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Cellulose-based Nanocrystals: Sources and Applications via Agricultural Byproducts

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Abstract

Purpose: Cellulose nanocrystals (CNCs) are natural polymers that have been promoted as a next generation of new, sustainable materials. CNCs are invaluable as reinforcing materials for composites because they can impart improved mechanical, chemical, and thermal properties and they are biodegradable. The purpose of this review is to provide researchers with information that can assist in the application of CNCs extracted from waste agricultural byproducts (e.g. rice husks, corncobs, pineapple leaves). **Methods & Results:** This paper presents the unique characteristics of CNCs based on agricultural byproducts, and lists processing methods for manufacturing CNCs from agricultural byproducts. Various mechanical treatments (microfluidization and homogenization) and chemical treatments (alkali treatment, bleaching and hydrolysis) can be performed in order to generate nanocellulose. CNC-based composite properties and various applications are also discussed. **Conclusions:** CNC-based composites from agricultural byproducts can be combined to meet end-use applications such as sensors, batteries, films, food packaging, and 3D printing by utilizing their properties. The review discusses applications in food engineering, biological engineering, and cellulose-based hydrogels.

Keywords: Agricultural byproducts, Biological engineering, Biomaterials, Cellulose nanocrystals, Food engineering

Introduction

Every year, agricultural byproducts such as rice straw and rice husk are produced in vast quantities. Large quantities of agricultural byproducts can be purchased at very low prices. However, agricultural byproducts not only cause various environmental problems associated with their disposal, but also face the problem of insufficient space for storage. To overcome this problem, many researchers are conducting various studies on agricultural byproducts (Ashori, 2008). In particular, agricultural byproducts are attracting attention as a new resource because of the abundance of hemicellulose and cellulose in plants. According to a number of studies, cellulose based on agricultural byproducts such as potato peel, wheat straw, and rice husks could be enhanced as a high value-added material (Chen et al., 2012; Helbert et al., 1996; Johar et al., 2012). Cellulose, a sustainable and abundant biopolymer, is generally present in the cell walls of all vascular plants, algae, phytoplankton, and fungi (O'sullivan, 1997). Cellulose extracted from plants is an environmentally friendly natural resource and is worthy of use in various bio-industries.

Nanocellulose can be classified into cellulose nanofibers (CNFs) or cellulose nanocrystals (CNCs) depending on

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how they are extracted from biomass. CNFs are generally produced by the mechanical treatment of plant fibers at nanoscale (Siró and Plackett, 2010). CNCs are produced by hydrochloric or sulfuric acid hydrolysis from cellulose materials (Nickerson and Habrle, 1947). Long fibers retain amorphous regions which weaken their mechanical properties, whereas CNCs remove this structural defect by subsequent processing steps (Hamad, 2006). In addition, CNCs are reported to be excellent materials because cellulose possesses fascinating characteristics such as sustainability, biocompatibility, biodegradability, nontoxicity, and easy surface modification due to the abundance of primary hydroxyl groups at the surface (Juntao, 2016). CNCs combined with polymeric materials such as poly (ethylene oxide) (PEO) and polylactic acid (PLA) have proven applicability as reinforcing agents due to enhanced dynamic and mechanical properties of the nanocomposites (Xu et al., 2013). Furthermore, composites with CNCs can be used as biodegradable films (Arrieta et al., 2014; Khan et al., 2012), proximity sensors (Sadasivuni et al., 2015), batteries (Lalia et al., 2013), drug delivery media (Akhlaghi et al., 2013; Roman et al., 2009; Wang and Roman, 2011), bioscaffolds (Shi et al., 2012; Zhou et al., 2013), and hydrogels for tissue engineering (Domingues et al., 2015).

This review provides information on the potential for various applications of cellulosic nanomaterials from agricultural byproducts. First, the structure, chemical properties, and mechanical properties of cellulose are introduced. Next, extraction and synthesis methods for nanocellulose applications are discussed. The chemical functionality of cellulose nanoparticles is also discussed in a variety of engineering applications such as food engineering, electronics, and biomedical and biological engineering.

