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REVIEW

Nanocellulose isolation characterization and applications: a journey from non-remedial to biomedical claims

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Abstract

Cellulose is a renewable, biodegradable, ecofriendly and sustainable biomaterial. Global market of nanocellulose is comprehensively very high due to its utility. Extraction of nanocellulose from bacteria and plant results in different morphology and size of nanocellulose. Biocompatibility, mechanical strength, biofabrication, crystallinity, high surface area per unit mass, hydrophilicity, porosity, transparency and non-toxicity of bacterial cellulose make it more attractive. The extravagant nanoscaled three-dimensional network of cellulosic structures possess extraordinary properties for biomedical application, evidencing its usage in skin therapy, cardiovascular implants, cartilage meniscus implants, tissue engineering, bone tissue and neural implants, wound care products, drug delivery agents, tablet modification, tissue engineered urinary conduits, and synthesis of artificial cornea. Hence due to potential benefits associated with nanocellulose effective and efficient techniques are required for the isolation of nanocellulose that should be economical, ecofriendly and non-toxic.

Keywords Nanocellulose · Plant and bacterial source · Extraction · Applications

Introduction

Increased concerns about the environment and market demand for sustainable products and services have pushed for the development and use of renewable materials and products [129, 176]. Presently, there is a strong need for replacing fossil fuel products with bio-based biodegradables which can resolve numerous issues such as reduction in crude oil stocks and their geographical localization, carbon footprint, plastic pollution and sustainability. Cellulose, the most abundant natural polymer on earth, is one potential alternative which can be used to propose rational solutions for these issues.

Cellulose is a renewable, biodegradable, ecofriendly and sustainable biomaterial with an estimated annual bio production of over 7.53×10^{10} metric tons [72, 106]. It is the most abundant natural polymer present in different biological entities such as in microbes like bacteria, all plants and very few animals such as tunicates (a marine animal) [45]. Cellulose present in tunicates is called as Tunicin, and is known to consist of 1β allomorph. It is well known for its high crystallinity and to determine the hydrogen bonding system and crystal and molecular structure of cellulose [185]. As animals tend to lack the presence of cellulose in their cell, apart from these marine entities and not much exploitation is done regarding the nanocellulose synthesis, it is not focused in this review. Cellulose acts as a major part of plant's cell wall material formed by the α-D-glucose [139] by condensation reaction linked through 1–4 glycosidic bond. Cellulose obtained from plant source is pronounced strengthen material in various matrices [52]. While bacterial cellulose (BC) or microbial cellulose (MC) is an auspicious natural polymer discovered in 1886 by A. J. Brown during vinegar fermentation but its applicability has been realized recently. It is unbranched polysaccharide comprising of linear chains of β-1,4-glucopyranose residues and produced by many species of nitrogen fixing bacteria. Bacteria produces cellulose to shield itself against the harsh chemical and ultraviolet effects and to access oxygen [182], while for plants it acts as a supportive backbone.

What is nanocellulose?

Nanocellulose is composed of cellulose fibrils having 1–100 nm in size. Nanocellulose is widely used to describe different cellulose-based nanomaterials like nano cellulose

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Table 1 Characteristics of various kinds of nanocelluloses

Type	Diameter (nm)	Length	L/D	Crystallinity (%)	References
CNF	10–100	> 1 µm	70–100	84.9	Dufresne [50], Lavoine et al. [112]
CNC	4–25	100–500 nm	15–50	91.2	Habibi et al. [72], Lu and Hsieh [126]
BNC	20–100	> 1 µm	50–100	70–80	Hu et al. [78], Castro et al. [29]

fibers, crystalline nanocellulose, cellulose composites etc. [1] with high surface areas and aspect ratios [52, 104]. On the basis of functions, structures, mode of productions, sources and reaction conditions, there are three major subdivisions of nanocellulose [17, 27]. These are bacterial nanocellulose (BNC), nanofibrillated cellulose (NFC) and cellulose nanocrystals (CNC) (Table 1).

Bacterial cellulose

Bacterial cell wall acts as the vehicle for cellulose production. Bacterial cellulose is less than 100 nm in width having ribbon-shaped fibril consist of fine nanofibrils of 2–4 nm [25]. For isolation and purification, no pretreatments are required due to the presence of pure cellulose [43]. The exclusive mechanical, physical and structural properties of BC extend its feasibility to become a vendible material in many fields of biomedical, electronic and industrial arena [94].

Cellulose nanocrystal

Cellulose nanocrystal is elongated, less flexible and rod shape crystalline structure [24]. Nanowhiskers [90], nanorods [84]; [51] and nanofiber or nanofibril cellulose [3, 5, 74] are other terms used for cellulose nanocrystals. Their production can be achieved by acid hydrolysis [19] with low aspect ratio of 2–20 nm diameter [80]. It is pure cellulose of 100 nm to several µm long, in between 54 and 88% crytstallinity index [139].

Nanofibrillated cellulose

Nanofibers of around 1–100 nm long and flexible intervening network [32] of nanofibrillated cellulose consist of compressed chain of cellulose fibers present in plant. Alternations of crystalline, amorphous forms are also present [24]. Along with chemical or enzymatic treatment [108], delamination of wood pulp by mechanical pressure can be used as a method for nanofibrillated cellulose production [10, 39, 199].

Structural arrangement of cellulose

In nature cellulose, glucose units are present in chains or threads of cellulose forming microfibrils in cell walls of different organisms. Plants cell wall is composed of two layers. Outer thin layer is primary wall while inner or secondary layer is thicker, composed of three more layers consist of amorphous and crystalline microfibrillar areas. Within matrix, cellulose array is present which give them shape and strength like a concrete rod [14, 55, 153]. In axial 20 and 60 nm, and in lateral dimensions around 5–30 nm crystal size is present [6]. Helically arranged microfibrils [98] from 15 to 18 nm thick clusters in wood cellulose fibers. Fibrils form the basic structural pillars which unite to form bigger unit known as microfibrils which constitute biggest unit called fibers. At surface alternate crystalline and amorphous form of microfibrils are present [11] which can be extracted as nano cellulose.

Bacterial cellulose is an unbranched polysaccharide comprising of linear chains of β-1,4-glucopyranose residues where well-arranged networks of fibril give rise to three dimensional nanofibers which help in the production of BC sheets with high surface area and pore size [194].The chemical foundation of BC structure is the chain molecules linked by cellobiose. Similar to cellulose it is free of contaminant molecules, such as lignin, hemicelluloses, and pectin, etc., that are normally present in plant-derived cellulose [43].The purification of BC using NaOH solution tends to be a low energy process, which is why the chemical purity of BC can be maintained without the use of harsh chemicals [173]. Degree of Polymerization (DP) of BC ranges from 300 to 10,000 residing on bacterial strains, cultivation conditions, and various additives [123]. Due to compact packing of cellulose/nanocellulose in plants, sophisticated techniques are required for their extraction to achieve maximum benefits associated with this biomaterial.

Extraction techniques

Various techniques have been in practice since long for isolation of cellulose/nanocellulose. These methods comprise of chemical, enzymatic and mechanical means for the production of cellulose microfibrils. The chemical methods like alkaline treatment [7, 8] and acid hydrolysis are used for the disintegration of compactly packed cellulose microfibrils [53], while enzymatic hydrolysis [74] is also employed for similar purpose. Mechanical methods involves cryocrushing [200], homogenization through high pressure [143], shredding/grinding [2] etc. In some cases more than one reactions are required to follow on the basis of applications.

