Conversion of Cellulosic Biomass to Valuable Materials

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Cellulose

Cellulose - the most ubiquitous renewable polymer resource in the nature

Estimated annual production of 7.5×10^{10} tons

Lignocellulosic matter - basic building block of plant matter and trees

Traditionally used as combustible and load-bearing materials in construction

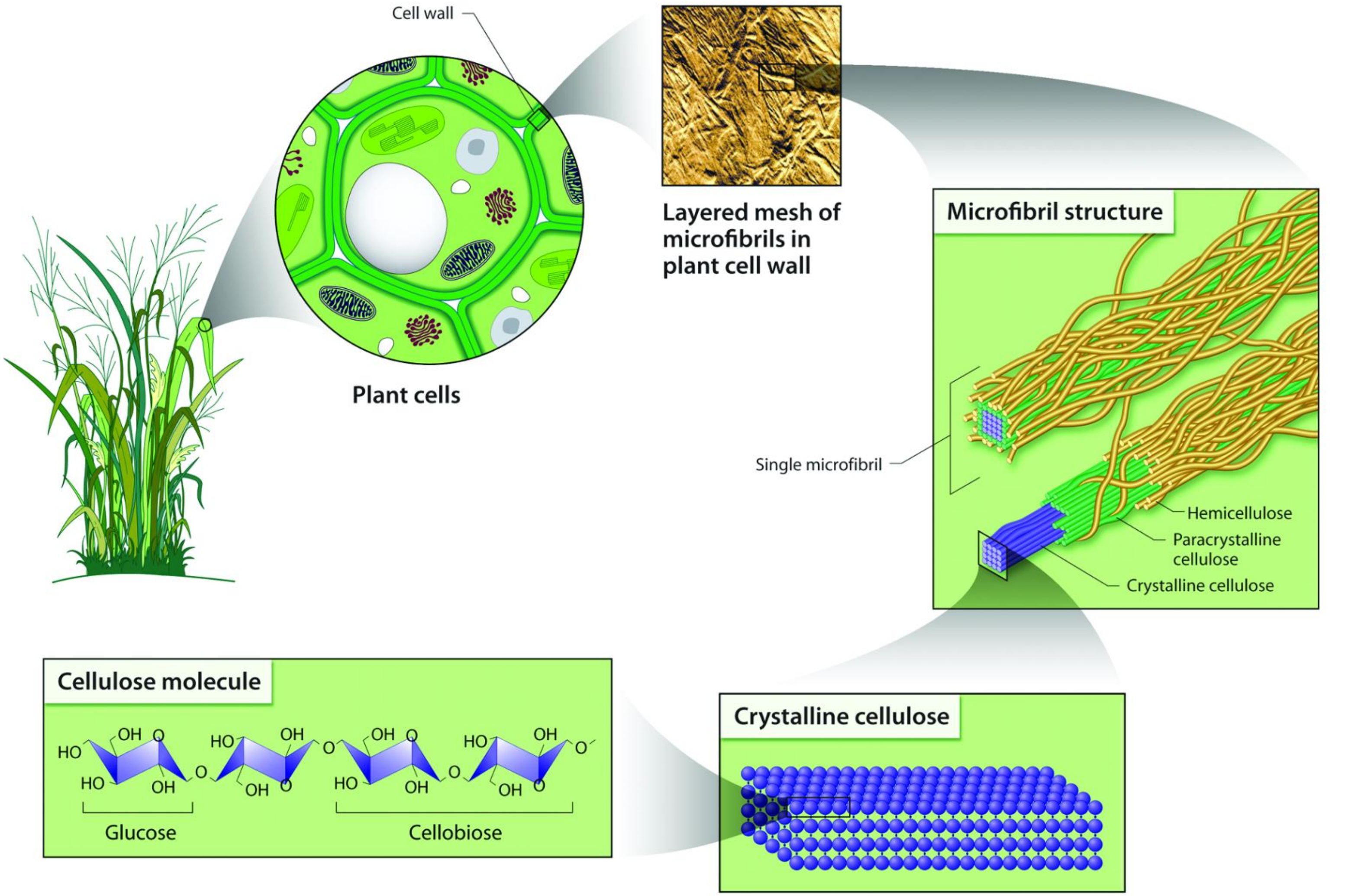
Paper, cellophane films, explosives, textiles, dietary fibers





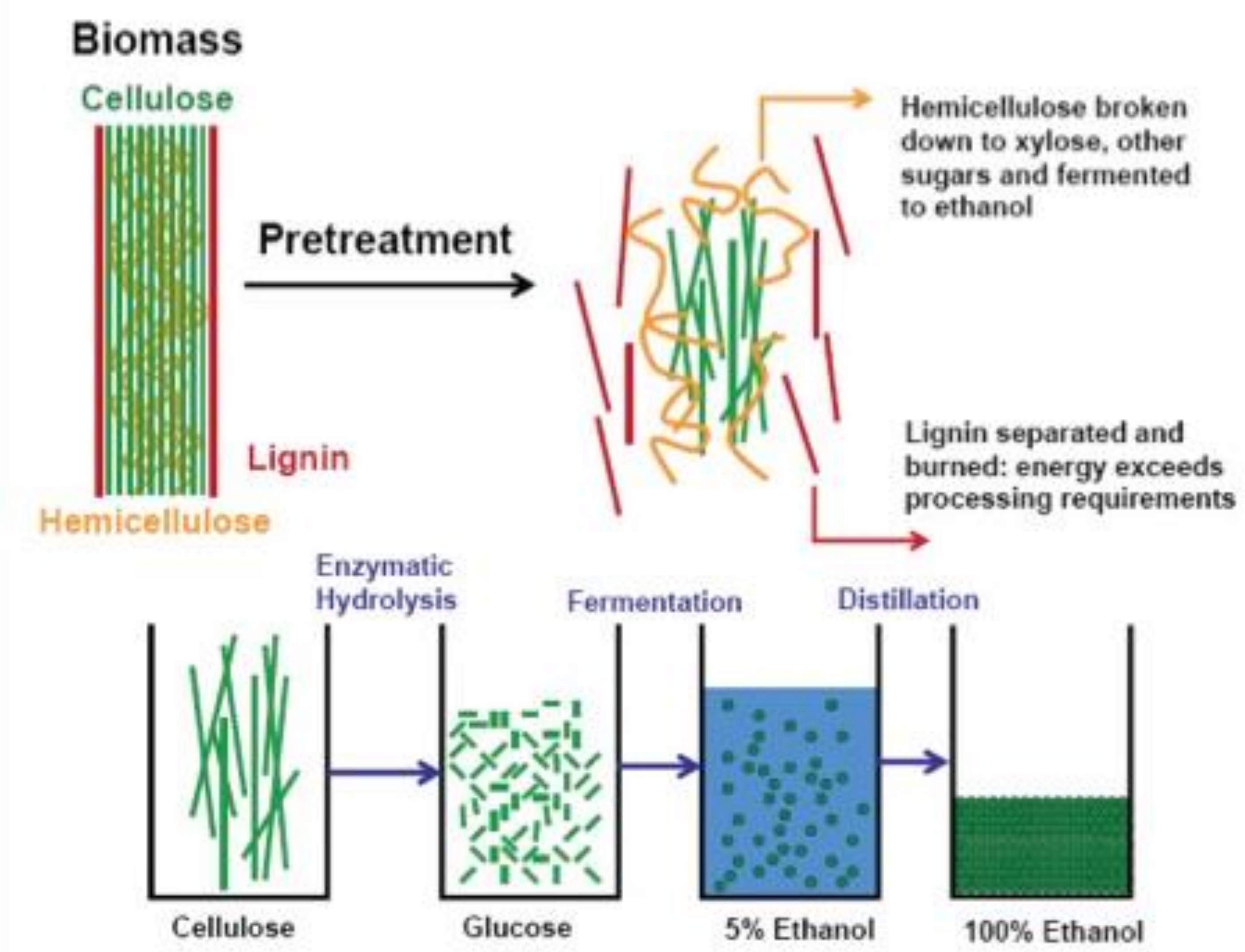
https://www.indiamart.com/

Cellulose



https://www.intechopen.com/books/sustainable-degradation-of-lignocellulosic-biomass-techniques-applications-and-commercialization/hydrolysis-of-biomass-mediated-by-cellulases-for-the-production-of-sugars