Chemical composition

Plant matter is composed mainly of cellulose, hemicellulose and lignin. Depending on the raw material, the proportions of these components may differ. The chemical composition of various agricultural byproducts is summarized in Table 1. Pure cellulose is a linear polymer formed from 1,4-β-D-glucopyranose monomers. Hemicellulose is a branched-chain polymer composed of several sugars such as 1,4-β-D-xylopyranose. Lignin is a three-dimensional phenolic polymer consisting of a hydroxyl or methoxy-substituted phenylpropane monomer. Soy hull contains more cellulose (48.2%) than softwood such as pine (40-44%) (Khalil et al., 2012; Neto et al., 2013). Methods using chlorine, the soda process, or sulfuric acid can remove amorphous cellulose, lignin, and hemicellulose to isolate pure cellulose.

Characteristics of CNCs

Structural organization of cellulose

Cellulose is a polysaccharide in which β-D-glucose is

Table 1. Chemical composition of cellulose-containing agricultural byproducts

Raw materials	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)	Ref.
Rice husk	35	33	23	25	(Johar et al., 2012)
Wheat straw	34-40	30-35	14-15	-	(Liu et al., 2005)
Corncob	31.2	43.1	16.5	2	(Silvério et al., 2013)
Pineapple leaf	36.3	22.9	27.53	2.85	(Dos Santos et al., 2013)
Soy hull	48.2	24.0	5.78	-	(Neto et al., 2013)
Kenaf fiber	43.7	34.7	11.5	-	(Kargarzadeh et al., 2012)
Carrot pomace	51.6	12.3	32.2	-	(Nawirska and Kwaśniewska, 2005)
Apple pomace	43.6	24.4	20.4	-	
Cherry pomace	18.4	10.7	69.4	-	
Chokeberry pomace	34.6	33.5	24.1	-	
Black currant pomace	12.0	25.3	59.3	-	
Pear Pomace	34.5	18.6	33.5	-	
Banana peel	11.1	5.36	-	13.35	(Bardiya et al., 1996)
Pineapple peel	19.8	11.7	-	10.6	

polymerized through β-glucosidic bonds. In the pyranose form of cellulose, two pyranose units form a β-(1,4) glycosidic bond through a condensation reaction, which results in linkage of the two via C-1 and C-4 atomic bonds (Habibi et al., 2010). The structure of cellulose is made up of repeating units of the cellulose polymer chain, as shown in Fig. 1. Intramolecular hydrogen bonding is formed mainly between the hydroxyl group of C-3 and the ring oxygen of the adjacent glucose unit (O-5), and intermolecular hydrogen bonds are formed between the primary hydroxyl group of OH-6 and the oxygen in position O-3 of the adjacent unit, as well as the hydrogen of OH-2 and oxygen in position O-6 (Lin and Dufresne, 2014). The α-configuration is on the same side as the hydroxyl group of C-1 and the C-6 carbon atom and the β-configuration is on the opposite side. These structures were characterized by the chirality, degradability, and porosity of the cellulose (Kalia et al., 2011; Sinha et al., 2015; Smith, 1937).

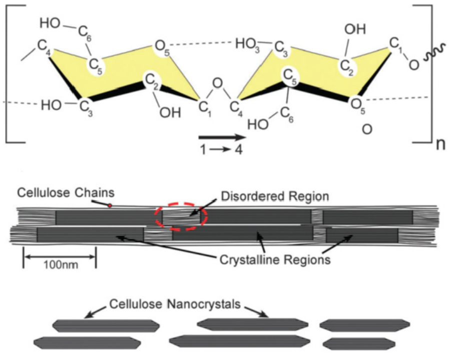

Figure 1. Schematic representation of the chemical structure and intra-, inter-molecular hydrogen bonds in crystalline cellulose (Moon et al., 2011).

Cellulose chains form hierarchical assemblies via van der Waals forces, as well as intermolecular and intramolecular hydrogen bonds. Individual chains assemble to form fibrils, which aggregate into microfibrils. Finally, these form cellulose fibers (Eichhorn et al., 2001). Cellulose fibers are formed with discontinuous crystallinity. There is a highly ordered structure in which the cellulose chains generate a crystalline region located next to disordered chains forming an amorphous region. These discontinuous crystalline regions are the precursors of crystalline nanocellulose (Moon et al., 2011; Sinha et al., 2015).