Sources of nanocellulose

Cellulose/nanocellulose can be extracted from various sources like plants, marine animals, fungi and bacteria. Among them, we discuss in detail the extraction of cellulose/nanocellulose from different plant materials and bacterial cultures (Tables 2, 3). Cellulose is fundamental building block of plant cell wall that can be extracted by chemical and enzymatic processes (Fig. 1). Functional properties of cellulose nanofibers and their abundance emphasize utilization of agricultural waste, as a major source of cellulose [89, 124] due to their availability in large quantities, cheaper and easy purchasing [66, 130]. Besides these, it will be helpful in the management of waste overcoming pollution or diseases associated with dumping of waste [145]. Utilization of biomass has attracted growing interest for the synthesis of cellulose-based novel composites [35]. Various plant materials act as a raw material for cellulose, including wood, cotton, flax, hemp, jute, ramie, straws, cornhusk, fruit remains, sugarcane bagasse and many more [110, 162, 224].

Biocompatibility, mechanical strength, biofabrication, crystallinity, high surface area per unit mass, hydrophilicity, porosity, transparency and non-toxicity of bacterial cellulose [41, 194] demands utilization of bacterial cultures for the isolation of bacterial cellulose. Various bacterial cultures act as a vital source of cellulose some of them are *Acetobacter*, *Agrobacterium*, *Alcaligenes, Pseudomonas, Rhizobium, or Sarcina* [54]. However, *Acetobacter xylinum* acts as efficient source of bacterial cellulose [107]. The bacterial cellulose is present in cell wall and the isolation process yield pure cellulose (Fig. 2).

Applications of nanocellulose

In ancient times Cellulose was used for making ropes, sails, paper, and timber for buildings and various other utilities [83, 208]. Non-toxic and ecofriendly nature of nanocellulose has diverted attention of scientists toward these materials for their applicability [101]. Nanocellulose is an interesting commodity which is applied in plenty of applications like textile, medicine, food packaging, cosmetics, pharmacy, fossil fuels, bioplastics, strengthening material, enhanced oil recovery, super absorbent, paints, electronic, biomimetic material [28, 88, 109, 122], optical and energy devices [147]. Other potential applications include use of nanocellulose as polymer nanocomposites with other polymers, hydrogels and technical materials (Fig. 3).

Biomedical applications

The elementary characteristics of an ideal biomaterial correlates to its biocompatibility, chemical composition, structural diversity (chirality), hydrophilicity, biodegradability/bio absorbability tendency to promote cellular interactions, proliferation, cell adhesion, porosity and excellent mechanical strength [160, 195]. Nanocellulose especially BC can be sterilized and modified without damaging the basic infrastructure and properties tending it to be a suitable implantable biomaterial [125] offering a wide range of special applications in medicines (Fig. 4). The biomedical applications of bacterial cellulose in contrast to nanocellulose are emphasized here due to its extensive use in medical sector (Tables 4, 5).

Skin therapy

The high mechanical strength, permeability for substances (liquids, gases) and less irritation of BC at wet state suggest its usage as a wound healer and artificial skin generator. Two commercial BC products are being used in surgery, health care sector and dental implants, i.e., Biofill® and Gengiflex®. Biofill®. These are used in case of second- and third-degree burns, ulcers and temporary skin substitute [213]. It is highly known for its effectiveness for more than 300 treatments due to its extraordinary behavior including close adhesion to the wound bed, spontaneous detachment, reduced treatment time and cost, reduced infection, post-surgery discomfort, faster healing, transparency, immediate pain relief but the restricted elasticity in mobility areas limitize its affectivity to some extent. Gengiflex® on another hand helps periodontal tissues to recover. Cellumed is also a product used to treat large surface wounds of dogs and horses [23].

Artificial blood vessels (cardiovascular implants)

Bacterial cellulose (BC) due to its shape retention ability, mold ability and good tear resistance tends to be the effective replacement of synthetic material being used for artificial blood vessels as it prevents the risks of blood clot. Mechanical strength and resemblance factor of BC in terms of inner lining (diameter of 1 mm, length of about

Table 2 Plant sources of nanocellulose; method of isolation, characterization and applications

Source	Method used	Size	Characterization	Application	References
Kraft Pulp	High-pressure homogenizer	50–100 nm	SEM	Exhibit great potential as reinforcement material for optically transparent composites	Iwamoto et al. [83]
Corn stalks	Mechanical and chemical treatment	50–100 nm	XRD, SEM	The structure and properties of cornstalk fibers indicate that the fibers are suitable for producing various textile products	Reddy and Yang [163]
Swede root	High-pressure food homogenizer	10–20 nm	SEM	Plant fiber is used in industrial composites	Bruce et al. [26]
Hemp fibers	Chemical and mechanical treatments	30–100 nm	SEM, TEM, AFM	Polymer matrix	Wang et al. [202]
Hemp fiber of Ontario, spring flax fibers, Kraft pulp, rutabaga	Chemical and mechanical treatments. Acid hydrolysis, cryocrushing, high shear and high energy	5–60 nm	SEM, TEM	Cheap and environment friendly reinforcement to process composite materials using polyvinyl alcohol as a polymer matrix	Bhatnagar and Sain [19]
Soybean	Cryocrushing	50–100 nm	AFM, TEM	Plastic reinforcement, gel forming and thickening agent	Wang and Sain [200]
Cotton Pulp	Ultrasound wave	6 nm	LS, TEM, FTIR, XRD	Nanocrystal	Xiao-quan [209]
Cotton linters	Hydrothermal intracrystalline deuteration and acid hydrolyze	3–20 nm	Neutron reflectivity	Textile, food, and pulp and paper industries	Jean et al. [86]
Cellulose cotton	Both physical and chemical techniques	60–570 nm	AFM, TEM, SEM	Sustainability and green chemistry	Zhang et al. [218]
Bagasse	homogenization process,	200 nm	SEM	Used as reinforcing elements in composites with biodegradable thermoplastic co-polyesters or other common engineering thermoplastics	Bhattacharya et al. [20]

Table 2 continued

Source	Method used	Size	Characterization	Application	References
Sisal fibers	acid hydrolysis, chlorination, alkaline extraction, and bleaching	100–500 again purify result in 7–31 nm	TGA, FTIR, XRD, DSC, SEM	Used in future works in the production of biodegradable nanocomposites with enhanced properties	Morán et al. [140]
Wheat straw	Cryocrushing followed by fibrillation and subsequent homogenization	20–120 nm	SEM, TEM	Starch-based thermoplastic polymer	Alemdar and Sain [7, 8]
Wheat straw and soy hulls	Chime mechanical technique	10–80 nm	TEM	Potential for use as reinforcement fibers in bio composite applications	Alemdar and Sain [7, 8]
Banana	High-pressure defibrillation and acid treatment	200–250 nm	FTIR, XRD, SEM	Reinforcing elements in nanocomposites.	Cherian et al. [34]
Banana rachis	Different combinations of chemical and mechanical treatments	3–5 nm	TEM, XRD, solid-state 13C NMR	Agro-industries	Zuluaga et al. [226]
Golden grass	Bleaching and acid hydrolysis	Size 4.5 and 300 nm,	XRD, SEM, TEM	Used as energy resources and in paper industries	Siqueira et al. [180]
Pineapple	Alkali treatment and acid hydrolysis	5–60 nm	SEM, AFM, TEM, XRD	Biodegradable plastic composites	Cherian et al. [35]
White cotton	Acid hydrolysis	6–18 nm diameter	XRD, SEM, STEM, AFM	Medical implants, tissue engineering, drug delivery, and other medical applications	Morais et al. [44]
Cassava	Acid hydrolysis	15 nm in diameter	SEM, XRD, DMA	Used in natural rubber as matrix	Pasquini et al. [151]
Curaua	Acid hydrolysis using 3 acids H_2SO_4, H_2SO_4/HC1, HC1	6–10 nm	XRD, TG, TEM, DP	Used as raw material applied to polymer composites by the textile and automotive industries	Corrêa et al. [38], Hill et al. [75]
Sesame husk	Alkali treatment	30–120 nm	XRD, TEM, SEM, AFM	Applied in nutraceutical and medical	Purkait et al. [158]
Banana, Coir, Sisal, Pineapple, Kapok	Alkaline treatment, bleaching and acid hydrolysis	10–25 nm	SE, AFM, TEM, XRD, TGA, IGC	Reinforcing agents in polymer nanocomposite sector	Deepa et al. [46]