Cellulose to Ethanol



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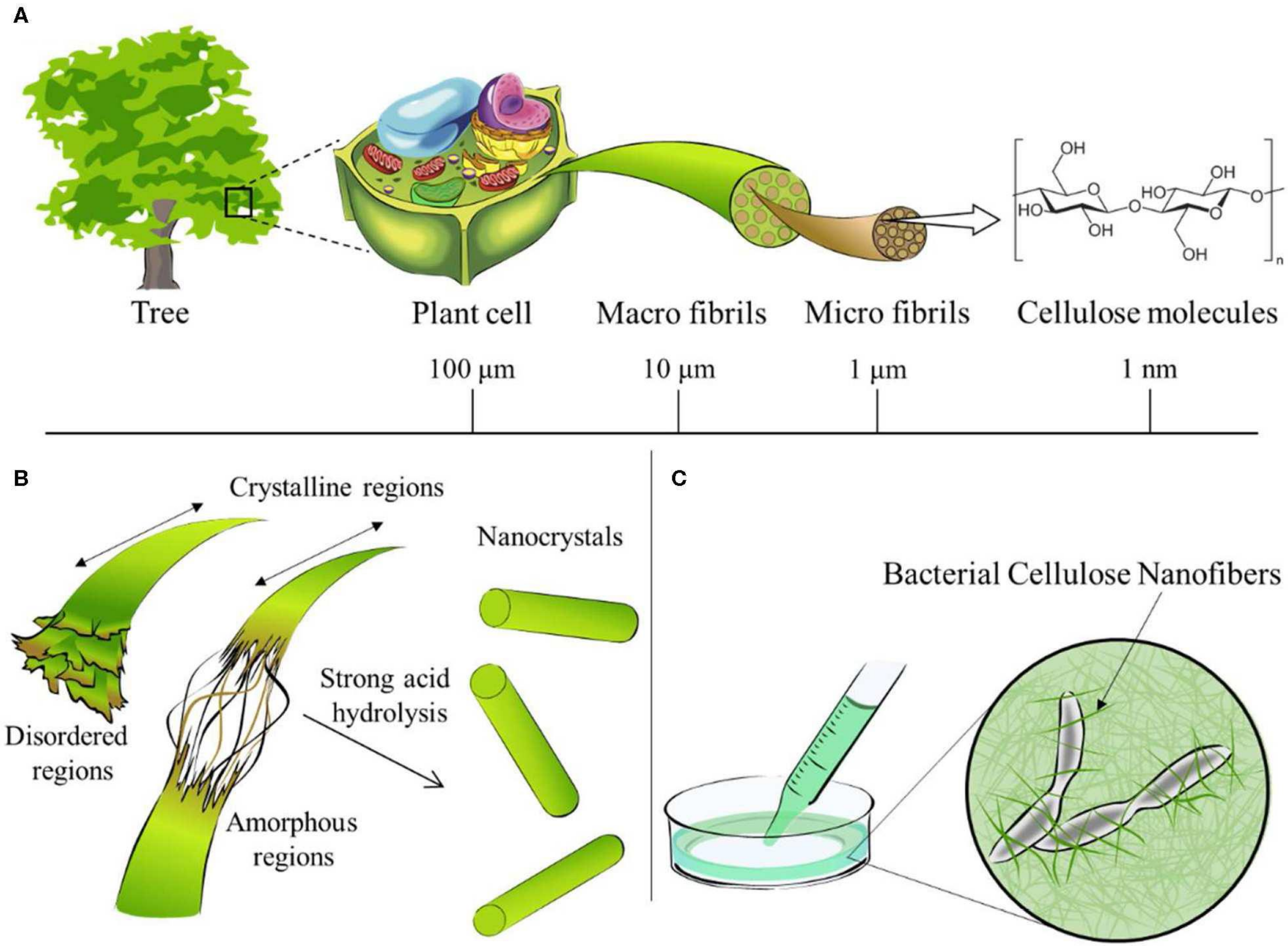
Structure of Cellulose Fiber



Nanocellulose: Fundamentals and Advanced Applications, Frontiers in Chemistry, 2020, Vol 8, 392

Sources for the Production of Cellulose Fibers

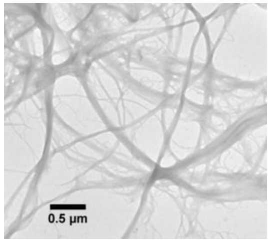
Source group	Sources
Hardwood	Eucalyptus, Aspen, Balsa, Oak, Elm, Maple, Birch
Softwood	Pine, Juniper, Spruce, Hemlock, Yew, Larch, Cedar
Annual plants/Agricultural residues	Oil palm, Hemp, Jute, Agave, Sisal, triticale straw, soybean straw, Alfa, Kenaf, Coconut husk, Begasse, Corn leaf, Sunflower, Bamboo Canola, Wheat, Rice, pineapple leaf and coir, Peanut shells, Potato peel, Tomato peel, Garlic straw residues, Mulberry fiber, Mengkuang leaves
Animal	Tunicates, *Chordata, Styela clava, Halocynthia roretzi Drasche*
Bacteria	*Gluconacetobacter,, Salmonella, Acetobacter, Azotobacter, Agrobacterium, Rhizobium, Alkaligenes, Aerobacter, Sarcina, Pseudomonas, Rhodobacter*
Algae	*Cladophora, Cystoseria myrica, Posidonia oceanica*

Nanocellulose: Fundamentals and Advanced Applications, Frontiers in Chemistry, 2020, Vol 8, 392

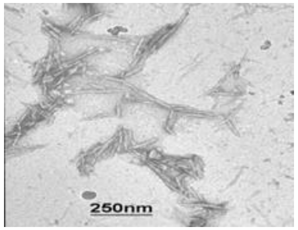
Nanocellulose

Nanocellulose

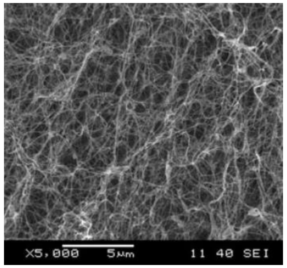
Cellulose nanofibres or microfibrillated cellulose	Cellulose nanocrystals or nanocrystalline cellulose	Bacterial nanocellulose



Produced by mechanical treatment of cellulose pulp



Produced by acid hydrolysis



Synthesized by bacteria

Adv: High production rate, no chemical waste, thermal stability
Disadv: Energy intensive , crystallinity 40-78%

Adv: High crystallinity 60-90%
Better dispersibility in polymers
Disadv: Low production rate, more chemical waste, low thermal stability

Adv: Purified form of cellulose, High crystallinity 80-90%
Disadv: Low production rate,

Properties and Applications

Sources for CNC and CNF extraction

Wood, cotton, hemp, flax, wheat straw, sugar beet, potato tuber, mulberry bark, ramie, algae, and tunicin

Lignocellulosic biomass contains

30−50 wt % cellulose,
19−45 wt %hemicellulose
15−35 wt % lignin.

Properties

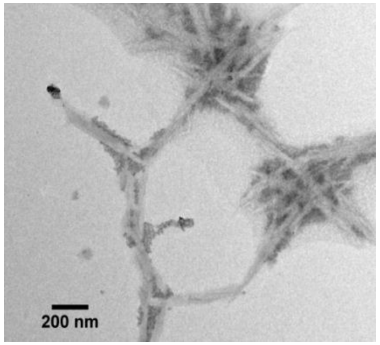
- Natural abundance
- Biodegradable
- Non-toxic
- Biocompatible
- Exceptional strength characteristics at par with Kevlar
- Light weight
- Functionalizable surface

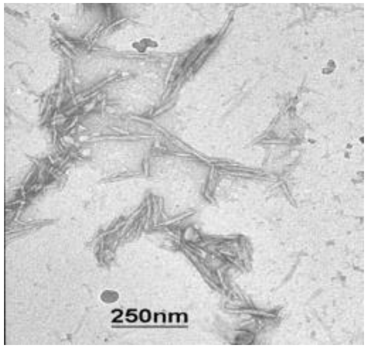
Applications

- Composites and foams for automotive, aerospace, and building construction, viscosity modifiers for cosmetics and oil drilling fluids,
- High performance fillers for paper, packaging, paints, plastics, and cement.
- Supercapacitors
- Battery separators
- Membranes
- Packaging
- Biomedical: Scaffolds, drug excipients and drug delivery, wound healing

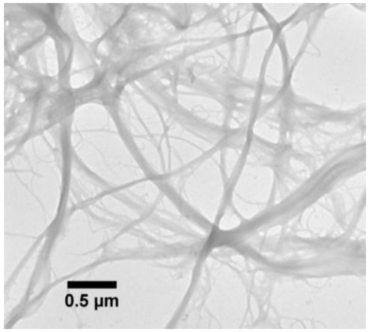
Cellulose Nanocrystals and Nanofibres

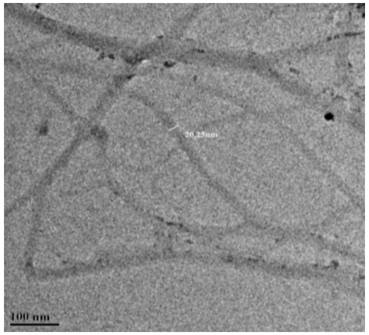
Acid hydrolysis





Mechanical treatment





Acid Hydrolysis

In acid hydrolysis, the hydronium ions penetrate the amorphous regions of cellulose chains and hydrolytically cleave glycosidic bonds, to release individual crystalline cellulose nanoparticles.

