibrillated cellulose (NFC) by mechanical diffusion and high pressure (up to 1500 bar) of homogenisation processes. The treatment eventuated in nanoscaled fibril networks. Two profitable fibrous celluloses produced bigger cellulose aggregates with micrometer dimensions and less homogeneous complex structure. Besides that, alkaline-treated pulp was soaked

overnight in an 8 wt. % solution of H_2O_2 (v/v). Then, bleached pulp was rinsed with abundant distilled water. Bleached pulp was next treated with 10% HCl (1 N) solution and mixed at temperature around $60 \pm 1^\circ\text{C}$ for 5 h using ultrasonicator. Finally, to neutralize the final pH, the fibres were taken out and washed a few times with distilled water and then dried. Fibres were suspended in water and continuously stirred for 15 min by practicing high shear homogeniser. High-shearing action resolves the fibre agglomerates and resulted in nanofibrils (Kaushik et al. 2010). Moreover, cellulose nanofibres have been developed by dissolving cellulose in solvents including ethylene diamine with its salt selected from the group consisting potassium thiocyanate and potassium iodide where the salt is present at their saturation points (Frey & Yong 2004).

Electrospinning Technique By using electrospinning technique, cellulose nanofibres can be obtained and the reticulation can be performed chemically or by UV irradiation of cellulose derivatives in concentrated crystalline liquid solutions containing isotropic solvents such as acetone, dimethylformamide, ethanol, methanol or water (Lisboa 2009). Figure 4 shows image of cellulose nanofiber by SEM analysis.

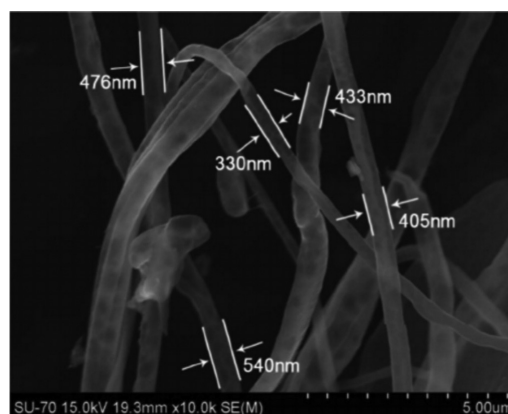


FIGURE 4. SEM image of electrospun cellulose fibres from a 8 wt. % polymer solution in $[\text{C}_2\text{mim}][\text{CH}_3\text{CO}_2]$ (after complete dissolution achieved with 72 h of homogenisation at 298 K) (Freire et al. 2011)

ELECTROSPUN CELLULOSE FIBRES AND NANOFIBRES

Since the early 2000s, reviews in the experimental setup variations, principle and theories for electrospinning techniques already can be determined (Lim 2010; Ohkawa 2015; Prasanth et al. 2015). Electrospinning is the most widely recognised technique for manufacturing microscale and nanoscale polymers. An essential electrospinning setup comprises a high voltage electric source, a syringe pump with vessels/tubes to convey the arrangement from a syringe to a spinneret and a collector. During electrospinning process, a polymer solution is held at the needle tip of the spinneret by surface strain. At the point

when an electric field is connected utilising the high voltage electric source, the charge is prompted inside the polymer, bringing about charge repulsion inside the solution. This electrostatic force eventually overcomes the surface pressure, bringing in a charged stream to be shot out. As this jet fly goes through the air, the solvent evaporates, leaving the strong polymer fibres to be deposited on the conducting collector. Most of the celluloses are dissolved in some solvents before electrospinning process as this processing condition parameter is easy and direct. When the solid cellulose is completely dissolved in a proper amount of solvent held, it becomes a fluid called cellulose solution. The polymer fluid is then introduced into the capillary tube for electrospinning process. It is noted that the same cellulose dissolved in different solvents may produce nanofibres after electrospinning technique. The schematic diagram of electrospinning process is shown in Figure 5.