Table 2 continued

Source	Method used	Size	Characterization	Application	References
Bamboo	Chemical purification and high-pressure homogenization	10–50 nm	SEM, TEM, FTIR XRD	–	Wang et al. [205]
Coconut	Chemical treatment, grinding and homogenization	50–100 nm	SEM, TEM, FTIR	Ideal reinforcing material for polymer composite, fabrication of films without using organic solvent	Zhao et al. [221]
Jatropha corcas L.	Cryocrushing, acid hydrolysis, dialysis and sonication	–	SEM, TEM, XRD, AFM	As an additive to improve the quality of composite for medical appliances, electronic and many other application	Mahadia et al. [131]
Raw jute	Steam explosion and alkaline treatment	50 nm in diameter	SEM, TEM, XRD, TGA, FTIR	Reinforcing agent in natural rubber latex, cross-linking agent	Thomas et al. [188]
Mexican feather grass	Pulping, bleaching and acid hydrolysis	Diameter 8 ± 2 nm	XRD, AFM, FTIR, TGA	Used as reinforcing phase to prepare bionanocomposite films or reinforcing agent for casting/evaporation methods preparation of bio nanocomposites	Youssef et al. [216]
Tomato	Acid hydrolysis, alkali treatment	3.3 nm thick, 7.2 nm wide, 13.5 nm long	FTIR, AFM, TEM, SEM, EDS, XRD, TGA		Jiang and Hsieh [87]
Sweet orange	Alkaline treatment, bleaching and enzymatic hydrolysis	Diameter 10 nm,	SEM, AFM, TEM, XRD, TGA, IGC	Reinforcing agents in polymer nanocomposite sector	Mariño et al. [133]
Garlic	Alkali treatment, bleaching and acid hydrolysis	6 nm diameter	TEM, AFM, XRD, TGA, FTIR	Used as reinforcement in the preparation of nanocomposite	Kallel et al. [97]

Table 2 continued

Source	Method used	Size	Characterization	Application	References
Kinnow	Alkaline treatment and acid hydrolysis	9.7 nm diameter	XRD, SEM	Used in production of biodegradable nanocomposite	Naz et al. [145]
Banana c.v. valery	Chemical treatment and high-pressure homogenization	100–200 nm	SEM, TEM, FTIR, TGA, XRD	–	Velásquez-Cock et al. [197]
East-Indian screw tree	Thermal, chemical and mechanical methods	50 nm diameter	TEM, SEM, XRD, FTIR	Nanocomposite preparation	Joy et al. [92]
Rubber wood	High-pressure homogenization, enzymatic and chemical pretreatment	37–85 nm	FTIR, SEM, XRD	Reinforcement agent	Podder et al. [156]
Pinecone	Alkaline treatment and grinding	5–25 nm	FTIR, SEM, XRD TGA	Manufacturing of bio-nanocomposites	Rambabu et al. [161]
Rice plant	Acid hydrolysis, bleaching and alkali treatment	5–50 nm	TGA, FTIR, AFM	Reinforcing agent	Castro-Guerrero et al. [30]
Date palm	Acid hydrolysis and sample pyrolysis	20 nm	SEM	Barrier properties	Hossain and Uddin [76], Nair et al. [142]
Organosolv Straw Pulp	Thermal and ultrasound treatment	10–40 nm	SEM, TEM	Its application for the preparation of new nanocomposite materials	Barbash et al. [15]
Satin tail	Alkaline treatment and acid hydrolysis	Single-fiber diameter 5 µm	SEM, FTIR, TGA, XRD	–	Coelho et al. [37]
False indigo	Grinding and high-pressure homogenization	10 nm in diameter	XRD, FTIR, SEM, TEM	–	Zhuo et al. [223]

Table 3 Bacterial sources of nanocellulose; isolated nanocellulose characteristics and applications

Source	Size	Extraction technique	Characterization	Application	References
Acetobacter xylinum (ATCC 23767)	500 nm	Microbial cell culture/alkaline	AFM, NMR spectroscopy	–	Gillis et al. [62]
Acetobacter xylinus	50 nm	Chemical/alkaline	SEM, VARI	Manufacturing rigid and robust natural fiber	Touzel et al. [191]
Gluconacetobacter	10–200 nm	Production of BC/PHEMA nanocomposite films	FTIR, 13C NMR, SEM, Crystallinity, XRD	Optical transparent, nanocomposites, electronic paper, fuel cell membranes	Nakagaito et al. [144], Ifuku et al. [81]
Glucanacetobacer xylinus	60–80 nm	Bacterial cell culture/Chemical	XRD, SEM	Hybrid BNC-TiO2 for purification of drinking water	Graber [67]
Glucanacetobacter xylinus	45–80 nm	Microbial cell culture/Alkaline	SEM	Cartilage regeneration/regeneration medicines	Graber [67]
Glucanacetobacter xylinus	60 nm	Microbial cell culture/alkaline	SEM	In 3D culturing for invitro studies of neurodegenerative mechanisms	Graber [67]
Glucanacetobacter xylinus (DSM 14666)	600 µm	Chemical/alkaline	SEM, FTIR, XPS	Cartilage implants	Klemm et al. [107]
Glucanacetobacter xylinus DSM (14666)	60 nm	Static microbial cultivation/chemical	FTIR, SEM	Enhance antimicrobial activity of silver nanoparticles (hybrid)	Klemm et al. [107]
Glucanobacter/acetobacter specie	10–200 nm	Silver plating on surface of bacterial nanocellulose. Chemical methods	–	Wound healing	Keshk and Sameshima [100]
G. xylinus (IFO 13693)	–	Static culture 28 °C for 168 h	IR spectroscopy, XRD	Artificial skin for scaled or wound healing	Keshk and Sameshima [100]
A. xylinum	≥ 100 than plant cellulose	Agitated condition	–	Wound healing	Czaja et al. [40]
Glucanacetobacter xylinus (DSM 14666)	0.12 µm	Microbial cell culture/Alkaline	SEM	Drug delivery system for the model protein albumin	Klemm et al. [107]
Glucanacetobacter xylinus (ATCC53582)	50 nm	Static microbial culture/chemical	X-ray photoelectron Spectroscopy, SEM, FTIR	Tissue engineering/tissue reconstruction	Kato et al. [99]
Acetobacter xylinum	10–80 nm	Agitated conditions	XRD, FTIR	–	Sun et al. [186]
G. xylinus	–	Enzymatic, temperature 30 °C at 160 rpm for 24 h	SEM	The nanofibers exhibit great potential as reinforcement material for optically transparent composites	El-Saied et al. [54]