Sulfuric acid, highly concentrated (~64%), is the most common reagent reported for acid hydrolysis

Results in partial functionalization of the surface hydroxyl groups with sulfate half-esters, which confer surface charges

Provides aqueous suspendability to the resulting CNCs

Other acids
Hydrochloric acid
Phosphoric acid
Hydrobromic acid
Nitric acid

Result in fewer or no charge incorporation to the surface.

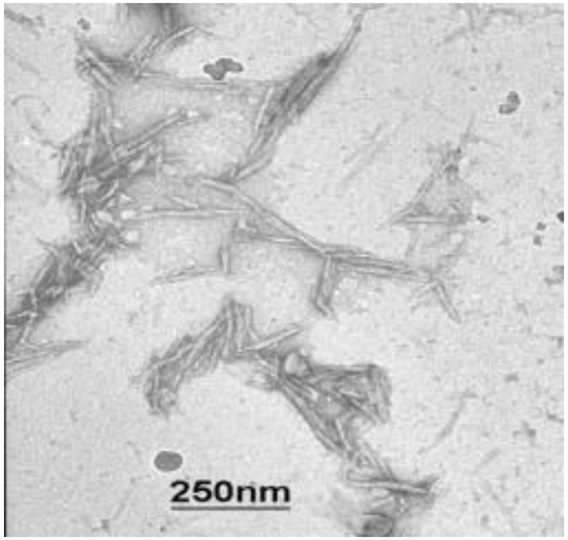
Biomacromolecules 2013, 14, 1223−1230
Cellulose 1998, 5, 19−32.

Morphology of Nanocellulose

Source	Length	Cross section	Aspect ratio
Tunicate	100 nm – microns	10-20 nm	5 to > 100 (high)
Algal (Valonia)	> 1000 nm	10 to 20 nm	50 to > 10 nm (high)
Bacterial	100 nm – microns	5-10 x 30-50 nm	2 to > 100 (medium)
Cotton	200-350 nm	5 nm	20 to 70 (low)
Wood	100–300 nm	3 – 5 nm	20 to 50 (low)

Beck-Candanedo, et. al. Biomacromol. (2005) 6:1048-1054

Acid Hydrolysis



CNCs are rods or whiskers

Typically ranging from 3 to 50 nm in width and 50−500 nm in length.

- High axial stiffness (105− 168 GPa)
- High Young's modulus (20−50 GPa)
- High tensile strength (∼9 GPa),
- Low coefficient of thermal expansion (∼0.1 ppm/K),
- High thermal stability (∼260°C),
- High aspect ratio (∼10−70),
- Low density (1.5−1.6 g/cm3),
- Lyotropic liquid crystalline behavior, and
- Shear thinning rheology

J. Appl. Polym. Sci. 2015, 132, 41607, ACS Sustainable Chem. Eng. 2016, 4, 4417−4423, Macromolecules 2004, 37, 7683−7687, Compos. Sci. Technol. 2007, 67, 2535−2544. ACS Nano 2015, 9, 10887- 10895, Bioresour. Technol. 2010, 101, 5685−5692. Macromolecules 2011, 44, 8990−8998.

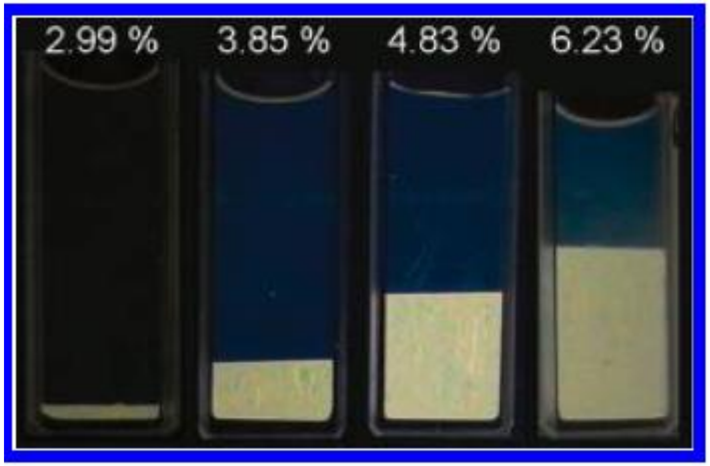
Acid Hydrolysis

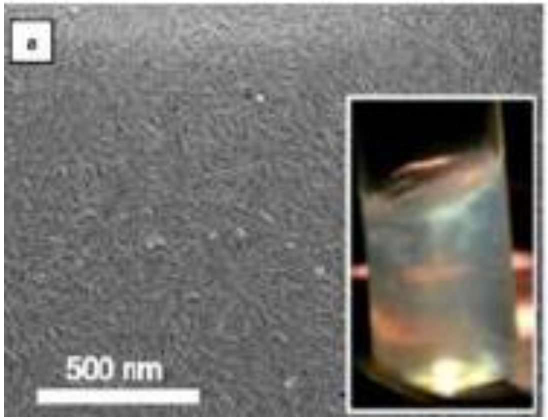
The phase behavior of lyotropic CNC suspensions of sulfonated CNCs produced from cotton.

Between 3.07 and 10.4 vol %,- phase separation into liquid crystalline and isotropic

~ 12.1 vol %, the isotropic phase disappeared, giving a fingerprint texture which is characteristic of a cholesteric liquid crystal.

At even higher concentrations, the fingerprint texture of the liquid crystal phase disappears and the suspension behaves as a rheological gel.





Macromolecules 2011, 44, 8990−8998.
Carbohydr. Polym. 2016, 149, 357−368.

Acid Hydrolysis

source	type	method of isolation	dimensions of isolated CNC/CNF (*l*)	(*d*)	application
sisal fibers	CNF	acetic acid hydrolysis	658 ± 290 nm	27 ± 13 nm	translucent CNF film
Amorpha fruticosa Linn.	CNF	acetic acid hydrolysis	~10 μm	~10 nm	transparent nanopaper
flax plant	CNC	sulfuric acid hydrolysis	20 nm	300 nm	reinforcing agents
garlic straw residues	CNC	sulfuric acid hydrolysis	~480 nm	~6 nm	reinforcing agents
rice straw, wheat straw, barley straw	CNC	sulfuric acid hydrolysis	~700 nm	~20 nm	reinforcing agents
bamboo	CNF	microwave liquefaction		2–30 nm	reinforcing agents
pine cones	CNF	mechanical grinding		~15 nm	reinforcing agents
waste pulp residues	CNF	mechanical disintegration		10–100 nm	permeable membranes
Gelidium elegans red algae	CNC	sulfuric acid hydrolysis	~547 nm	~21.8 nm	reinforcing agents
corncob residue	CNC	sulfuric acid hydrolysis	~198 nm	~5.5 nm	further study required to determine end-user applications
	CNF	TEMPO oxidation; pulp refining	~438 nm μm	~2.1 nm	
				~43.1 nm	
sunflower stalks	CNC	sulfuric acid hydrolysis	~175 nm	5–10 nm	reinforcing agents
	CNF	steam explosion		5–10 nm	
cotton stalks	CNF	1. sulfuric acid hydrolysis	100–500 nm	10–50 nm	industrial applications
		2. TEMPO oxidation	10–100 nm	3–15 nm	