Mechanical and chemical properties

In a cell, the structural stiffness and strength of the cell wall are determined by the completeness of the cellulosic and hemicellulose networks (Pauly et al., 1999). CNCs are 2-20 nm in width and 100-600 nm in length. The length, width, and crystallinity of the CNCs can vary widely depending on the source of the cellulose. Physical characteristics of the derived agricultural byproduct CNCs are presented in Table 2. Chemical treatment of rice husk not only induced an increase of cellulose content, but also of the crystallinity index from 46.8% to 59.0% (Johar et al., 2012). Properties such as crystallinity and morphology of CNCs derived from agricultural byproducts result in improved tensile strength and excellent thermal stability when used as reinforcing agents for composites (Silvério et al., 2013). Therefore, the values of physical characteristics shown in Table 2 can be used to determine the mechanical properties of the CNCs. In addition, the elastic properties of CNCs can be calculated by theoretical calculations using atomic force microscopy (AFM), X-ray

Table 2. Physical characteristics of cellulose from agricultural byproducts

Raw materials	Length (nm)	Width (nm)	Crystallinity (%)	Ref.
Rice husk	10-15	-	46.8-59.0	(Johar et al., 2012)
Rice straw	1000	4-26	63.2-71.5	(Agustin et al., 2014; Jiang et al., 2013)
Pineapple leaf	249.7	4.45	73	(Dos Santos et al., 2013)
Corncob	210.8	4.15	83.7	(Silvério et al., 2013)
Soy hull	122.7	2.8	73.5	(Neto et al., 2013)
Kenaf fibers	82.7	-	60.8	(Kargarzadeh et al., 2012)
Tomato peel	100-200	5-9	80.8	(Jiang and Hsieh, 2015)
Potato peel	410	-	85	(Chen et al., 2012)
Wheat straw	150-300	5	47.4-77.2	(Helbert et al., 1996; Liu et al., 2005)
Switchgrass	148.1	21.3	11.2	(Wu et al., 2013)

diffraction (XRD), inelastic X-ray scattering, Raman scattering, and indirect experimental measurements. The elastic modulus values measured by these various analytical methods are generally reported to be in the range of 100-200 GPa (Moon et al., 2011; Sakurada et al., 1962; Šturcová et al., 2005).

There are a large number of hydroxyl groups on the surface of CNCs, which are hydrophilic. The hydroxyl group in the sixth position of CNC acts as a primary alcohol, where modification mainly occurs (Roy et al., 2009). Also, CNCs from acid hydrolysis can be dispersed in water due to their negatively charged surface. Amorphous cellulose is removed by hydrolysis with sulfuric acid to prepare CNCs having a newly introduced sulfate ester group ($-SO_3^-$) on the surface. Freeze drying, moreover, significantly improves mesoporosity and specific surface area compared to that of the original cellulose. Ultimately, CNCs have improved thermal conductivity (Lu and Hsieh, 2010) compared to cellulose.

Mechanical and chemical processes for cellulose nanoparticle production

Cellulose extracted from natural products can be isolated by mechanical or chemical treatments. The prepared cellulose fibrils can be divided into two types, namely CNC or CNF (Fig. 2).

Mechanical processes for cellulose nanoparticles

Homogenization and microfluidization are the basic techniques used for mechanical separation of ultrafine microfibrils. Microfluidization, a technique for pressurizing fluids at high pressures, can reduce cellulose into nanoparticles. In addition, a microfluidizer was used to prepare a uniform dispersion of CNC in a matrix to fabricate bionanocomposite films (Khan et al., 2014). The basic principle of the microfluidizer is shown in Fig. 3.

Chemical processes for cellulose nanoparticles

Four different forms of cellulose fibril can be prepared at the nanoscale: (1) bacterial CNFs, (2) CNF, (3) microfibrillated cellulose plant cell fibers and (4) CNCs (Gardner et al., 2008). It is important to remove amorphous cellulose segments with inferior mechanical and chemical properties. The production of cellulose nanocrystals from cellulose fibers involves a two-step chemical process. The first step removes matrix material such as hemicelluloses, lignin, fats, waxes, proteins, and inorganic