Table 3 continued

Source	Size	Extraction technique	Characterization	Application	References
Agrobacterium	$\geq$ 100 nm	Enzymatic	FTIR, XRD, SEM	Higher water capacity, used commercially, high crystalinity	El-Saied et al. [54]
Acetobacter xylinus	1/100 of plant cellulose	Super-critical drying for porous structure preparation	FTIR, SEM	Pre-vapouration process	Phisalaphong et al. [155]
Acetobacter xylinum	–	Agitated on a shaking plate at 150 rpm	Electron microscopy,Single fiber tensile tests, X-ray photoelectron spectroscopy, Inverse gas chromatography	Wound dressings, burn treatments, tissue regeneration	Pommet et al. [157]
Gluconacetobacter xylinus	–	Static culture conditions (liquid medium)	FTIR, XRD,SEM,EDS, TGA	Food additive, scaffold in tissue engineering, food packaging, preparation of composite materials	George et al. [61], Lee et al. [113]
Gluconacetobacter xylinus	500 µm	TO and SiO_2 films were deposited onto dried BC membranes	AFM Optical absorption and transmission measurement, PTI fluorimeter for electroluminescence spectra	Flexible substrates for the fabrication of organic light emitting diodes (OLED), Photodynamic therapy (PDT) to treat skin cancer, electronic paper	Legnani et al. [117]
Acetobater xylinum	10–80 nm	Treatment with tween 80(0.20 g/l) for 36 h	FTIR, UV analysis	Wound healing, tissue regeneration	Deng and Wu [47]
Glucon acetobacter hansenii (PJK)	8 µm	Static centrifugation, physical and enzymatic methods	–	Paper industry, oil recovery	Ha et al. [71]
Acetobacter xylinum	0.8–1.0 cm	static culture of coconut water	UV analysis X-ray diffraction	Desserts, fruit, cocktails, jellies and reduced lipid level of consumer	Jagannath et al. [85]
Glucon acetobacter xylinus strain (K3)	22 mm	BC film was harvested green tea as supplementary material	–	Extend bacterial life nanostructure, morphological similarities with collagen	Nguyen et al. [146]
Gluconacetobacter hansenii	8 µm	Static culture using a medium containing ethanol	–	Nutritional source for the production of water-soluble oligosaccharide.	Ha et al. [71]

Table 3 continued

Source	Size	Extraction technique	Characterization	Application	References
Gluconacetobacter xylinus	35–70 nm	Static Bacterial Culture/Chemical	SEM, XRD, FTIR	–	Nguyen et al. [146]
Glucanacetobacter xylinus	40–80 nm	Static bacterial culture/Alkaline	SEM, XRD	Neuroma prevention	Pecoraro et al. [152]
Acetobacter xylinum	40–60 nm	Microbial culture/chemical	XRD,SEM, Rama Spectroscopy	High-performance, composite	Cheng et al. [33]
Gluconacelobacler hansenii or Gluconacelobacler xylinus	40–60 nm	Photo-catalytic membrane prepared by incorporating photo catalytic particles with the BC hydrogel membrane	UV analysis	Wound care, skin, ulcer, burns	Limaye et al. [121]
Acetobacter xylinum X-2	120 nm	Chemical method	SEM, TEM, XRD, FTIR	Higher mechanical properties, scaffold in tissue engineering	Yang et al. [212]
Acetobacter sp. V6	141 nm	Combination of ball milling, acid hydrolysis and ultrasound	X-ray analysis, XRD, FTIR, SEM, TEM	Doubled tensile modulus of the polymer and optically transparent composites	Qua et al. [159]
A. xylinum X-2	70–150 nm	Enzymatic preparation	FTIR, XRD, SEM, TEM, XPS	Biomedical applications (blood related)	Goelzer et al. [63]
G. xylinus (ATCC 53524)	120–150 nm	Static culture at 30 °C for 96 h	FE-SEM, FEI, FTIR, ATR-FTIR	Paper, cotton, pharmaceuticals and wound care industries	Mikkelsen et al. [135]
Acetobacter xylinum (NBRC 13693)	100 nm	Static culture at 30 °C for 96 h	XRD, SEM	–	Kurosumi et al. [111]
Acetobacter xylinum (JCM 9730)	130–170 nm	Stirred culture at 30 °C and 125 rpm for 288 h	XRD, SEM, FTIR X- ray analysis	Supramolecular structure, exceptional product characteristic	Kurosumi et al. [111]
Gluconacetobacter	170–200 nm	Stirred culture at 30 °C and 125 rpm for 280 h	SEM, XRD	Electrospinning candidate, good mechanical properties	Gatenholm and Klemm [60]
Acetobacter sp. V6	200 nm	Stirred culture at 30 °C and 200 rpm for 168 h	Wide-Angle X-ray Diffraction, SEM, AFM, SAXS	Remarkable strength, structural and chemically engineered at nano- , micro- and macro-scale	Jung et al. [93]
Acetobacter xylinum	180 nm	Chemical preparation	FTIR, SEM,	Better mechanical properties	Li et al. [118]

Table 3 continued

Source	Size	Extraction technique	Characterization	Application	References
Acetobacter xylinum(ATCC 23769)	7–13 nm,	Ultrasonic and heating process	SEM, AFM, SAXS, DTA, Wide Angle XRD	Higher crystallinity and lower surface roughness	Tischer et al. [189]
A.xylinum subspecies *sucrofermentas* (IBPR2001)	170 nm	Mechanical method	XRD, FTIR, TEM, SEM	Higher porosity, scaffold for bone regeneration	Zaborowska et al. [217]
Acetobacter xylinum (ATCC 23669)	200 nm	Chemical-based method	FE-SEM, FEI, FTIR, ATR-FTIR	High porosity, tissue engineering	Zaborowska et al. [217]
Gluconacetobacter xylinum (AX 5)	180 nm	Agitated cultivation	ATR-IR, XRD, SEM	Mechanical strength, bio-medical devices	Gu et al. [68]
Glucano bacter/acetobacter	10–80 nm	–	Mechanical properties evaluation	Biomedical applications, new generations of cardiovascular, orthopedic implants	Bodin et al. [22]
Gluconacetobacter sp(RKY5)	50–100 nm	Static fermentation	–	Plastic composite	Gu et al. [68]
Glucanacetobacter xylinus (ATCC 700178)	30 nm width	Microbial Cell Culture/Alkaline	SEM	Cartilage replacement	Dahman et al. [42]
Gluconacetobacter xylinum sucrofermentans (BPR2001)	–	Enzymatic, pH	SEM, TEM	High tensile strength, commercial applications, food industry	Siró and Plackett [181]
Gluconacetobacter (G. xylinus and *G. Hanseni)*	20–100 nm	Enzymatic method	LS, TEM, FTIR, XRD	Textile industries, high mechanical strength polymers, high crystallinity, high tensile strength, high water binding capacity, good compatibility	Siró and Plackett [181]
Glucanacetobacter xylinus (KCCM 41431)	500 nm	Microbial cell culture/Alkaline	SEM	Application in flexible energy storage devices	Kim et al. [102]
G. xylinus (IFO 13693)	170 nm	Ultrasonic and heating process	SEM,FTIR	Biodegradability, renewable, inexpensive	Zimmermann et al. [225]
Acetobacter xylinum (23769)	100–180 nm	Chemical base method	X-ray analysis, XRD, FTIR, SEM, TEM	High crystallinity, hydrophillicity, ultrafine network architecture and purity	Kalia et al. [96]