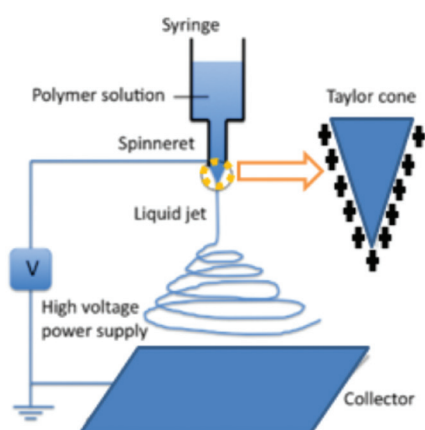


FIGURE 5. A schematic diagram showing the electrospinning process

An overall summary list of publications on cellulose fibres and nanofibres mainly from 2006 to 2018 that have been successfully electrospun into super fine fibres is listed in Tables 1 and 2 respectively, with corresponding details including electrospinning solvents, parameters for electrospinning process in different cellulose solution, average diameter of fibres and perspective applications of the corresponding fibres. It was found in the open literature that more than 20 cellulose solutions have been successfully electrospun into fibres with diameters ranging from <30 nm to over 4 mm. Strictly, the terms 'nanofibres' and 'nano-scaled fibres' are referred to those having average diameters of less than 100 nm (Huang et al. 2003) when at most publications in Table 1 have used the term 'nanofibres' for their products even in the cases where the average diameters were 200-1000 nm. Besides, many studies reported in Table 1 included the wording 'Electrospun cellulose nanofibre' in their publication headline when in fact the reactant used was cellulose

acetate. The readers should pay attention to not confuse with the starting materials used, processing solvents and the presence or absence of electrospun non-woven fabric processing.

STRUCTURE AND PROPERTIES OF CELLULOSE FIBRES AND NANOFIBRES

Various microscopic techniques have been used to study the structure of cellulose nanofibres such as transmission electron microscopy (TEM), scanning electron microscopy (SEM), field-emission scanning electron microscopy (FE-SEM), atomic force microscopy (AFM), wide-angle X-ray scattering (WAXS) and NMR spectroscopy (Kalia et al. 2011). By assisting image analysis, a consolidation of microscopic techniques can provide information on the widths of cellulose nanofibres. However, it is quite troublesome to identify the length of nanofibres because of complexity and difficulties in distinguishing both ends of individual nanofibres. It has been frequently reported that microfibrillated cellulose (MFC) suspensions consist of cellulose nanofibres and nanofibre bundles (Siró & Plackett 2010). It has also been reported that de Moraes Teixeira et al. (2010) obtained the suspensions of coloured and white nanofibres through the acid hydrolysis of natural coloured and white cotton fibres. Conceivable differences among them were investigated due to their morphology and other characteristics. Morphological study of cotton nanofibres revealed a diameter of 6-18 nm and a length of 85-225 nm. It was shown that there were no significant differences in terms of morphology among the nanostructures from different cotton fibres. The main differences found were the slightly higher yield, effectiveness of sulfonation and thermal stability under dynamic temperature conditions of the white nanofibres. On the contrary, a better thermal stability has been shown by the coloured nanofibres compared to the white in isothermal conditions at 180°C.

Besides, Alemdar and Sain (2008b) investigated the structure of the cellulose nanofibres from agricultural residues. The FTIR spectroscopic analysis demonstrated that chemical treatment also conveyed the partial removal of hemicelluloses and lignin from the structure of the fibres. PXRD results proved that this has resulted in enhanced crystallinity of the fibres. By applying TGA technique, thermal properties of the nanofibres were studied and found to be dramatically increased. Moreover, to prepare cellulose nanofibres from two commercial hard- and softwood cellulose pulps, Stelte and Sanadi (2009) have studied the mechanical fibrillation process.