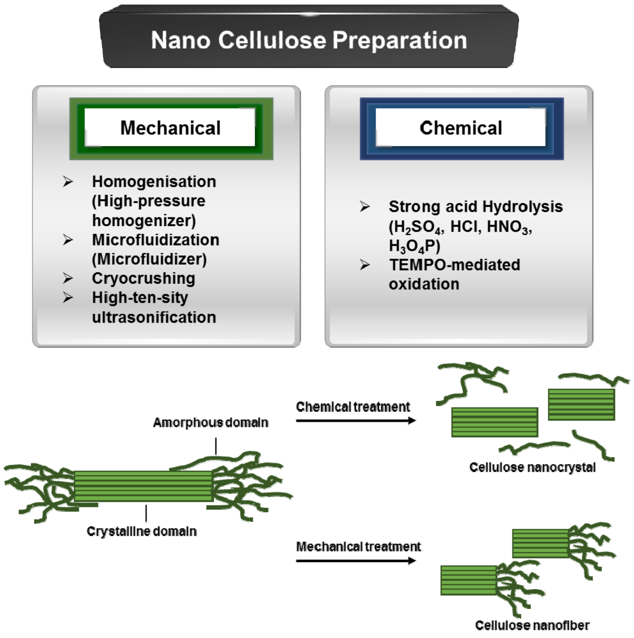

Figure 2. Preparation of nanocellulose by mechanical and chemical treatments

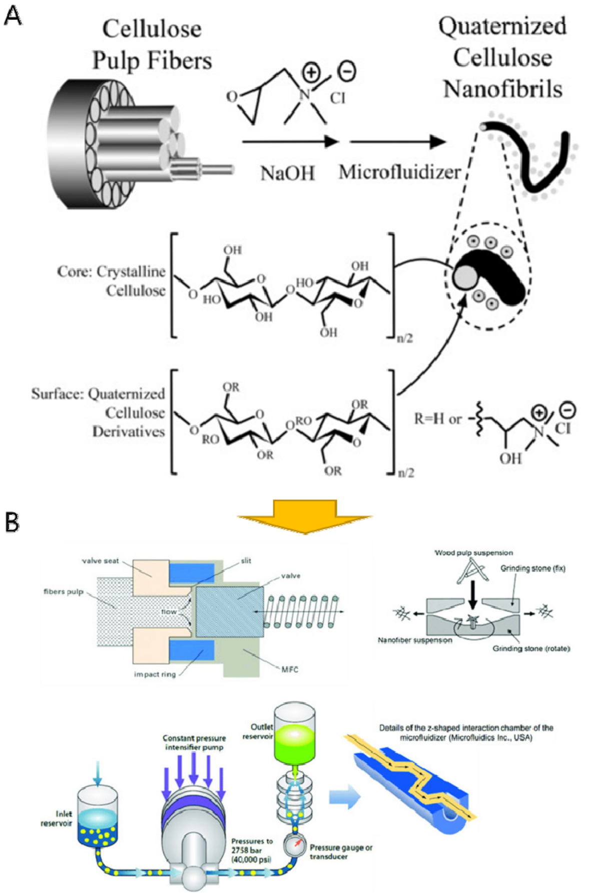

Figure 3. (A) Schematic illustration of mechanical processes (Pei et al., 2013). (B) Operating principle diagram of microfluidizer from Microfluidics Inc. (Dufresne, 2012; Kalia et al., 2014; Vilela et al., 2017).

contaminants (Sinha et al., 2015). Various chemical treatments for producing cellulose from agricultural byproducts are listed in Table 3. The fibrils rearrange themselves along the tensile deformation, as the interfibrillar region is likely to be less dense and less rigid when the hemicelluloses are removed. This results in an excellent load-sharing of the cellulose and a high stress development. (Gassan and Bledzki, 1999). Bleaching after alkaline treatment removes residual lignin. The prepared cellulose fibrils are divided into two types of nanocellulose, i.e. CNC and CNF (Fig. 2). CNCs are obtained by a chemical hydrolysis process that dissociates the amorphous region and releases the crystalline regions from the cellulose fibers. The most popular method for laboratory or pilot scale is acid treatment. Cellulosic amorphous or paracrystalline regions are disrupted, but crystalline regions of higher resistance to acid treatment are not damaged (Juntao, 2016). Sulfuric acid and hydrochloric acid are commonly used solvents for this hydrolysis. Sulfuric acid treatment esterifies the surface of the remaining crystallites. The surface of the CNC from sulfuric acid hydrolysis is abundant in negatively charged sulfuric acid ester groups and is easily dispersed in water. However, CNCs obtained from hydrochloric acid hydrolysis have poor colloidal stability. The concentration of acid used in agricultural byproduct-derived cellulose is approximately 60-65% (Ditzel et al., 2017; Dos Santos et al., 2013; Neto et al., 2013). The optimal extraction time for kenaf bast fibers was found to be around 40 min during hydrolysis at 45°C with 65% sulfuric acid (Kargarzadeh et al., 2012). CNCs from tomato peel were isolated at 15.7% yield via 65% sulfuric acid at 45°C (Jiang and Hsieh, 2015). According to these hydrolysis conditions, variation in size of the CNCs