Table 3 continued

Source	Size	Extraction technique	Characterization	Application	References
G. xylinus (CGMCC 2955)	120–200 nm	Chemical base method	XRD, FTIR, SEM, TEM	Artificial skin, paint industry (thickener for ink)	Biao et al. [21]
Acetobacter xylinum (ATCC 23773)	130–180 nm	Chemical method	ATR-IR, XRD, TG/DTA	Biomedical applications, paper industry, optical industry	Lee et al. [114]
G. sacchari	70–100 nm	Static culture at 30 °C for 96 h	XRD, SEM	Biomedical, mechanical strength, chemical and morphologic controllability, used in medical devices	Trovatti et al. [192]
A. xylinum 186	130–180 nm	Static culture at 30 °C for 144 h	FE-SEM, FEI, FTIR, ATR-FTIR	Synthesis of composites, used in packaging materials, good thermo-mechanical properties	Lu et al. [127]
Gluconacetobacter xylinus	20–100 nm	Agitated cultivation	SEM, FTIR	Industrial applications; pharmaceutical, cosmetic and paper industry	Klemm et al. [108]
Acetobacter xylinum, subspecie (BPR2001)	200 nm	Static cultivation	Wide-angle X-ray scattering, SEM, Dielectric analysis	Produce xylan films, Improved strength	Stevanic et al. [183]
Glucanacetobacter xylinus (ATCC700178)	600 nm	Chemical/physical	ESCA, XRD, SEM	Cartilage regeneration	Guo and Catchmark [69]
Anerobic Microbial Consortium	134 nm	Chemical/Enzymatic	FTIR, AFM	Drug delivery/biomedical application	Satyamurthy and Vigneshwaran [174]
Gluconacetobacter sacchari	200 nm	Chemical method	FTIR-ATR spectra, SEM	Biocompatibility, biodegradability	Gomes et al. [64]
Gluconacetobacter xylinus (NRRL B-42)		Inoculate were cultured for 48 h in Erlenmeyer flasks containing Hestrin and Schramm (HS) medium (%, w/v): glucose, 2.0; peptone, 0.5; yeast extract, 0.5; anhydrous disodium phosphate, 0.27; citric acid, 0.115. pH 6.0 with dil. HCl or NaOH	High-performance anion exchange chromatography, TEM, NMR	The nanofibers exhibit great potential as reinforcement material for optically transparent composites	Vazquez et al. [196]
Acetobacter pasteurianus	–	Mechanical, Temperature 22–60 °C during electrospinning	AFM, TEM, SEM	Higher purity, biocompatibily, polymerization	Mohite and Patil [137]

Table 3 continued

Source	Size	Extraction technique	Characterization	Application	References
Pseudomonas	–	Enzymatic, 30 °C at 160 rpm for 24 h	XRD, SEM	Bio-compatibility, high degree of polymerization, commercial applications	Mohite and Patil [137]
A. xylinum 23,769	–	Wood hot water extraction pH 5–8, temperature 26–30 °C	TGA,FTIR,XRD,DSC,SEM	Textile industries, non-woven cloths, pharmaceuticals, cosmetics	Kiziltas et al. [105]
Gluconacetobacter xylinus (NRRL B-42)		Enzymatic, pH 6.0, 28 ± 1 °C for 14 days	TEM	The nanofibers exhibit great potential as reinforcement material for optically transparent composites	Kiziltas et al. [105]
Glucanacetobacter xylinus (KCCM40216)	300 µm	Chemical/alkaline	FE-SEM, XRD	–	Park et al. [150]
Glucanacetobacter xylinus (ATCC 23769)	Gel 0.7 cm	Chemical	SEM	Bioactive mass for facial treatment	Lee et al. [115]
G. xylinus (CH001)	–	Enzymatic, fermentation at 28 °C for 5 days	TEM	Sewage purification, paper industry, high yield, high mechanical strength	Huang et al. [79]
Komagataeibacter xylinus	500 nm	Microbial cell culture, chemical/physical	SEM	Wound dressing	Fan et al. [56]
G.sp. gel_SEA623-2	–	–	SEM	Laboratories, high yield, polymers	Kim et al. [103]
Acetobacter xylinus (AGR60)	50–80 nm	Static microbial culture/chemical	XRD, SEM, FTIR	Biocompatible materials	Dourado et al. [48]