Chem. Rev. 2018, 118, 11575−11625

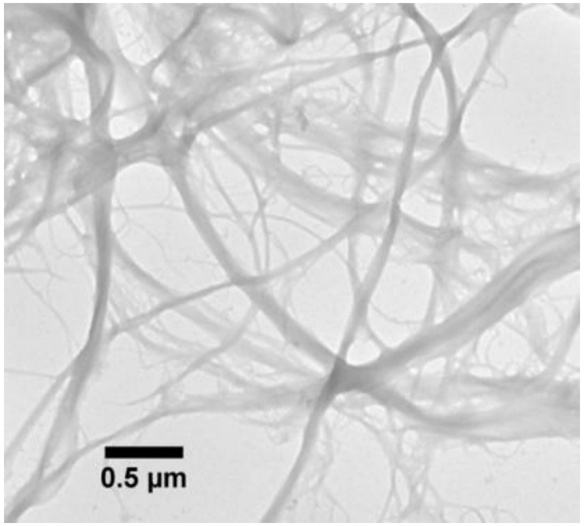
Acid Hydrolysis

source	type	method of isolation	dimensions of isolated CNC/CNF (l)	(d)	application
tomato peels	CNC	sulfuric acid hydrolysis	~135 nm	~7.2 nm	biocomposites
waste sackcloth	CNF	H_2O_2/HNO_3 hydrolysis medium	hundreds of nm	20−50 nm	
jute fibers	CNF	steam explosion		~50 nm	reinforcing agents
Agave tequilana bagasse, barley husks	CNC	sulfuric acid hydrolysis	~322 nm	~11 nm	reinforcing agents
			~329 nm	~10 nm	
banana peels	CNF	sulfuric acid hydrolysis	455 nm	~10.9 nm	reinforcing agents
		enzymatic treatment: xylanase	2890 nm	~7.6 nm	
Helicteres isora	CNF	steam explosion		~60 nm	reinforcing agents
maize straw	CNW[r]	sulfuric acid hydrolysis	~388 nm	15−25 nm	nanofillers in polymer matrixes
sawdust wastes	CNC	hydrothermal processing	101−107 nm	18−35 nm	biomedical applications
coir fiber	CNF	steam explosion		~37.8 nm	industrial, biomedical
dry softwood pulp	CNF	high shear homogenization		16−28 nm	optical applications
sugarcane bagasse	CNC	high pressure homogenization		10−20 nm	
eucalyptus kraft pulp	CNF	sulfuric acid hydrolysis	100−150 nm	10−20 nm	polymer composite applications

The current limitations with acid hydrolysis - corrosive nature of the acids and the production of large amounts of chemical waste
Although recycling strategies have been devised at the industrial scale.

Chem. Rev. 2018, 118, 11575−11625

Mechanical Treatment to make Cellulose Nanofibers



- High pressure homogenization
- High shear homogenization
- Cryocrushing
- Microfluidization
- Grinding
- High intensity ultrasonication
- Milling
- Steam explosion

Energy consumption and production costs are high when mechanical treatment alone is used to delaminate the fibers

A pretreatment can reduce the energy consumed by mechanical processing from between 20,000 and 30,000 kWh/ton to 1000 kWh/ton

Cellulose - Fundamental Aspects and Current Trends; Intech: 2015; Chapter 8, pp 193−228

Pre-treatment to make Cellulose Nanofibers

- Alkaline treatment - removal of the lignin and degradation of hemicelluloses, some hemicellulose might remain.
- Reaction conditions should be controlled, to prevent cellulose degradation.
- The obtained pulp is then washed with deionized water until neutralized.
- The cycle may be repeated two to three times depending on the lignin content of the source material.
- Bleaching treatment with peroxide or hypochlorite removes more lignin to yield a white pulp
- The hemicellulosic content that remains after alkali treatment is usually removed via hydrolysis.

Cellulose - Fundamental Aspects and Current Trends; Intech: 2015; Chapter 8, pp 193−228

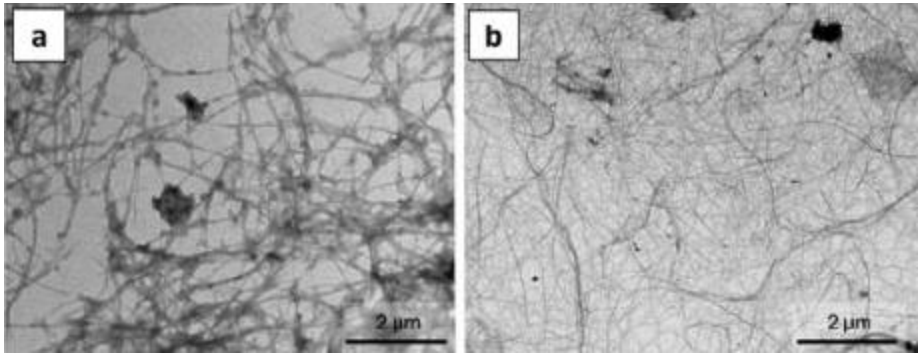
Carboxylated Cellulose Nanocrystals

- Cellulose may be oxidized with TEMPO radicals prior to a mechanical treatment.
- TEMPO-mediated oxidation facilitated CNC isolation under mild aqueous conditions, with surface hydroxyl groups being converted to carboxylic acid.
- Ammonium persulfate has also been used to afford similar materials.
- Hydrogen peroxide in ethanol allowed going directly from biomass to oxidized CNCs.
- The aqueous suspension, which is then Soxhlet extracted, air-, freeze-, or spray-dried
- Spray drying being the method of choice for large-scale production.

Cellulose 2008, 15, 177−185. Small 2011, 7, 302−305. Cellulose 2014, 21, 2567−2577. Green Chem. 2016, 18, 1010−1018.

Enzymatic Hydrolysis

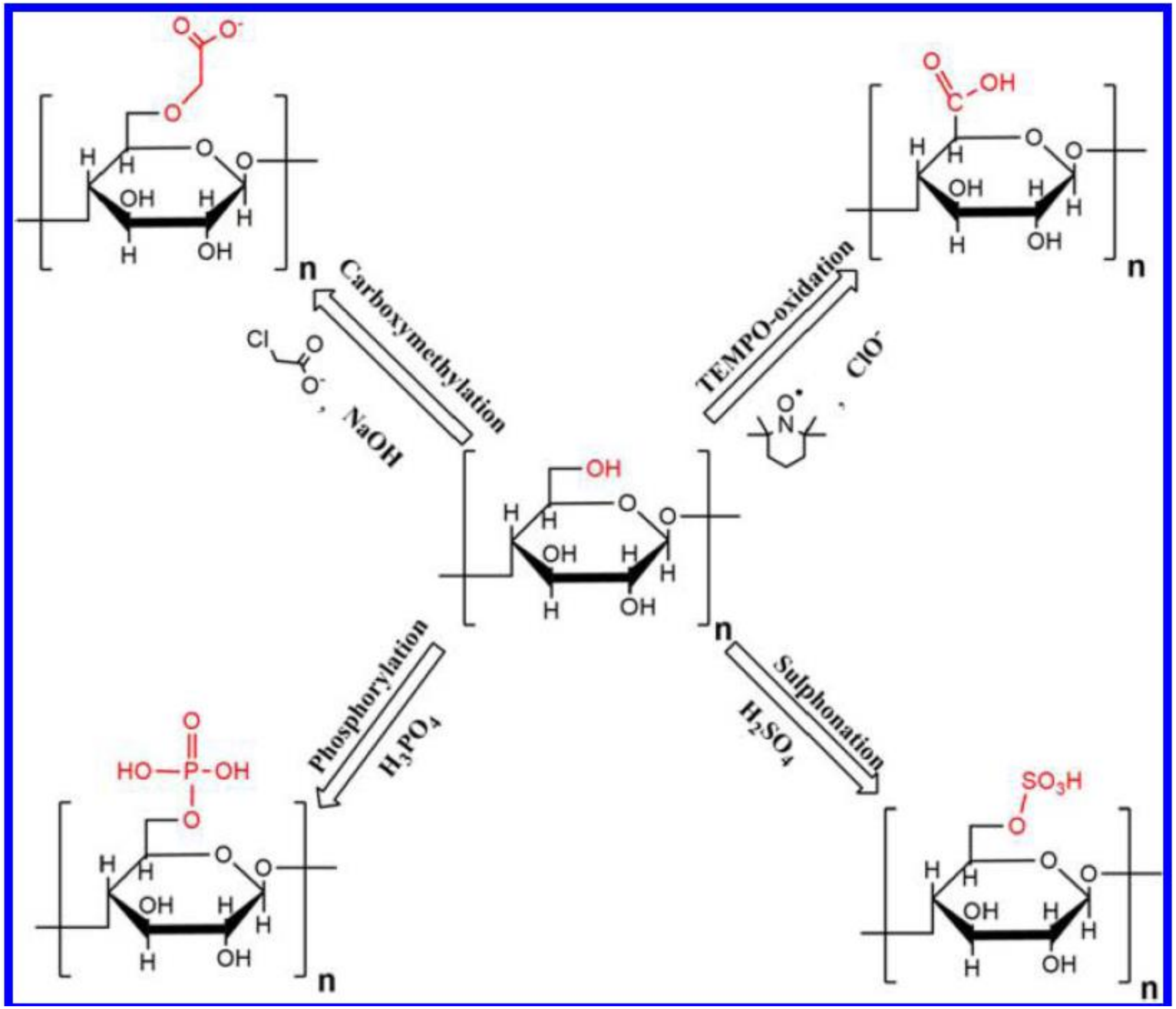
- Enzymatic hydrolysis is considered to be environmentally friendly.
- Enzymes modify or degrade the lignin and hemicellulose, restricting the degree of hydrolysis or selectively hydrolyzing specified components in the cellulosic fibers.
- Xylanases are hydrolytic enzymes that modify the hemicelluloses.
- Production of materials and fine chemicals.
- Co-production of nanocellulose and biofuels using multifunctional cellulolytic enzymes using Caldicellulosiruptor bescii.
- Yield low
- Can be tuned to meet societal demands on clean chemical processes for the production of materials and fine chemicals.