Table 3. Various chemical treatments for hemicellulose and lignin removal from cellulose in agricultural byproducts

Raw materials	Chemical treatments	Conditions	Ref.
Rice husk (1)	4 wt% NaOH	Reflux temperature, 2 h	(Johar et al., 2012)
	Acetic acid and $NaClO_2$ (1.7 wt%)	100-130°C. 4 h	
Rice husk (2)	3% KOH and 10% HCl	Boiling for 30 min and then left overnight	(Ludueña et al., 2011)
	0.7% $NaClO_2$, 5% Sodium bisulphite	Boiling for 2 h and room temperature for 1 h	
	17.5% NaOH	Room temperature, 8 h	
Pineapple leaf	2% NaOH	100°C, 4 h	(Dos Santos et al., 2013)
	27 g NaOH and 75 ml glacial acetic acid, diluted to 1 L in distilled water and 1.7% $NaClO_2$	80°C, 4 h	
Kenaf fibers	4% NaOH	80°C, 3 h	(Kargarzadeh et al., 2012)
	2.7 g NaOH and 7.5 ml glacial acetic acid, diluted to 100 mL in distilled water and 1.7% $NaClO_2$	80°C, 4 h	
Potato peel	0.5N NaOH	80°C, 2.5 h	(Chen et al., 2012)
	2.3% $NaClO_2$ in acetate buffer (pH 4.9)	70°C, 2 h	
Tomato peel	1.4% $NaClO_2$ with acetic acid	70°C, 5 h	(Jiang and Hsieh, 2015)
	5% KOH	Room temperature for 24 h and then 90°C for 2 h	
	5% NaOH	90°C, 5 h	
Corncob	2% NaOH	100°C, 4 h	(Silvério et al., 2013)
	27 g NaOH and 75 ml glacial acetic acid, diluted to 1 L in distilled water and 1.7% $NaClO_2$	80°C, 4 h	
Switchgrass	1.4% $NaClO_2$ adjusted to pH 3-4 with acetic acid	70°C, 3 h	(Wu et al., 2013)
	5% KOH	90°C, 4 h	

Table 4. Nanocomposites containing CNCs from natural sources in various polymers

Raw materials	Matrix	Nano cellulose content (wt%)	E (MPa)	σ (MPa)	Ref.
Rice husk	poly (lactic acid) (PLA)	20-25	-	-	(Battegazzore et al., 2014)
Garlic stalks	Starch	5	439.6	15.6	(Agustin et al., 2013)
Okra	poly (vinyl alcohol) (PVA)	1-10	~1900	-	(Fortunati et al., 2013)
Sunflower stalks	Gluten	1	440-500	10.1-12.8	(Fortunati et al., 2016)
New Zealand hemp leaves	PLA	1-3	2000-2550	25-29	(Fortunati et al., 2014)
Cassava and Kenaf fibers	Starch	6	326.1	8.2	(Zainuddin et al., 2013)
Wheat straw	poly (styrene-co-butyl acrylate) latex	0-30	6000	-	(Helbert et al., 1996)
Pea hulls	Starch	2	-	7.9	(Chen et al., 2009)
Potato peel	PVA Thermoplastic starch (TPS)	1-2	An increase of 19% and 33% (starch composite) and 38% and 49% (PVA composite) in tensile modulus		(Chen et al., 2012)
Corncobs	PVA	3-9	The ultimate tensile strength improved by 140.2%, the water vapor permeability decreased up to 28.73%.		(Silvério et al., 2013)

determines anisotropic phase formation and reinforcement properties.