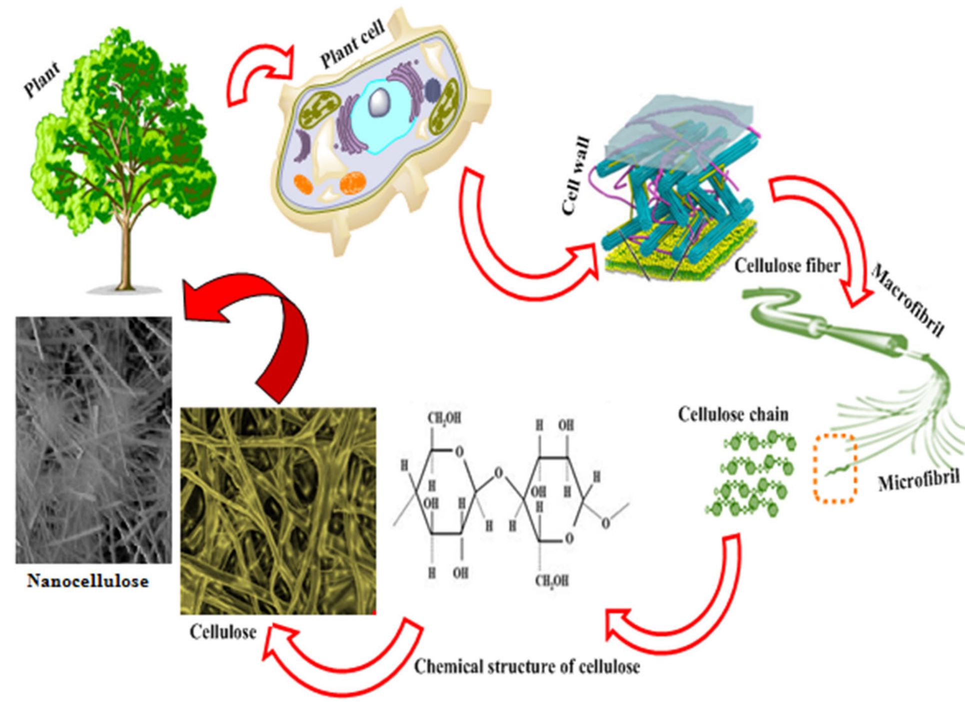

Fig. 1 Occurrence of cellulose from Plant material

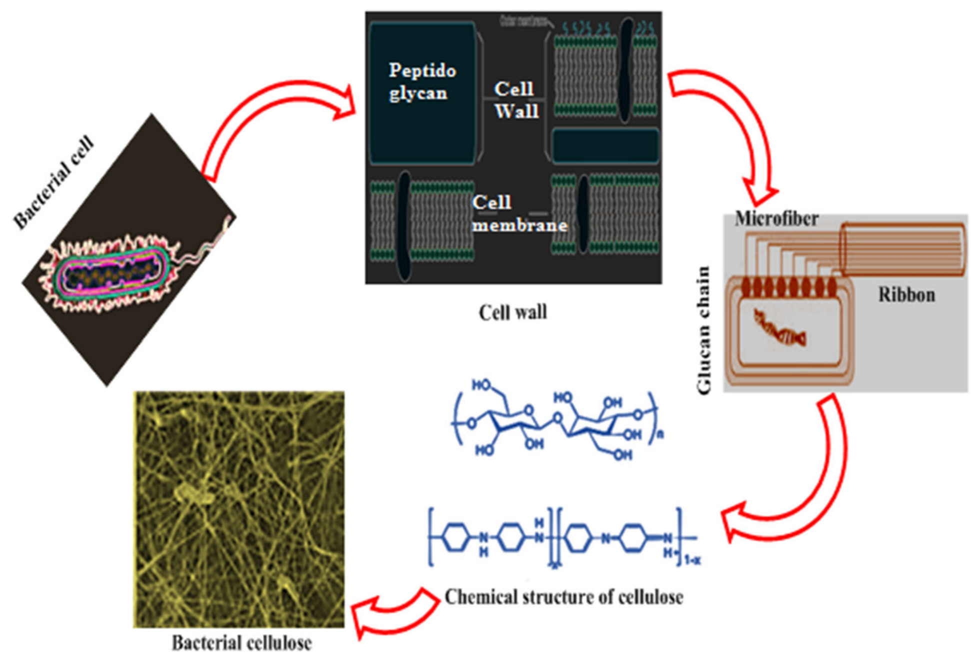

Fig. 2 Occurrence of cellulose in bacterial sources

5 mm and wall thickness of 0.7 mm), to that of natural blood vessels helps to fulfill microsurgical requirement making it a potent candidate in major bypass operations [175]. BASYC tubes are synthesized in a way to resist mechanical strains and anatomize blood pressure. In comparison with organic sheets (polyethylene-terephthalate or cellophane and polypropylene) processed BC sheets represents high mechanical strength and compatibility to native tissue [136]. Anisotropic PVA-BC composite replicates the porcine aorta (10% PVA with 0.3% BC at 75% initial strain) depicting mechanical properties that favor its usage as a vascular graft and replacement to connective and cardiovascular tissues [207]. In order to enhance the cellular adhesion, metabolism and cell metastasis, xyloglucan is used as a carrier molecule along with BC. Varying components have been tested in combination with BC to test the thrombogenic properties of BC depicting its slower coagulation potency representing lower platelets consumption and low throm-

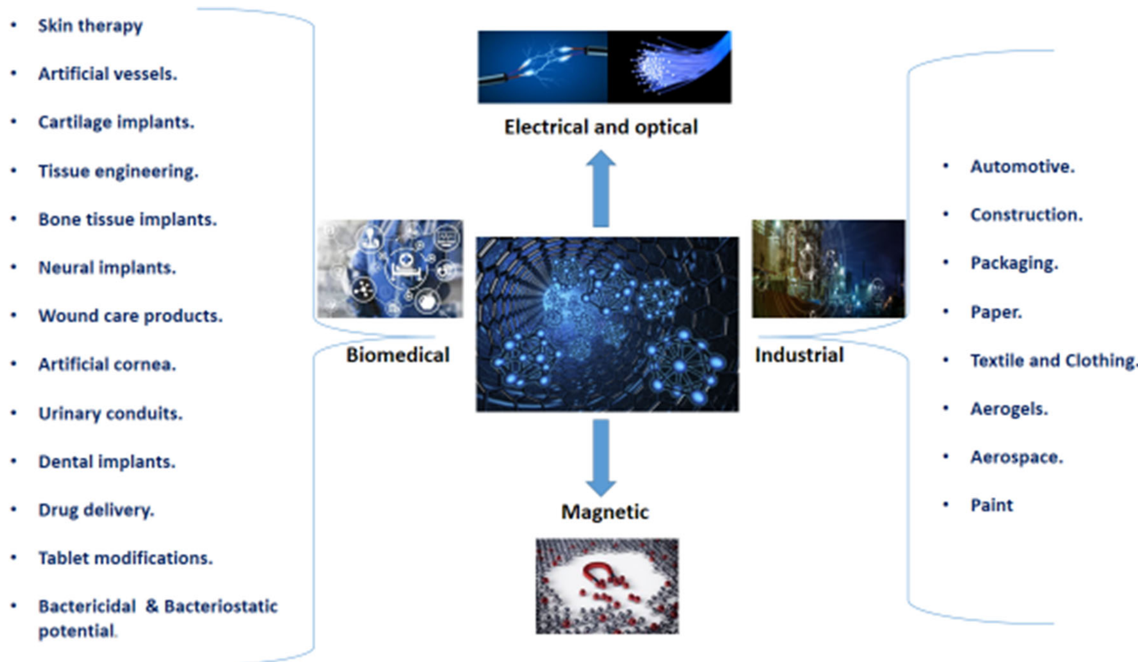

Fig. 3 Applications of nanocellulose extracted from plant and bacterial sources

Fig. 4 Biomedical Applications of nanocellulose isolated from bacterial and plant sources

bin values in comparison with Dacron® and Gore-Tex®. The mechanical properties of bacterial cellulose are comparable to porcine carotid artery and better than expanded poly-tetra-flour-ethylene [13].The tubular-shaped bacterial cellulose (BC-TS) is reported to be used as a blood vessel replacement [13, 107].

Table 4 Bacterial cellulose (BC)-based commercial products having biomedical applications

Product	Application	Company
Biofill®	Treat burns and ulcers.	Human med AG; Fibrocel
Gengiflex®	Regeneration of periodontal tissues, guided bone tissue regeneration	Organogenesis Inc.
Cellumed	Treat large surface wounds of animals	Cellumed Co. Inc
BASYC®	Artificial blood vessel, cuff for nerve suturing.	Sutumed
XCell®	Treatment of venous leg ulcers	Xylose corporation

Cartilage meniscus implants

The limited regeneration capacity of cartilage tissue makes it a major area of focus. Artificial cartilage needs to be tough and must resist biodegradation as living material deteriorates with time, they must possess stability. BC materials act as a major scaffold material for this purpose along with their capability. As a major matrix, they also prevent pro-inflammatory cytokines during in vitro macrophage. Chondrocytes impregnated on BC membranes showed proliferation and collagen type II production, indicating suitability of BC as a bio-mimicking scaffold [107]. Metabolically engineered *Gluconacetobacter xylinus* is mainly focused for the modified BC production for cartilage repair that act as a novel in vivo degradable scaffold for chondrogenesis [210]. BC is also used for auricular cartilage replacement as it matches the mechanical strength and host response of human auricular cartilage [160].

Tissue engineering

In order to maintain the cell proliferation, shape and differentiated function of tissues, a variety of natural (alginate, chitosan, fibrin glue, collagen and hyaluronic acid) and synthetic polymeric (polylactic acid (PLA), polyglycolic acid (PGA), polyvinyl alcohol (PVA),polyhydroxy ethyl methacrylate (pHEMA) and polyN iso propyl acrylamide (pNIPAA)) scaffold materials have been used for tissue engineering of cartilage [172]. *Gluconacetobacter xylinus*-based native and modified BC materials (phosphorated and sulfonated BCs) when evaluated using bovine chondrocytes, the native one depicted approximately 50% of proliferation of collagen type II substrate, significant mechanical properties, and higher chondrocyte growth in comparison with calcium alginate and tissue culture plastic [164, 165, 168, 169]. While the chemically modified BC had zero effect on chondrocyte growth but had an effect on its viability [59]. Insignificant activation of pro-inflammatory cytokine production during macrophage screening was observed in these cases. TEM analysis and RNA expression of collagen II from human chondrocytes indicated the tendency of unmodified BC supports growth and proliferation of chondrocytes suggesting the potential of BC as an important biomaterial candidate for tissue engineering [160]. Tissue replacement of connective and cardiovascular tissues is also an important aspect of BC composites especially BC-PVA composites due to their mechanical and anisotropic behavior similar to that of body tissues [214]. BC-COL composites are also well known for their use in this field due to their high mechanical strength, biodegradability, cell-binding properties and low antigenicity [128].