The degree of fibrillation was studied using scanning electron microscopy (SEM), light microscopy (LM) and atomic force microscopy (AFM). SEM and LM images of hard- and softwood fibres showed that the hardwood fibres were fibrillated only on the surface during the refining step, which are now degenerated into a network of small fibres. Meanwhile, AFM images of the final products after high pressure homogenisation showed that the size distribution of the hard- and softwood nanofibres is in 10-25 nm in

TABLE 1. List of publications of electrospun cellulose fibres

Matrix	Solvent	Parameter for electrospinning	Diameter fibre	Perspective application	Details
Cellulose acetates (CA) of three different degrees of substitution ($M_w=38\ 000$) 1) Cellulose monoacetate (CA 1.85) 2) Cellulose diacetate (CA 2.45) 3) Cellulose triacetate (CA 2.8)	Acetone (99%) N,N-dimethylacetamide (DMAc) (99%)	CA 2.45=20 wt. % in 2:1 acetone-DMAc Voltage = 0.7 to 2.5 kV/cm Distance between the nozzle and the collector = 15 cm Flow rate = 1 to 9 mL/min	2 μ m (2000 nm)	Improved thermo-mechanical properties while keeping the unique features of the cellulose polymer	(Vallejos et al. 2012)
Cellulose with different molecular weight (DP=210) & (DP=1140)	a) Lithium chloride (LiCl)/N,N-dimethyl acetamide (DMAc) b) N-methylmorpholine oxide (NMMO)/Water	Voltage = 15-25 kV Distance between the nozzle and the collector = 10-20 cm Flow rate = 0.005 to 0.03 mL/min	250-750 nm	Study the degree of polymerization of cellulose, spinning conditions and postspinning treatment such as coagulation with water on the microstructure of electrospun fibres	(Kim et al. 2006)
Cellulose Acetate (CA): Polyvinyl alcohol (PVA)	CA, Acetone/DMAc = 2:1 (17 wt. %) PVA, DW (10 or 15 wt. %)	(CA) Voltage = 12.5 kV Distance syringe tips-to-collector = 15 cm (PVA) Voltage = 12 kV Distance syringe tips-to-collector = 15 cm	CA, 740 nm PVA, 340 & 710 nm	Evaluation of hydrophilic properties before and after deacetylation	(Khatri et al. 2012)
Cellulose Acetate	Acetone/DW = 5:1 (8%)	Voltage = 18-19 kV Distance syringe tips-to-collector = 9 cm Flow rate = 90 μ L/min.	300-500 nm	Detection of metal ions	(Wang et al. 2012)
Cellulose (Dp, 1100)	[EMIM][OAc] (1.75 wt %)	Voltage = up to 40 kV Flow rate = 1 mL/h	1000-2500 nm	Fabrication for ligand carrier	(Miyachi et al. 2011)
Cellulose Acetate Phthalate ($M_w=60\ 000$ g/mol)	Acetone/DMAc = 3: 1 (25 wt/v %)	Voltage = 12 kV Distance needle tips-to-collector = 12.5 cm	701-1280 nm	Antivirus activity	(Huang et al. 2012)
Cellulose Acetate (CA) ($M_w=30\ 000$)	Acetone/DMAc = 2:1 v/v% (17 w/w %)	Distance syringe tips-to-collector = 12 cm Flow rate = 0.4 mL/h	170 \pm 40 nm	Optimum parameter gallic acid-loaded electrospun CA fibres	(Phiriyawit & Phachamud 2011)
Cellulose Acetate ($M_w, 25\ 000$ g/mol)	Acetone/DMAc = 1: 4 (14 wt. %)	Voltage = 12-15 kV Distance syringe tips-to-collector = 9 cm Flow rate = 90-100 μ L/min	Cellulose/chitosan, 150-450 nm Cellulose/PMMA, 150-350 nm	Antibacterial activity expression by fabrication of nano-composite ZnO	(Anitha et al. 2013)
Cellulose (Dp, 1100)/chitosan (800 cP) or/PMMA	[EMIM][OAc] (Cellulose, 2 w/w%)/chitosan, 0.4 w/w % [EMIM][OAc]/DMSO/TritonX100 (cellulose, 2.25 w/w %/PMMA 0.5 w/w %)	Voltage = 22 kV Distance between the nozzle and the collector = 15 cm Flow rate = 0.5 mL/h	Cellulose/chitosan, 150-450 nm Cellulose/PMMA, 150-350 nm	Antibacterial wound dressing materials	(Miao et al. 2011)
PMIA/CA (1:2) or cellulose (6:1)	PMIA, 8 wt. % LiCl/DMAc (15%) Cellulose, swelled in 8 wt. % LiCl/DMAc (10%) CA, MDAC (15 wt. %)	Distance syringe tips-to-collector = 20 cm Flow rate = 0.5-100 mL/min	PMIA/CA, 250-300 nm PMIA/cellulose, 250-350 nm	Development of electrospinning process and reinforcement of mechanical properties of ESNWs	(Yao et al. 2011)
Cellulose Acetate (CA) ($M_w, 30,000$ g/mol), Acetylation 39.8% / Polyethylene oxide (PEO) ($M_n, 300,000$ g/mol)	AcOH (20 wt/v %) PEO 90% EtOH (3 wt/v %)		CA solution/ POE solution = 99.6/0.4-91.9, 950-1170 nm	Food wrapping technology	(Pittarate et al. 2011)