TEM images of the cellulose nanofibers obtained by (a) chemical treatment and (b) enzymatic treatment.

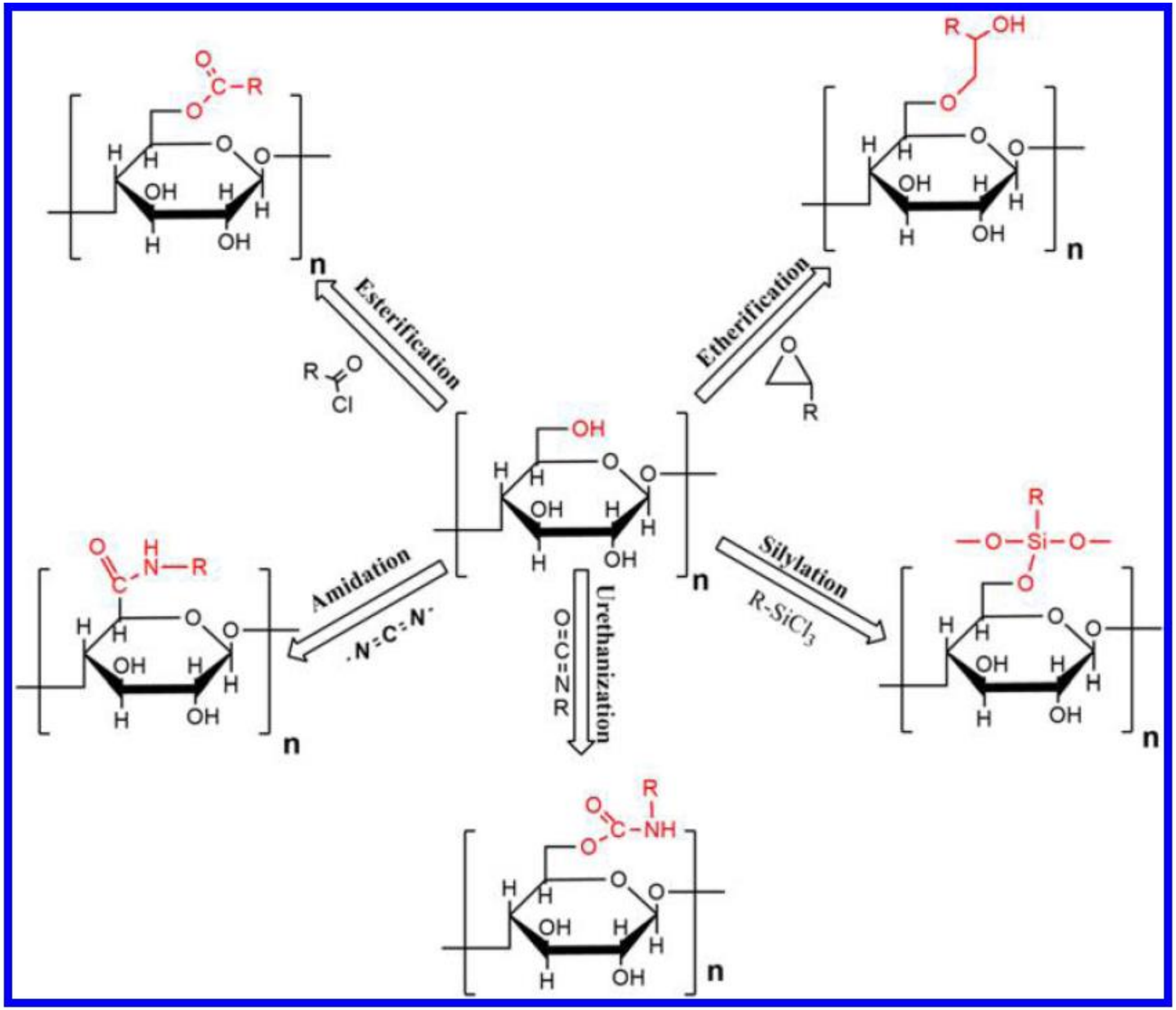
Food Sci. Technol. 2014, 59, 1311−1318.