Bone tissue implants/bone tissue engineering

BC composites are being synthesized as a template for biomimetic apatite formation [154]. Calcium chloride/calcium phosphate precipitated in BC hydrogel makes it suitable for bone implant. HABC nano composites are also reported for the formulation of phosphorylated BC enhancing its biocompatibility and its use in bone tissue engineering [160]. BC goat bone apatite (GBA) nano composites promotes cell differentiation and proliferation when observed on L929 cells. This suggests that GBA is an important bone filler to treat bone defects and their reconstruction [154]. *Acetobacter xylinum* (ATCC 52582)-based BC gave similar results [187]. BC obtained using *A. xylinum* M-12 and impregnated using poly-lysine (PLL) makes it structurally similar and molecularly different from natural ECM. PLL coated BC nanofibers acts as nano templates and induces formation of nano sized platelet and calcium deficient B-type carbonated HAp [160]. BC also acts as delivery system for BMP-2 and promotes bone formation [12]. *Glucoacetobacter xylinus* synthesized BC incorporated with growth peptides via hydrogen bonding facilitates bone regeneration. Significant mineralization in BC was observed in osteogenic medium making it an effective scaffold as seeding cells in bone tissue implants [160].

Neural implants

The most challenging tissue reconstruction is of nervous tissues. BC being an effective scaffold material/fiber when adheres to mesenchymal stem cells, proliferates nuetrophin (nerve growth factor) promoting neuronal regeneration [160]. Consortium of five bacterial and four yeast strains

Table 5 Biomedical applications of nanocellulose

Application	Advantages	Disadvantages	References
Skin therapy	Extraordinary mechanical strength and permeability. Less irritation. Suitable barrier. Reduced treatment cost. Faster healing	Restricted elasticity in mobile areas	Yaron and Romling [213]
Cardiovascular implants	Good tear resistance and mold ability. Prevent blood clot as observed in synthetic materials. Mechanical strength and resemblance to the core vessels	Intricate conditions needed to prevent thrombosis and occlusion	Yadav et al. [210], Klemm et al. [107]
Cartilage meniscus implants	Biodegradation resistant with higher stability. Prevent pro inflammatory cytokines production	Still under trials	Yadav et al. [210]
Tissue engineering	High mechanical and anisotropic behavior similar to that of body tissues. High cell-binding property. Low antigenicity	Much work needed for long term satisfactory results. Expensive as Expression of tissue specific proteins needs to be analyzed	Yilmaz et al. [214], Fu et al. [59]
Bone tissue implants	Good mechanical and tensile strength. Enhanced biocompatibility for bone regeneration	Mineralized nanocellulose tends to be more favorable than native nanocellulose	Bacakova et al. [12], Petersen and Gatenholm [154]
Neural implants	Good biocompatibility. Less toxic effects. Facilitated neural regeneration	Long term effects need validation in larger animals	Rajwade et al. [160], Kalashnikova et al. [95]
Wound care products	Provide moist environment. Effective barrier against infection. High mechanical strength. Low irritation	Effectivity highly rely on culture conditions and co agent attached	Figueiredo et al. [57], Ul-Islam et al. [194]
Artificial cornea	High water holding capacity. High thermal and mechanical properties. High light transmittance tendency	Limited research work on engineered corneas	Wang et al. [204]
Urinary conduits	Expression of urothelial markers. Effective for patients with bladder cancer	Still in preclinical trials.	Bodin et al. [22].
Dental implants	High expansion capacity. High tensile strength. High liquid adsorption capacity	Specific conditions required for synthesis	Yoshino et al. [215]
Drug delivery application	High diffusion potential. Facilitated transport and adsorption. Good for oral and transdermal drug delivery	Small drug molecules are mainly facilitated	Abeer et al. [4], Trovatti et al. [193]
Tablet modification	High crystallinity. Better affinity	Requirement of intricate conditions making synthesis complicated	Simm et al. [179]
Bactericidal and Bacteriostatic potential	Enhanced antimicrobial activity. Rapid applicability. Safety	Bacterial elements need to be attached	Ul-Islam et al. [194]

have used to obtain BC membranes for the preparation of nerve conduits that possess good biocompatibility and less toxic effects [154]. Implanted BC tubes are also reported to facilitate nerve regeneration procedure [91, 95].

Wound care products

Microbial cellulose usage is evident from early 1980s when it was used as a liquid loaded pad for wound care introduced by Johnson & Johnson (US Patent 4,655,758; 4,588,400). The ideal characteristics like reduced pain, autolytic debridement and accelerated granulation makes it a significant player in wound dressing industry [160]. It also helps to create moist environment and acts strictly as a barrier in between wound and the surrounding to prevent infections. Its thrombogenecity also accentuates its usage in wound healing procedures [58]. XCell® is one such BC-based commercial product in clinical trials and depicts excellent characteristics for the treatment of venous leg ulcers [170]. Biofill, a brazillian industry intended to investigate the market specific use of microbial cellulose in wound care market [213]. They successfully purified and commercialized BC gelatinous membrane as an artificial skin for wound dressing [213]. In comparison with quaze, an artificial skin for temporary wound covering, BC gelatinous membrane has high mechanical strength, high permeability for liquids and gases and low irritation [23]. BC composites by blending with poly ethylene glycol (PEG), gelatin and chitosan followed by freeze drying have widen application in biomedical fields of tissue engineering and wound dressing [138] due to their high porosity, morphology, larger aspect surface and biocompatibility when studied using 3T3 fibroblast cells [171]. BC-Ch composites due to their cell adhesion, biocompatibility, water holding capacities and cell proliferation properties facilitate its use in wound healing process [194]. The degradation [36] and non-toxic effect [123] of BC-Ch makes it potent candidate for wound healing procedures. BC impregnated with superoxide dismutase and poviargol stimulated thermal burns healing of the skin in acute radiation disease [116]. BC modified with a synthetic polymer, viz., poly (2-hydroxyethyl methacrylate) (PHEMA), is also used for dry wound dressing [57].

Artificial cornea

One of the major cause of blindness is corneal malfunction. Approximately 10 million have lost their eyesight due to corneal disease or malfunction. This situation demands the corneal transplants and demands wide variety of biomaterials for bioengineered corneas [204]. The non-porous structure, intraocular pressure, definite pellucidness and excellent mechanical properties of BC makes it a significant material for artificial cornea generation. One such example is of BC-PVA hydrogel possessing high water holding capacity, excellent thermal and mechanical properties [204].

Urinary conduits

Functional and biocompatible urinary conduits are of prime importance due to increased number of bladder cancer patients. 3D porous BC after seeding with human urine-derived stem cells (USC) expressed higher urothelial markers. Porous BC scaffold provides favorable conditions for the development of tissue engineered urinary conduits paving way for patients at the end stage of bladder diseases [22, 31].

Dental implants

BC has tremendous potential as a dental canal treatment material for intracanal asepsis [215]. One such case was observed for BC membranes produced using two *Acetobacter hansenii* (ATCC 700178 and ATCC 35059) strains depicting higher liquid absorption and expansion capacity, tensile strength and drug deliverance tendency facilitating its use in root canal treatment.

Drug delivery applications

The reproducibility loss of material issues during topical drug delivery system paves way for BC membranes (hydrogels) for drug delivery. BC membranes possess high diffusion potential, facilitate transport and adsorption of drugs [184] giving them an edge as precise drug delivery and holding capacity to avoid loss. BC membranes when loaded with lidocaine (anesthetic) and Ibuprofen gave successful results having enhanced bioavailability and easy application [192]. Drugs loaded on BC membranes modulate their bioavailability for percutaneous administration and facilitate their adherence to irregular skin surface [193]. BC also depicted successful transdermal drug delivery using diclofenac sodium salt as a model drug and glycerol as a plasticizer [177]. Thermo and pH responsive BC hydrogels have been synthesized using lyophilized BC powder and acrylic acid (AA) suggesting its usage in gastric environments [9]. Solubilized BC are reported a good source of oral drug delivery [149, 211]. HPMC-BC (HBC) is mainly reported to be used for delivery of small drug molecules [4].