continue

Continued TABLE 1.

Matrix	Solvent	Parameter for electrospinning	Diameter fibre	Perspective application	Details
Cellulose Acetate (Mw, 30 000)	Acetone/DMAc = 2:1 (16 wt. %)	Voltage = 15 kV Distance syringe tips-to- collector = 14 cm Flow rate = 0.6 mL/h	385 nm	Metal ion adsorption	(Stephen et al. 2011)
Cellulose Acetate (Mw, 61 000 g/mol)	Acetone/DMAc = 2:1 (20 wt. %)	Voltage = 20 kV Distance syringe tips-to- collector = 15 cm Flow rate = 4 mL/min	750 nm (500-1500 nm)	Graft polymerization and evaluation metal ion adsorption	(Tian et al. 2011)
Cellulose Acetate (Mw, 30,000)	Dichloromethane (DCM) /Acetone = 1:1-3:1 (v:v) (5.0, 7.5, 10 w:w %)	Voltage = 15 kV Distance syringe tips-to- collector = 10 cm Flow rate = 1 mL/h	DCM/Acetone = 1:1, CA, 10 wt. %, 300-1000 nm 2:1, CA, 7.5 wt. %, 750-1500 nm 3:1, CA, 5 wt. %, 1500-3500 nm	Development of CA fine fibres having porous structures Application of filtration due to their very high surface to volume ratio	(Celebioglu & Uyar 2011)
Cellulose Acetate (Mw, 61 000, acetylation 40%)	Acetonitrile/0-30 w/w% Ethanol (15-21 w/w%)	Voltage = 5-30 kV Distance syringe tips-to- collector = 10-25 cm Flow rate = 0.1-1.5 mL/h	Sub-micrometric fibre	Bio-battery	(Baptista et al. 2011)
Cellulose Acetate (Mw, 30 kDa, acetylation 39.7 wt. %)/ Ethyl Acetate (14-76 kDa) 91:9, 77:23, 66:34 (w/w)	AcOH/formic acid/DW/tween40 (CA/EA = 91:9, 19.25 wt. %; 77:23, 18.25 wt. %, 66:34, 17.25 wt. %)	Voltage = 15 kV Distance between the nozzle and the collector = 15 cm Flow rate = 2.2 mL/h	CA/EA = 91:9, 242 nm ± 32 77:2, 384 nm ± 54 66:3, 410 nm ± 38	<i>In vivo</i> sustainable release materials	(Wongsasulaket al. 2010)
Alpha cellulose from wheat bran powder	12% w/v in TFA/MC solution	Voltage = 22 kV Distance needle tips to collector = 40 mm Flow rate = 3.5 mL/h	6 mm diameter 0.3 mm thickness	- <i>Staphylococcus aureus in vitro</i> -Superficial wound of rat	(Yazdanbakhsh et al. 2018)
Cellulose acetate (Mn, 30 000, acetylation 39.8)	Acetone/DMEF/DW = 85%/10%/5% (v/v/v) (17 v/v %)	Voltage = 25 kV Distance = 12 cm Flow rate = 2.5 mL/min	500 (100-1000) nm	antimycotic activities	(Dixit et al. 2010)