Chemical Modification of CNC



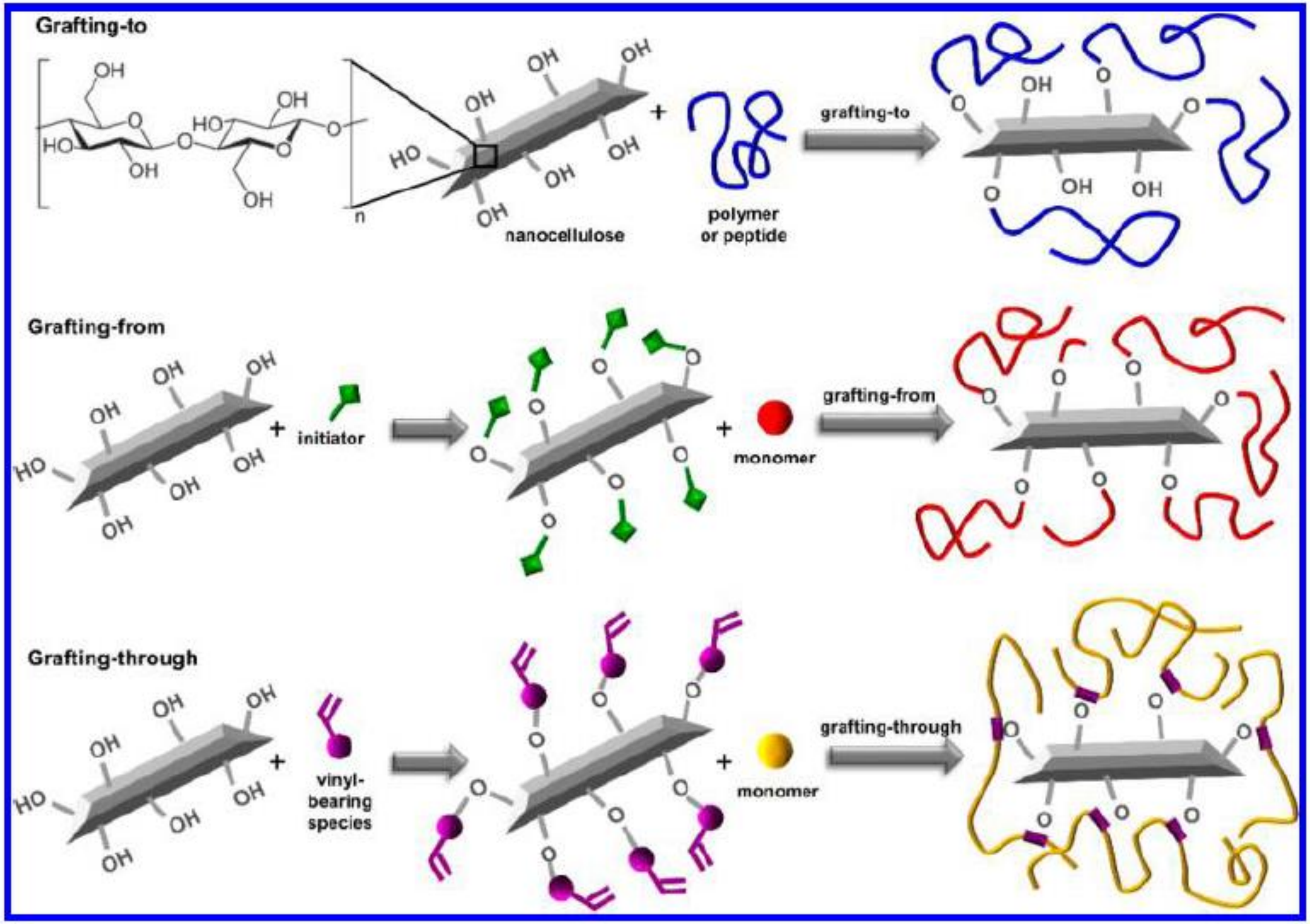
Chem. Rev. 2018, 118, 11575−11625

Chemical modification of CNC



Chem. Rev. 2018, 118, 11575−11625

Chemical modification of CNC



Chem. Rev. 2018, 118, 11575−11625

Applications

Applications of Nanocellulose

High Volume Applications	Low Volume Applications	Novel and Emerging Applications
Cement	Wallboard facing	Sensors – medical, environmental, industrial
Automotive body	Insulation	Reinforcement fiber – construction
Automotive interior	Aerospace structure	Water filtration
Packaging coatings	Aerospace interiors	Air filtration
Paper coatings	Aerogels for the oil and gas industry	Viscosity modifiers
Paper filler	Paint – architectural	Purification
Packaging filler	Paint – special purpose	Cosmetics
Replacement – plastic packaging	Paint – OEM applications	Excipients
Plastic film replacement		Organic LED
Hygiene and absorbent products		Flexible electronics
Textiles for clothing		Photovoltaics
		Recyclable electronics
		3D printing
		Photonic films

Nanocellulose Applications in Paper Industry

Paper manufacturers typically add fillers in paper to reduce cost and enhance properties

Paper with CNF is less porous, the printing quality is higher, and it is less translucent.

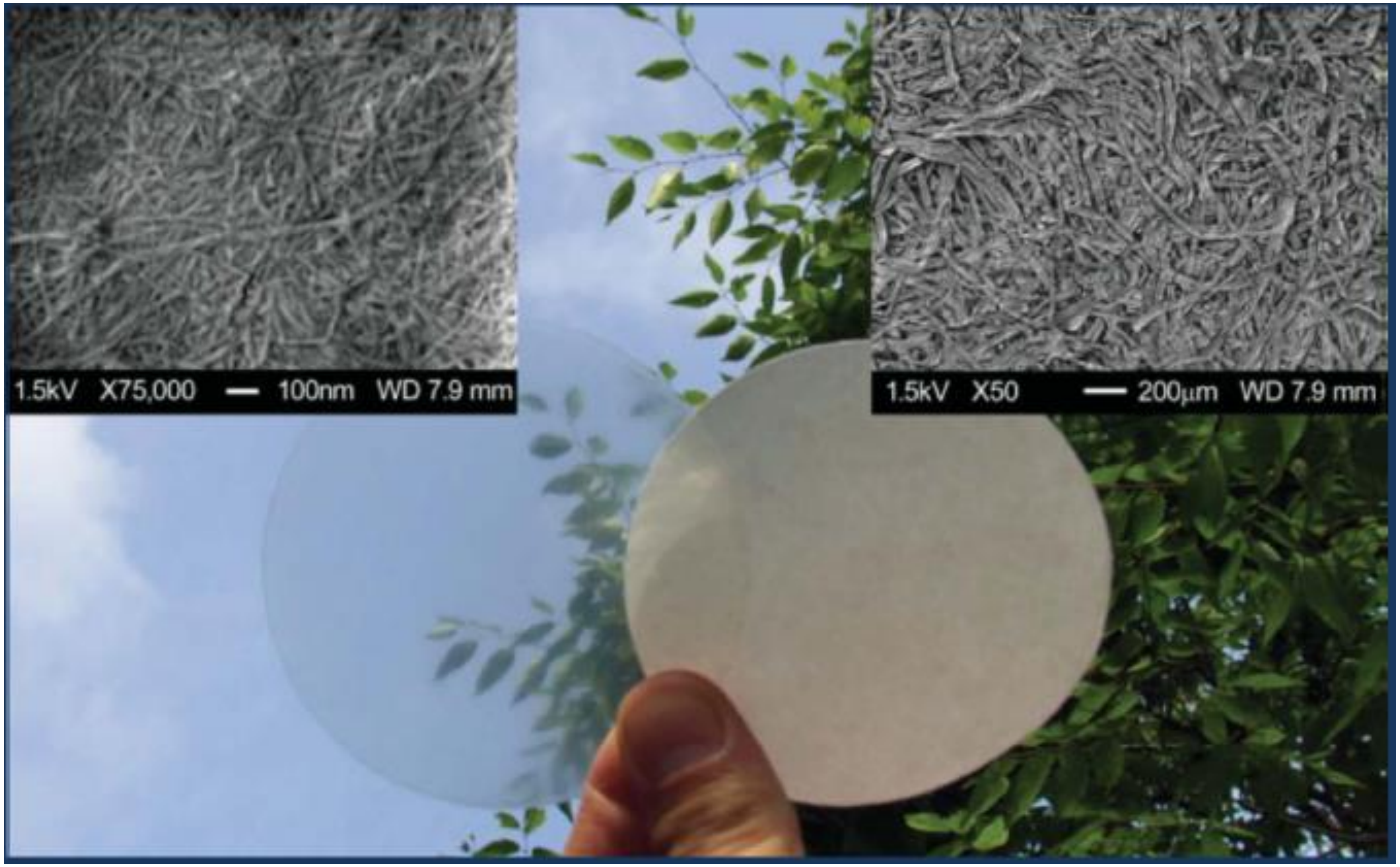
In addition, it takes less energy to dry the paper because much less cellulose is needed through the thickness.

This application reduces material inputs and energy in the production stage

3 g/m^2 coating of CNF will permit less use of nano-clays, resulting in a reduction in weight of the paper by as much as 12.5 g/m^2 while maintaining the paper's strength.

UPM-Kymmene Corporation, pat. WO 2013072550 A3, 2013.