Surface modification of CNCs

Chemical modification of CNC is used to enhance dispersibility in other materials such as organic solvents and polymer resins while improving physical properties (Juntao, 2016). The functional groups of cellulose can be changed using various chemical treatments (Fig. 4). The abundant hydroxyl groups (-OH) on the CNC surface are commonly used as sites to attach various functional groups. Oxidation reactions of cellulose can introduce carboxylic acid or aldehyde functional groups (PÉrez and Samain, 2010). CNC surfaces modified using TEMPO-mediated oxidation have excellent biological properties (Akhlaghi et al., 2013). Esterification of the surface of the CNC increases its dispersibility in polystyrene due to surface acylation (Yuan et al., 2006). Etherification, amidation, carbamation, nucleophilic substitution, and click chemistry have also been reported as techniques to modify the surface of CNCs (Eyley and Thielemans, 2014).

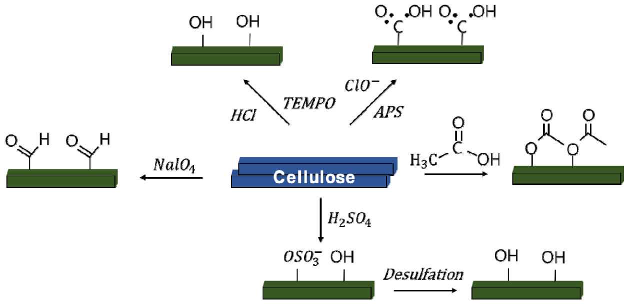

Figure 4. Various structures of cellulose nanocrystals with distinctive surface chemistry extracted by different processes (Juntao, 2016).

Applications in biological and agricultural engineering

CNCs have attracted a great interest in the nanocomposites field due to their essential properties such as nanoscale dimensions, high surface area, unique morphology, low density, mechanical strength, renewability, and biodegradability. Furthermore, they are easily modified and readily available. Therefore, CNCs have been widely used as reinforcing fillers in different

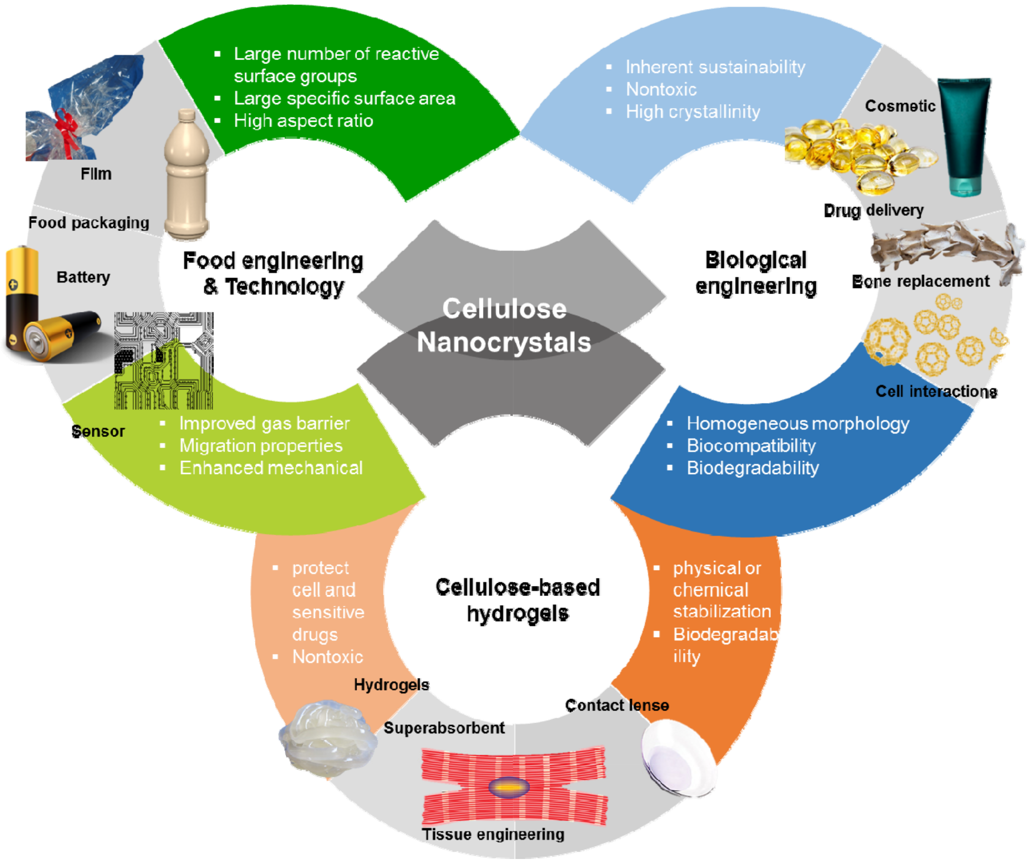

Figure 5. CNC-based composites properties and their application in the various field