Tablet modification

Microcrystalline cellulose from *G. xylinus* (BC) and kenaf (KF) depicted cellulose lattice with high crystallinity (DBC (85%) and DKF (70%) [134]. During a comparative study in between commercially available microcrystalline cellulose; Avicel® PH101 and DBC showed loose density [201]. Avicel® PH101 and DBC demonstrated similar flow and binding behavior. Increased thermal stability was observed within DBC materials during thermo-gravimetric analysis (TGA) [179].

Bactericidal and bacteriostatic potential

Non-bactericidal activity of BC has caused the urge for the use and synthesis of several bactericidal BC composites having the potential to be used as bacteriostatic and bactericidal activities against Gram positive and Gram negative bacteria [36] enhancing their antimicrobial activity. BC-Ag nanocomposites is one such example that tends to be effective against ample bacterial and fungal species enhancing its applicability in rapid and safe wound healing and dressing procedures [132]. Metallic oxide composites (BC-TiO_2) also impart antibacterial properties enhancing its biomedical application [70]. Clay material BC composites (BC-MMT) also possess unique antibacterial properties [194].

Electrical, magnetic and optical applications

Biocompatibility, crystallinity, nanoscale and high tensile strength of natural BC while the transparency, mechanical properties, non-toxicity and low thermal coefficient of nanocellulose (CNF and CNC) polymer has widened its application arena in magnetic, optical and electrical fields. Nanomaterials (electrical, optical and magnetic) have captivated the attention of novel technologies and the scientific community for the development of high-tech equipment (intelligent clothes, sensors and electronic devices) in fields of agriculture, defense and medicine [190, 206].

Electrical materials

Cellulose nanofibers act as an auspicious candidate for conductive supplement due to its stiffness and tensile strength linked to its renewability and biodegradability [82]. The conducting properties of nanocellulose on its own are restricted and needs to be reinforced with a better conductive material resulting in composites having enhanced conducive properties. Nanocellulose technically lacks the conducting property and is only exploited in electrical material synthesis due to their light weight, environmental friendly nature and low cost while the conductivity is usually added by combing a conductive material (Conductive Polymer (PPy, Pani), conductive carbon (graphene, CNTs) and metallic particle (Silver, copper) to these magical composites [49]. PPy-BC, PAni-BC, CNC/PU composites are being produced through in situ oxidative chemical polymerization using $FeCl_3$ $6H_2O$ turned out to possess continuous conducting layers along the core shell structure facilitating the conductive nature [141]. The electrical conductivity of nanocellulose composites associates to monomer concentration, retention time and nature of the oxidant. Even the developed composites are morphologically (ordered flake type, multi-walled) modified for enhanced capacitance, electrochemical stability (nanocellulose core and PAni shell) interaction and conductivity. One such example is graphene-PANI nano composites (*300 F/g) relying mainly on the dispersion and flake size of PAni flakes [65]. Nanocellulose derivatives are also known for its extensive use as sensors, optical and high-level piezoelectric materials at thermo-trophic liquid crystalline state like bezoylated bacterial cellulose (BBC) [203]. For the development of photonic and optoelectronic devices, nanocellulose membranes are used for the fabrication of organic light emitting diodes (OLED) due to the ease of synthesis, low operating tendency, wide selection of emission colors using organic material and low voltage of electro luminescent (EL) devices give them an edge over usual devices [117]. Electrochemical scrutiny frequently uses carbon paste electrodes (CPE) in order to enhance the sensitivity and selectivity of electrode a carbonized nanocellulose-based CPE is developed [119]. The high electrical conductivity of pyrolyzed BC (p-BC)/poly dimethyl siloxane (PDMS) composites (0.20–0.41 S/cm) stands out even among the conventional carbon nanotubes and graphene-based composites. The robust and 3D interconnected networks of p-BC aerogels facilitate electron to move quickly [73, 120]. After the orientation of nanocellulose microcrystals the ionic strength of suspension facilitates its application as security papers [11]. Two novel sensors (humidity sensor and a formaldehyde sensor) with high sensitivity, low cost, good linearity and reversibility fabricated by the use of quartz crystal microbalance coating with nanocellulose membranes and polyethyleneimine [77]. BC is not only used as the proton exchange membrane fuel cells but also as membrane electrode having platinum (Pt) nanoparticles incorporated within having comparable electrolyte value to that of Pt/C (19.9 mW/cm^2) [212]. BC-Au nanocomposite having its application in biomedical filed is also well known for its specific use as biosensor and enzyme immobilization [219]. A novel H_2O_2 biosensor, prepared using BC-Au nanocomposites act as outstanding supports for horse radish peroxidase (HRP) immobilization. For immobilization of many enzymes nanocomposites can be processed enabling their use in bio-electro-catalysis and bio-electroanalysis [219]. Metallic oxide composites (BC-TiO_2) imparts conducting properties along with their biomedical application [70].

Magnetic materials

Magnetic nanoparticles when combined with nanocellulose polymer matrix, results in polymer-nanoparticles composites making them strong candidates for devices, biomedical and data storage applications [220]. They have high mechanical strength, outstanding porosity and strong skeletal backbone to the basic structure. CNC's and CNF's are known to be used as magnetic aerogels and for making magnetic nanopaper [18]. Ni-BC composites conduce to possess ferromagnetic properties at room temperature [198]. In order to escalate the surface roughness and self-cleaning properties of magnetic and flexible nanocellulose, it can be fabricated to boost the amphiphobicity and decrease the surface energy of the material on such example is the synthesis of Fe_3O_4 nanoparticles on BC nanofibers using fluroalkyl silane (FAS) modification [220].

Optical materials

Cellulose nanocomposite is a probable aspirant for optical applications due to the light transmittance and optical transparency (low light scattering) of nanosized fibers. Apart from these, they also possess iridescence, selective reflection of left circularly polarized (LCP) light, and transmission of right circularly polarized (RCP) light. High strength and large surface area also make them ideal candidates for optical materials [222]. The light transmittance of nanocellulose (middle of visible wavelength range), self-assembling tendency and absorption of harmful UV rays make them potent UV blocking agents with higher transparency [50, 178]. Optically transparent nanocomposites like PHB-BC (poly (3-hydroxybutyrate)/bacterial cellulose) and CNC/PU have promising applications as lenses, display devices and coatings [148, 222]. BC- silica hybrids (BC membranes and tetraethoxy-silane (TEOS)) display broad emission band under UV excitation [16] and also have significant tunable emission color potential widening the application arena to new phosphors. Through surface modification using spiropyran photochromes, photochromic BC nanofibrous membranes and CNF's biofilms having 10,30,30-trimethyl-6-nitrospiro (2H-1-benzopyran-2,20-indoline) (NO2SP) were successfully synthesized [77]. CNC's combined with SiO_2 and ZnO nanoparticles are also significant to possess UV resistance and certain other nanocellulose are known for possessing significant photosensitivity expanding its usage as biosensors, sensitive displays and optical devices creating their extensive use as nano photonics.

Conclusion

From detailed survey on the importance of nanocellulose, it can be concluded that nanocellulose is a widely applicable material throughout the world. Most important sources include plant and bacterial sources. Different techniques are there for isolation of nanocellulose that can be easily applicable and scale up. Nanocellulose being a vital molecule has being used in almost all fields from biological to non-biological application. Hence due to potential benefits associated with nanocellulose effective and efficient techniques are required for the isolation of nanocellulose that will be economical, ecofriendly and non-toxic.

Compliance with ethical standards

Conflict of interest Authors declare no conflict of interest.

Ethical approval This article does not contain any studies with human or animals participants.

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