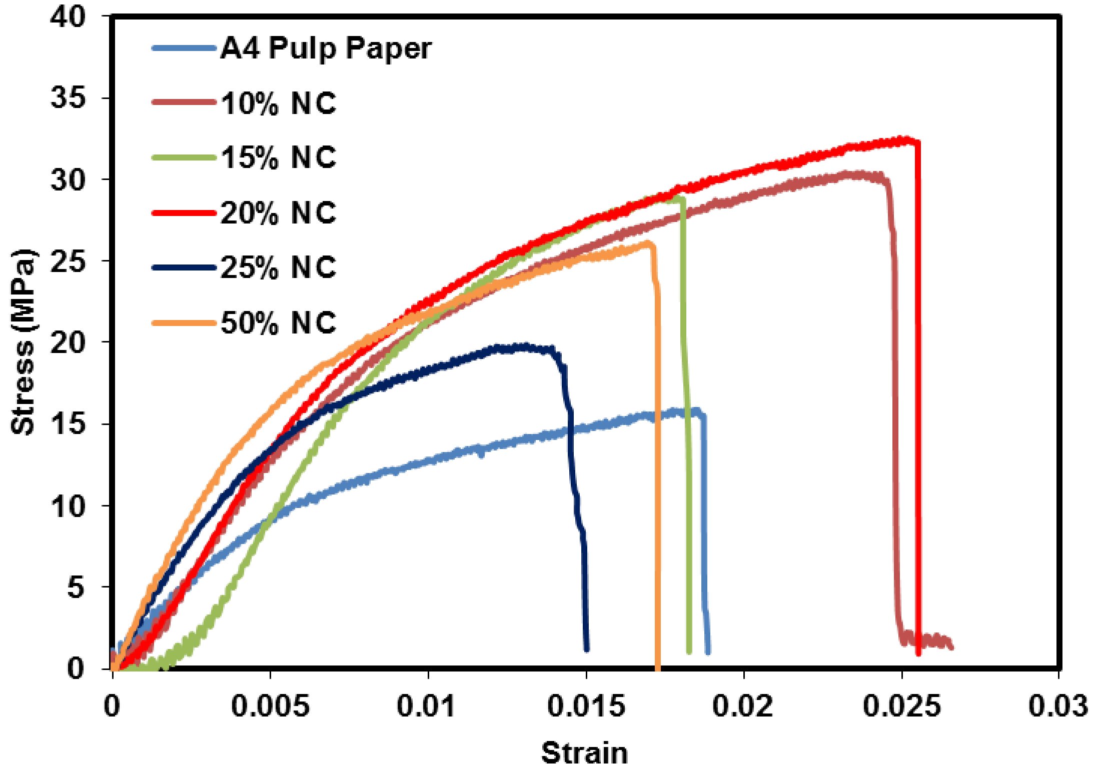
Transparent Paper



Nogi, et al. Adv. Mater. 2009, 20, 1–4

Enhancing Strength of Paper

By adding fibrillated cellulose nanomaterials during the production process, tear strength of paper can be increased



Barrier Properties and Packaging

Packaging industry mostly uses non-degradable petrochemical-based polymers, creating considerable environmental impact.

The ability of nanocellulose to form a dense percolating network due to hydrogen bonds results in lower permeability- desirable for filtration and packaging, especially food packaging

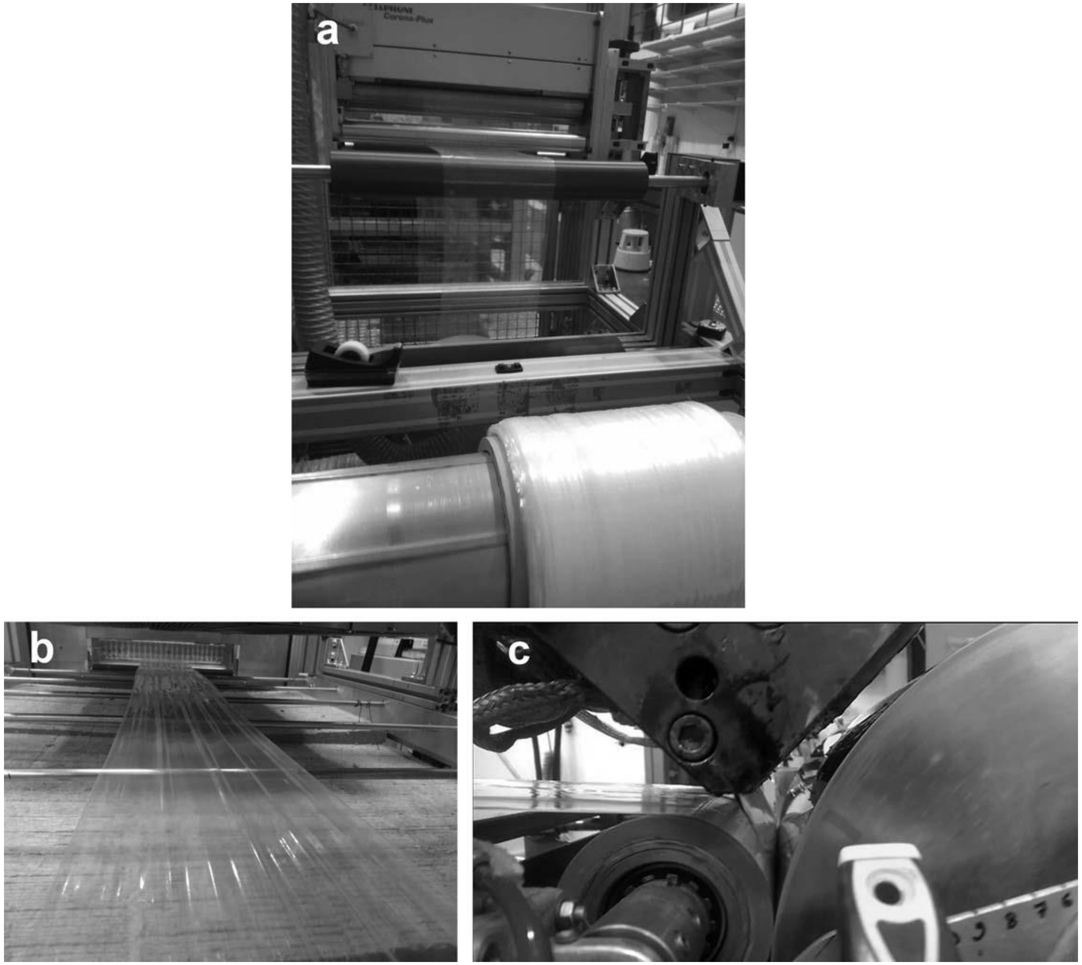
Cellulose nanocrystal coatings on plastic films reduce friction in flexible packaging while retaining the optical properties of the coating

Polyethylenimine (PEI) functionalized NFC and PEI/carboxymethyl cellulose have oxygen permeabilities of 0.34 and 0.71 $cm^3 \cdot \mu m/m^2 \cdot day \cdot kPa$ at 23 °C and 50% relative humidity, close to poly(vinyl alcohol) and ethylene vinyl alcohol deposited on PLA.

J. Appl. Polym. Sci. 2017, doi: 10.1002/app.44830

Cellulose 2013, 20, 2491−2504.

HDPE with CNF Coating

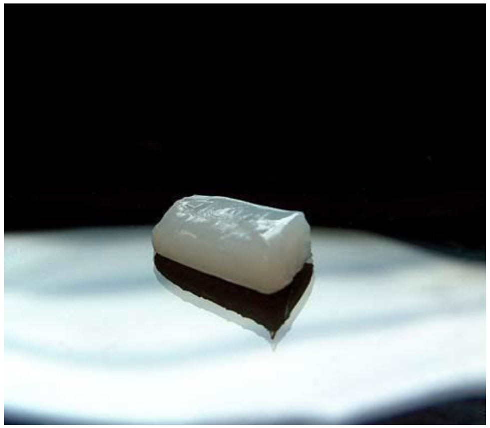


Pilot facilities used to produce the biobased multilayer films with casting of the bio-HDPE (high density polyethylene) (a), coating with the CNF (b), and finally extrusion coating with the bio-LDPE resin (c).

J. Appl. Polym. Sci. 2017, doi: 10.1002/app.44830

Hydrogels of Nanocellulose

Hydrogels are highly hydrated (> 90% water uptake) chemically or physically cross-linked networks



Can be produced from nanocellulose alone, or with additional polymers such as PVA

CNCs gel in water above a concentration of 10 wt %.
pH can influence CNC gelation behavior, as CNC is itself a charged species

CNFs, as longer and more flexible forms of nanocellulose, create more elastic gels than CNCs.

CNFs will afford such structures at concentration <6 wt %.

Hydrogels of CNF have been used as starting materials to spin fibers with excellent strength

The mechanical properties of CNCs allow the formation of aerogels with much improved mechanical resistance compared to inorganic oxide based systems.

Chem. Mater. 2017, 29, 4609−4631. Macromolecules 2011, 44, 8990−8998.

Nanocarbons and Nanocellulose

The favorable interactions between the nanocarbon and the cellulose interrupt the tendency for both cellulose and nanocarbons to autoaggregate.

Carbon nanotube−cellulose composites have been predominantly investigated as conductive papers and conductive fibers for wearable electronics

Graphene oxide−cellulose composites : sensitive and selective solvent sensors. The adsorption of ethanol, acetone, toluene, chloroform, and n-hexane could all be distinguished from one another based on the relative capacitance change.

The role of the cellulose is to provide a strong, flexible scaffold for the nanocarbon, allowing the desirable properties of the nanocarbon to be integrated into a nontoxic, environmentally friendly device.