TABLE 2. List of publications of electrospun cellulose nanofibres

Matrix	Solvent	Parameter for Electrospinning (ES)	Diameter Fibre	Perspective Application	Details
Cellulose/nanocrystal (CNC)	Cellulose, NMMO/DW=4:1 wt(1.5wt)	Voltage = 20 kV Distance between the nozzle and the collector = 10 cm	100 nm	Development of ES process using layered nozzles having shell (cellulose in NMMO) and core (CNC dispersion in DMSO)	Magalhaes et al. (2009) and Vallejos et al. (2012)
Cellulose/Chitosan hybrid nanofibres	Butyric anhydride, Perchloric acid, acetone, glacial acetic acid and DMAc	Voltage = 15-25 kV Distance syringe tips-to- collector = 15-20 cm Flow rate = 1 mL/h Concentration = 15% in 1/1 w/w acetone/acetic acid mixture, CA and DBC	30-350 nm	Cellulose-Chitosan nanofibrous products for medical	Hsieh (2009)
Cellulose-based Nanofibres	2,2,2-Trifluoroethanol	EC NFs Voltage = 5-28 kV Distance syringe tips-to- collector = 5 cm Flow rate = 0.001-0.01 mL/min HPMC NFs Voltage = 10-15 kV Distance syringe tips-to- collector = 5-15 cm Flow rate = 0.05 mL/min	EC = 155 nm HPMC = 162 nm	HPMC used for wound healing & drug delivery system	(Lim & Pyo 2010)
Cellulose (wood)	2:1 mixture of toluene/ethanol		15 nm	Optoelectronic devices, Tissue engineering scaffold	(Abe et al. 2007)
Cellulose (Dp, 12000)	8.5 wt. % LiCl/DMAc (1.0-1.35 wt. %)	Voltage = 0-30 kV Distance syringe tips-to- collector = 10-15 cm Flow rate = 0.01-0.06 mL/min	80-100 nm	Development electrospinning process for high molecular weight cellulose preparation	(Lim & Pyo 2010)
Cellulose Acetate (acetylation, 29.6%)	Acetone/DMAc = 3:2 (15 wt %)	4.2 mg/mL NaIO4 content reaction time 6.8 h reaction temperature 30.8°C at pH 6.1	200 nm	Generate aldehyde groups to immobilize an enzyme, lipase, and evaluation of immobilized enzyme activity	(Huang et al. 2011)
Cellulose Acetate	Trifluoroethanol (150 g/L)	Voltage = 15 kV Distance between the nozzle and the collector = 10 cm Flow rate = 2.4 mL/h	200 nm-3000 nm	Evaluation of scaffolding properties for cell culture	(Filion et al. 2011)
Cellulose Acetate (CA) (d, 1.184 g/cm ³)/ Poly (acrylonitrile) (PAN) (D, 1.184 g/cm ³) / multiwalled carbon nanotubes (MWCNT) (D, 1.2-1.7 g/cm ³)	CA, Acetone/DMAc = 1:2 (15 wt. %/10 wt. %), core solution PAN/MWCNT, DMF (10 wt. %/35 wt. %), shell suspension	Voltage = 30 kV Distance syringe tips-to- collector = 15-20 cm Flow rate = 0.2 mL/h	150 nm (core, ~60; shell, ~50)	Electronic Devices	(Lisunova et al. 2010)
Cellulose Acetate (Mw 30,000g/mol, acetylation 39.8 wt. %)	1:1=DMSO:THF + 0.1 wt. % diethylamino ethyl chloride	Voltage = 15 kV Distance needle tips to collector = 25 cm Flow rate = 0.8 mL/h	58-60 nm	Bio-synthesis (multi-dimensional hybrid structure)	(Ly et al. 2018)

continue

Continued TABLE 2.