polymers, such as poly (styrene-co-butyl acrylate) (Favier et al., 1995), polyvinyl alcohol (Kaboorani et al., 2012), polycaprolactone (Lin et al., 2009), polypropylene (Agarwal et al., 2012), starch-based polymers (Cao et al., 2008), polyethylene (De Menezes et al., 2009), carboxymethyl cellulose (Choi and Simonsen, 2006), polylactic acid (Lin et al., 2011), poly (methylmethacrylate) (Dong et al., 2012), polyurethane (Cao et al., 2007), and other polymers. Nanocomposites with agriculture-based CNCs have been prepared from a variety of polymers, as listed in Table 4, which shows the raw materials and polymer matrix used, and mechanical properties. Nanocomposites can be used for application in many industries. The potential applicability of agriculture-based CNCs lies in food engineering, electronics, and biomedical applications as well as tissue engineering (Fig. 5).

Food engineering and technology

Nanocomposite applications of CNC for food engineering and technology are mainly in films. In particular, CNC-based polymeric packaging films have made remarkable progress as materials for improving food preservation. These films have the potentials to improve the stability of food by providing an antibacterial film when in contact with food (Cha et al., 2002). Nanocomposites containing polylactic acid and CNC were observed to have strong mechanical properties in a package containing sliced cooked ham as a model food and acted as a strong antimicrobial agent by adsorption of nisin on the PLA-CNC surface (Salmieri et al., 2014). CNCs can reinforce polymers by forming a percolation network that connects hydrogen bonds with well-dispersed CNCs (Favier et al., 1995). Nanocomposites of alginates and CNCs not only significantly improve water vapor permeability but also improve thermal stability (Huq et al., 2012). CNCs produced by ammonium persulfate (APS) treatment provide higher oxygen barriers than CNCs treated with sulfuric acid, with properties such as carboxyl group formation, high crystallinity, high transparency of solution, and high charge density (Mascheroni et al., 2016). Therefore, nanocomposite films using APS-treated CNCs not only improve the characteristics of existing food packaging solutions, but also can be applied as a thin layer to reduce environmental deterioration. Furthermore, polymers such as polylactic acid (Fortunati et al., 2012), chitosan (Khan et al., 2012), and polyoxyethylene (Ben Azouz et al., 2011) have been investigated as CNC composites for film production. The nanocomposite of carboxymethyl cellulose with CNCs obtained from various agricultural byproducts (rice straw, wheat straw, and barley straw) improved its mechanical and water vapor barrier properties and confirmed the possibility of CNCs being reinforcing fillers for products such as food packaging films (Oun and Rhim, 2016).

Biological engineering

The use of CNC for biosensing and bioimaging has also been studied due to the possibility of attaching nucleic acids, protein moieties, and fluorophores (Lam et al., 2012). A biosensor study to detect human neutrophil elastase (HNE), a biomarker of chronic wounds, using CNC has been reported, and it is expected that diagnostic and field detection methods could be developed for sensitive rapid detection in other inflammatory diseases suitable for HNE levels (Edwards et al., 2013). In addition, studies of CNC / iron oxide complexes have been reported because of the excellent access of NO_2 molecules to the sensor surface through CNC, which has proved to be a useful new sensing material in several applications, including environmental pollution and leak detection in research laboratories (Sadasivuni et al., 2016).

Based on its stability and efficacy, CNC is most notable in the biomedical field. It also has an attractive property as a nanoscale carrier for bioactive molecules. CNC is not toxic to cells and has proven its potential as a carrier in targeted drug delivery applications (Roman et al., 2009). Recently, composites with encapsulated curcumin-cyclodextrin/CNC were reported to have an antiproliferative effect in colorectal cancer and colorectal and prostate cancer cell lines in preliminary *in vitro* experiments (Ntoutoume et al., 2016). Additionally, hydrogel was prepared by using gelatin in CNC extracted from agricultural byproducts. The prepared CNC-gelatin hydrogel is sensitive to pH changes and has excellent mechanical properties, suggesting that it is an excellent substance carrier (Ooi et al., 2016).