Carbon 2008, 46, 169−171. Smart Mater. Struct. 2007, 16, 1471−1476. Mater. Lett. 2015, 159, 20−23.

Nanocellulose– Polymer Composites

Chem. Rev. 2018, 118, 11575−11625

Nanocellulose−Polymer Composites

- Nanocellulose has been used to reinforce a wide range of polymer matrixes, such as poly(styrene-co-butyl acrylate), poly(vinyl acetate), poly- (ethylene oxide-co-epichlorohydrin), poly(styrene-co-butadiene), polyurethane, and epoxy resins

- A number of methods such as compression molding freeze-drying, hot pressing, and solution impregnation are employed for the preparation of these organic composites

- Nanocellulose fibers are added to cement to decrease shrinkage during drying, to increase sound absorption, and to produce a more environmentally friendly, less hazardous material.

- Such composites are an alternative to asbestos.

- Hydrophilicity of the cellulose component could affect long term performance

Medical Applications

Nanocellulose is interesting for biomedical materials : mechanical properties, its nanofibrous network, and its natural source.

Poly(vinyl alcohol)-based hydrogels containing nanocellulose good for ophthalmic applications: soft and flexible, yet mechanically strong. They can also be transparent and can have a water content of up to 90%.

Soft Matter 2017, 13, 3936−3945.

Nanofibrillated cellulose cross-linked with calcium ions to form a hydrogel for wound-healing dressings The hydrogel is nontoxic and non-inflammatory. It retained a desirably moist environment to promote healing.

Carbohydr. Polym. 2017, 174, 299−308.

A double membrane hydrogel composed of alginate and CNC shows great promise for the targeted released of antibiotic drugs via controlled swelling mechanisms

ACS Appl. Mater. Interfaces 2016, 8, 6880−6889.

CNC−chitosan hydrogels produced via a solvent-free process - for stomach specific drug delivery due to their mechanical properties and pH sensitive drug delivery characteristics

Polymers 2017, 9, 64.

Toxicity of Nanocellulose

Nanocellulose has been found to be non-cytotoxic and has been explored as a tissue culture medium to support cell proliferation.

<u>Conflicting observations</u>

- Hydrosoluble phosphorous acid functionalized cellulose was evaluated for cytotoxicity and for use as a tissue scaffold material.
- The obtained water-soluble films were subjected to cell compatibility studies and found to exhibit good cytocompatibility due to their nontoxic nature.
- However, a more recent report has found that cellulose nanocrystals induced an inflammatory response and were capable of entering cells, where nanofibrillated cellulose was relatively toxic
- Thus, the size and shape seem to have a large influence on the cytotoxicity and inflammatory response to nanocellulose. The surface chemistry has also been shown to have a large effect on inflammatory response.

J. Mater. Sci.: Mater.Med. 2014, 25, 1115−1127. RSC Adv. 2014, 4, 2892−2903. Chemosphere 2017, 171, 671−680. Biomacromolecules 2015, 16,2787−2795.

Electronic and Engineering Applications

Lightweight, flexible supercapacitors

Nanocellulose provides the needed mechanical support for free-standing and flexible materials

A conductive material such as polypyrrole, polyaniline, and poly-(ethylenedioxythiphene).
is coated to provide high volumetric capacitance

ACS Nano 2015, 9, 7563−

Biosensors

TEMPO-oxidized nanofibrillated cellulose used as a platform for immobilizing C-phycocyanin, as an effective biosensor for copper ion detection

Soy protein could be cross-linked to CNC to afford robust films with flexible electromechanical properties for applications in sensing

ACS Sustainable Chem. Eng. 2017, 5, 7063−7070. Adv. Funct. Mater. 2017, 27, 1604291.

CNC and silver have been 3D printed with high resolution into conductive tracks, reducing the quantity of silver needed

RSC Adv. 2017, 7, 15372−15381.

Field effect transistors

CNCs have been reported in composite electronics with tin oxide layers for flexible organic field effect transistors

Mater. Lett. 2014, 126, 55−58.

Adsorption, Separation, Decontamination, and Filtration

Nanocellulose is valued in adsorption and separation due to its high hydrophilicity as well as its morphology and mechanical properties to form supports and membranes

Nanocellulose composites

- Water and air purification
- Catalytic degradation of toxic organic compounds,
- Adsorbents for oil contamination,
- Sensors for waterborne pathogens

Nanocellulose based systems have been used in chromatographic columns for the separation of chiral enantiomers, necessary to pharmaceutical, clinical, food, and environmental science

Enzymatically phosphorylated nanocellulose adsorbents removed metal ions (Ag^{+}, Cu^{2+}, and Fe^{3+}) from an aqueous model of industrial effluents

Phosphorylated nanocellulose was able to remove above 99% of theCu^{2+} and Fe^{3+}.

Environ. Sci.: Nano 2018,5, 623−658. Environ. Sci. Technol. 2011, 45, 1992−1998. J. Hazard. Mater. 2015, 294, 177−185

Subjects of Patents

•FPI+UBC+McGill - manufacture of CNC, dispersion of dried CNC, CNC as base for thermoplastic composites and scaffolds, hydrogels, barrier coatings, semiconductor, chiral surfaces, binding drugs, adhesive, controlled color/irredescence, wood coatings, fire retardant coating

•Rhone Poulenc/Rhodia/Danisco - CNC in oil drilling fluid

•AITF - CNC in de-icing fluid/rheology control

•Intelligent Nano - magnetic means of entering cells

•UPM - base for cell culture

•Kruger – coating for fabrics and textiles

•Chalmers – CNC as base for tissue scaffolds

•U of T – transparent conductive coatings

•Shingua – rubber reinforcement

Commercial Interest

Commercial interest in nanocellulose is growing at a phenomenal rate following predictions of a possible 35 million tonnes per year market by the 2020s

bioplus
Advanced materials. Naturally.

Bio Vision (Canada), CelluForce (Canada)
US Forest Service Forest Products Laboratory (USA);
Centre Technique du Papier (France),
Stora Enso (Finland),
UPM Fibril cellulose (Finland),
Borregaard Chemcell (Norway), etc

In 2011, Innventia opened the world's first pilot plant for the production of nanocellulose, which has a capacity of 100 kg/day.

Innventia AB
Drottning Kristinas väg 61
Stockholm, Sweden
Phone +46 (0)8-676 70 00

Nanocellulose Facility - Nanocellulose Requests

The UMaine Process Development Center is pleased to supply nanocellose samples to the research and business communities. Currently, we are producing cellulose nanofibrils (CNF) as slurries of approximately 2.8% solids, as well as CNF in a spray-dried form. UMaine is also distributing Cellulose Nanocrystals (CNC) manufactured at the U.S. Forest Products Laboratory **(FPL)**. The FPL nanocrystals are available as a 11.8% slurry, and also in both freeze-dried and spray-dried form. In the near future we will carry a number of other types of nanocellulose , in both slurry and dry forms. If you would like to request a sample, please fill in the Nanocellulose Request Form and e-mail it to us at umaine.pdc@maine.edu or fax it to us at 207-581-4174.

nvw75@yahoo.com

ICAR - Central Institute for
Research on Cotton Technology
(Indian Council of Agricultural Research)
Adenwala Road, Matunga, Mumbai 400019,
India

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ICAR-CIRCOT NANOCELLULOSE PILOT PLANT

inaugurated On August 21, 2015

by

Padma Vibhushan Dr. R.A. Mashelkar

National Research Professor, CSIR-NCL, Pune

President, Global Research Alliance & Former DG, CSIR, New Delhi

IMAGE GALLERY

INDIA'S FIRST NANOCELLULOSE PILOT PLANT

at ICAR-CIRCOT, Mumbai IS OPERTIONAL NOW.

PLEASE SEND YOUR QURIES TO

nvw75@yahoo.com

Training Programme on

"Advances in Applications of Nanotechnology"

October 5-9, 2015

Venue: ICAR-CIRCOT, Mumbai

BROCHURE

Challenges

1. **Moisture sensitivity of nanocellulose**
2. **High aspect ratio of cellulose nanofibrils leads to a gel at low concentrations**
3. **Manufacturing dry nanocellulose**
4. **Economically efficient productions of films, aerogels and filaments are lacking**
5. **Most nanocellulose product development -TRL 2 to 4**


Thank You
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