Matrix	Solvent	Parameter for Electrospinning (ES)	Diameter Fibre	Perspective Application	Details
Cellulose/PAN (DP = 1200)	Cellulose/PAN blending ratio (100:0, 75:25, 50:50, 25:75, 0:100)	Voltage = 25 kV Distance needle tips to collector = 15 cm Flow rate = 1 mL/h	214 to 323 nm	Medical service field	(Xiao et al. 2018)
Cellulose acetate (Mn 61,000 with 40% acetyl group)	Solution pyrrole concentration (0.025-0.075 M)	Voltage = 20 kV Flow rate = 02 mL/h	243 nm	Fully organic batteries	(Baptista et al. 2018)
Cellulose Acetate (CA) (Mn 30,000)	CA in 2:1 (w:w) N/N-dimethyl acetamide:acetone	Voltage = 8 kV Distance needle tips to collector = 12.5 cm Flow rate = 0.6 mL/h	175-890 nm	Airbone nanoparticle filtration	(Ahne et al. 2018)
Cellulose Acetate (MW 30,000 g/mol) PVP (MW 1300,000 g/mol)	DMF:acetone = (6:4, 4:6, 2:8 v/v) DCM: acetone = (3:1 v/v)	Voltage = 8 kV Distance needle tips to collector = 12.5 cm Flow rate = 0.6 mL/h	nanofibres	-controlling morphology nanofibres	(Lee et al. 2018)
PEO/PVP/CNC CNC (extract from cellulose powder)	64 wt. % sulfuric acid	Voltage = 15 kV	9 nm	Sustainable green composite development	(Qinglin Wu et al. 2018)
Polystyrene & Cellulose Acetate (PS/CA) CA = Mn 30,000	DMF:THF = 1:1	Voltage = 40 kV Distance needle tips to collector = 8 cm Flow rate = 2 mL/h	100-800 nm	-	(Rosdi et al. 2018)
Cellulose Triacetate (TAC)	MC: DMF = 9:1 (v/v)	Voltage = 15 kV Distance needle tips to collector = 15 cm Flow rate = 0.4 mL/h	Average 10 nm	Oil water separation	(Xu et al. 2018)

diameter ranging. In addition, using chemomechanical isolation, Wang and Sain (2007) synthesised soybean stock-based nanofibres with a diameter ranging from 50-100 nm. Then, X-ray crystallography was accomplished to investigate the percentage crystallinity after various stages of chemomechanical treatment. It has been found that samples crystallinity increased after each stage of nanofiber development. The nanofibre suspension achieved after the high pressure defibrillation was analysed to determine diameters using AFM. The AFM image displays the surface of air dried soybean stock nanofibres. It was seen that the fibres were nanosized with diameter of nanofibres within the range of 50-100 nm.

NANOCELLULOSE APPLICATION

Biomedical Application Silver nanoparticles combined with cellulose nanofibers maybe connected as antibacterial specialists in wound dressing, swathes, inserts, medicaments as well as in antimicrobial nourishment pressing, face veils, water cleaning frameworks and air channel products (Kozłowski et al. 2007; Laborie & Brown 2009). The discoverer expressed that nanocomposite included by silver nanoparticle and cellulose nanofibre considered natural cordial and the planning technique is straightforward and flexible for scaling (Chandrabhas 2008; Moon et al. 2011). The blend of nanocellulose and silver nanoparticles can be utilised for microbicidal medicaments. Cellulose spinning solution mixed with silver nanoparticles can serve as bacteriostatic, bactericidal and fungicidal. Cellulose nanofibres prepared with nanosilver have been observed to be productive across *Staphylococcus aureus* amid the bacterial development process (Moon et al. 2011). Essentially, oxidised carboxyl groups in cellulose nanofibres have many applications for antibacterial activity. Along these lines, *E. coli* as the representative exhibited microbicidal activity for water purification procedure in view of an oxidised cellulose nanofibrous film (Benjamin et al. 2010).