Due to the excellent mechanical properties and biocompatibility of CNCs, it is advantageous to substitute traditional 3D printing thermoplastics with them. CNC aerogels are used for 3D printing using direct ink writing technology, which can be applied to tissue scaffold templates due to the CNCs' inherent sustainability, biocompatibility, and biodegradability (Li et al., 2017). The CNC enables customization of physical signals within the surrounding extracellular matrix (ECM), potentially promoting the phylogenetic differentiation of stem cells. Thus, reinforced nanocomposites with CNCs enable the design of scaffolds with various functions to control cell fate (Domingues et al., 2014). Cellulose-based 3D scaffold extracted from apple showed that animal cells could be attached and proliferated (Modulevsky et al., 2014). Cellulose-based 3D printing techniques from agricultural sources produce better representations of natural cellular microenvironments and have great potential in bioengineering.

Cellulose-based hydrogels

Hydrogels are three-dimensional water-swollen structures composed from hydrophilic polymers, and can be used as drug delivery carriers, contact lenses, and scaffolds (Peppas et al., 2004). Hydrogels protect cells and sensitive drugs that can be incorporated in the network for controlled delivery at the site of injury because of their aqueous environment (Gkioni et al., 2010). Cellulose-based hydrogels, prepared by physical or chemical stabilization of aqueous solutions, can be combined with natural or synthetic polymers to obtain composite hydrogels (Chang et al., 2008; Sannino et al., 2009). A hydrolyzed polyacrylamide / cellulose nanocrystal nanocomposite hydrogel had an adsorption efficiency of more than 90% and can be an excellent sorbent when removing dye from aqueous solutions (Zhou et al., 2014). Hydrogels based on cellulose extracted from pineapple and sepia ink are very effective for the removal of methylene blue, one of the causes of serious environmental pollution (Dai and Huang, 2016). They can also be employed for the absorption of toxic metals in wastewater treatment. Strong adsorption of modified poly(oligoethylene glycol methacrylate) polymers onto the surface of CNCs promotes uniform dispersion of CNCs within the hydrogel and enhances mechanical properties (De France et al., 2016). Hydrogels were prepared using gelatin fortified with CNCs extracted from rice husk, and showed high dynamic mechanical stability and excellent pH sensitivity (Ooi et al., 2016). It is proposed that CNCs from agricultural byproducts could be used in biomaterial field applications such as drug delivery.

Future direction and conclusions

CNCs are already promising new materials that have attracted attention from many engineering fields. It has been found that CNCs can be extracted from various agricultural byproducts by chemical treatment. Researchers have produced polymeric composites with improved mechanical and chemical properties due to the incorporation of CNC materials with high aspect ratios and good dispersion. CNCs have the advantage of being able to bind various functional groups to their surface due to the negative charge on their surface. Comparison of the properties of CNCs derived from various sources will determine the broad applications of each type. Various chemical treatment methods for agricultural byproducts can be suggested as optimal conditions for manufacturing CNC. CNCs extracted from agricultural byproducts are relatively simple to produce with low energy costs. Although yields are low, producing CNCs from underutilized agricultural byproducts has commercial applicability and can generate additional income for farmers. Because CNCs tend to aggregate with each other, there has been some difficulty in dispersing them. When hydrophilic CNCs are not well-dispersed in a hydrophobic matrix, the mechanical properties of the nanocomposite are degraded. Despite much research on surface modification of CNCs for specific applications, surface modification of CNCs for homogeneous dispersion in polymer matrices will require further research.

In this review, the unique characteristics of CNC extracted from agricultural byproducts and its applications to various fields are described. The superior mechanical and chemical properties of CNC have proven their utility as fillers for various composites. CNCs secured from millions of tonnes of agricultural byproducts generated annually could be used as a cost-effective material for commercialization. The physical properties, excellent biocompatibility, biodegradability, and hydrophilicity of CNCs based on agricultural byproducts can lead to various applications in food engineering and biological engineering. CNCs have potential in many fields, but research on them as new materials should be continued. Finally, utilization of waste agricultural byproducts could be a new source of income for farmers and is expected to contribute greatly to the development of agricultural life science.

Conflict of interest

The authors have no conflicting financial or other interests.

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