In 2009, Anderson depicted the employment of nanocellulose for skin treatment in the conveyance of makeup and medicaments (Andersen 2009). The mix with the first layer comprises biomaterial including cellulose while the second layer is made out of polymer nanofibres that contain the dynamic cosmetic content similar to a vitamin or peptide (Andersen 2009). Additionally, nanocellulose can be applied for cosmetic treatments including the evacuation of cosmetics, cleaning of skin and hair as well as the treatment for dry or delicate skin using cellulose film made up from oil in water emulsion without surfactants. According to Rebecca Davies, it has been reported that cellulose nanoparticle hydrogels and aerogels with normal pore distances across of under 100 nm can be connected in a few biomedical applications such as biosensors, platforms for tissue engineering, pathogen recognition, drug conveyance process, contact focal points, medical electrodes, breast embed, therapeutic gadgets and biocatalysts (Thielemans & David 2011). Anna et al. (2007)

have contemplated various novel materials considering cellulose nanofibres such as froths, nanopapers, aerogels and composite of starch nanocellulose. Henriksson et al. (2007) produced cellulose nanofibres from wood mash and amylopectin rich potato starch for biofoams application.

Many investigators are interested in applications of biomedical and packaging material using the concept of cellulose nanocomposite biofoams. Nanocellulose in its naturally feature state is unharmed to people and biocompatible. Therefore, nanocellulose can be utilised for health care use like personal hygiene products, biomedicines and cosmetics. Besides, nanocellulose dispersions can be accounted for stabilisation of medical suspensions against phase separation and sedimentation of huge contents. From a view of chemical, immobilisation of enzymes and other drugs can be utilised by mutated cellulose as a promising carrier. For example, bearer drug complex can permeate through skin pores and treat skin infections due to its nano size molecule and can be connected as a peeling operator in beautifying agent products (Ponomarenko et al. 2008). Figure 6 shows the production of cellulose nanoparticles and nanocomposites for biomedical applications (Rojas et al. 2015).

Technical Applications Cellulose has a unique feature and can be transformed in many different forms such as crystallisation, nanocrystals, whiskers, nanofibrils, and nanofibres that are usually used in many technical applications. Nanocellulose combines fascinating physical and morphological properties such as large surface area, hydrophilicity, sites for chemical modifications, formation of semicrystalline fibres that allow numerous applications (John & Thomas 2008). Normally, filtration membranes can be applied using cellulose nanofibres (Benjamin et al. 2010, 2008; Koslow 2003). According to Benjamin (2010), the electrospinning technology for preparing cellulose nanofibrous membranes with average fibre diameter of 100 nm, homogeneous handling and the ability for surface functionalisation has significantly improved water flow and can be used as microfiltration membranes. These are beneficial for low pressure-microfiltration, nano filtration, ultra-filtration and forward osmosis. Moreover, Koslow (2003) expressed that cellulose nanofibre filter contains a microbiological interception enhancing agent consisting biologically active metal with the ability of imparting a positive charge at the very least portion of micropores.

Cellulose surface chemical modifications are the encouraging strategies to enhance mechanical and thermal properties of varied polymers such as elongation at break, tensile strength at break, biodegradability and water-retention for technical applications (John & Thomas 2008; Vallejos et al. 2012). Correspondingly, cellulose nanofibres surface modified can be used in coating, filters, membranes, adhesives, sealings, packing and cosmetics (Bordeanu & Eyholzer 2009). Other technical applications for nanocellulose emerged up on its existence in composites for reinforced biomaterials (Oksman et al. 2006; Sain

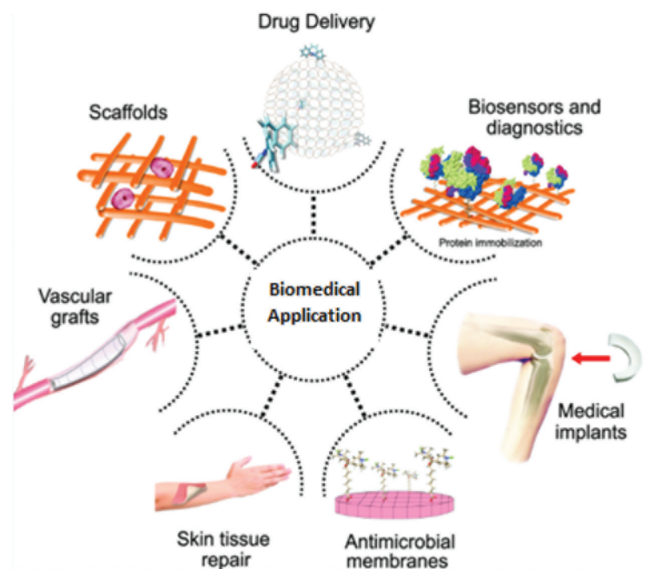


FIGURE 6. A diagram shows the production of cellulose nanoparticles and nanocomposites for biomedical applications (Rojas et al. 2015).

2004). In 2008, Sain explained about reinforcing material from cellulose nanofibres in plastic composite for blood bags, medical devices and aerospace industry. Oku (2009) describes an optically transparent, flexible substrate comprising cellulose nanofibres and very low-melting point glass deposited by impregnation as a benefit in devices such as digital cameras, cellular telephones, flat displays and integrated circuits.

Aerogels have turned into another class of materials for catalysis applications and in structures for fluid stock piling. They have excellent heat protective properties. Pääkkö et al. (2007) learned about aerogels arranged by the freeze drying of cellulose nanofibril water suspensions. Fortifying filler of nanocellulose can be utilised to produce water dissolvable polymer composites, and with acrylic as well as other latex to build the mechanical properties of dry composites and change the viscosity. Other than that, other use of nanocellulose include the expansion of nanocellulose into biodegradable polymers permitting both for speeding up the rate of degradation and change of mechanical properties (Ioelovich 2008).

Others Applications Nanofibril of cellulose suspensions can likewise be changed into nanopaper structures. In 2008, the amazing capability of such nanopaper from its outstanding mechanical execution has been seen by Henriksson et al. (2008). Svagan et al. (2007) concentrated on the capacity of cellulose nanopaper to keep up its uprightness at high strains. Lately, studies have demonstrated the likelihood to expand paper quality with added substance of nanocellulose particles into paper pieces. Besides, the production of board or paper for printing and recording facts can be applied using nanocellulose (Knox et al. 2005; Ogino 2010; Yamada et al. 2010). The papers produced by nanocellulose consist

of high density support material with at least one coating layer with cellulose nanofibres. Thus, it leads to a large print smoothness and best glossiness for printing (Holik 2006).

Nanocellulose can be used for optical diffusers, transparent substrates and liquid crystals for transparent lamps, windows or dials of clocks, as reported by Godinho (2010) and Kundu et al. (2010). Similarly, Yamada et al. (2010) explained an optical film gained by laminating a hard coating layer consists of cellulose nanofibres with average fibre diameter from 4-200 nm, which can be used as a display device free of curling, cracks and breakage.

CONCLUSION

All in all, description of the preparation of cellulose microfibrils and nanofibers utilising electrospinning technique has been presented. Amid the previous three decades, cellulose, the derivatives and cellulose-based composites have progressively enhanced and created in numerous applications. Due to an incredible number of properties, uses of are chiefly thought to be in an extensive variety of utilisations such as construction, furniture, automotive, paper, bundling products and hardware. Beauty care products, biomedical applications and pharmacy have additionally been considered. In this overview, the use of electrospun cellulose for biomedical, technical and other applications has been addressed, which have a great potential for the viewpoint of sustainable and renewable technology.

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