Chapter 16
Nanocellulose from Agro-Residues and Forest Biomass for Pulp and Paper Product

N. Vigneshwaran, A. K. Bharimalla, A. Arputharaj and P. G. Patil

Abstract Nanocellulose, a nanoform of cellulosic material, is a newer material showing interesting properties and has potential for diversified applications. Nanocellulose, having any one of the dimensions in the size range between 1 and 100 nm, is extracted from cellulosic biomass derived from plants, animals, or microbial origin. Cotton and other natural lignocellulosic fibers, agro-residues, forest biomass, and bacterial cellulose are important raw materials to produce nanocellulose. In the top-down approach of synthesis, the macroscale cellulosic particles are converted into nanocellulose by mechanical, chemical, or biological ways or their combinations. The extracted nanocellulose can be spherical or whisker-shaped nanocellulose (NCC) and nanofibrillated cellulose (NFC); but many other nomenclatures are also being used like cellulose nanofibres (CNF), nanocellulosic fibers (NCF), cellulose nanocrystals (CNC) and microfibrillated cellulose (MFC). Nanocellulose exhibits very large surface area to volume ratio, high level of crystallinity, liquid crystalline behavior, thixotropic behavior, and enhanced mechanical properties. Major areas of applications include furnish and coating additive in paper, filler in packaging and composites, non-calorific additives in food materials, thickening agents in paints and adhesives and as fillers and carriers in pharma products. Other areas of applications could be reached after surface chemical modification of nanocellulose. Pulp and paper industries are the first one where the nanocellulose is being used commercially for improving the strength, printability, and barrier properties of paper. Nanocellulose also helps to reduce the weight of the paper without compromising its strength and other quality parameters. This chapter covers the various aspects of nanocellulose production, characterization, and application in pulp and paper product.

Keywords Nanocellulose · Agro-residues · Forest biomass · Lignocellulosic fibers · Paper · Packaging

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16.1 Introduction

Lignocellulosic biomass, like agro-residues and forest biomass, forms the largest source of raw materials to produce pulp and paper, bioethanol, syngas, hydrogen gas, construction materials, specialty chemicals and bio-based composites. They are going to be a major competitor for the petroleum-based products. The main components of any lignocellulosic biomass include cellulose, hemicellulose, lignin, and minerals. Lignin provides stiffness, water impermeability, and microbial resistance to the material. Hemicellulose, a heteropolymer of pentoses and hexoses, attaches to cellulose through hydrogen bonding and Van der Waal's forces. Cellulose imparts strength and water insolubility of the biomass. Cellulose is a linear polysaccharide with the molecular formula of $(C_6H_{10}O_5)_n$, containing $\beta(1 \rightarrow 4)$ linked D-glucose units. Cellulose is an important structural entity of primary cell wall of plants, cotton fibers, and algae. They are also present in fungi, tunicates, and bacteria.

Among the various natural sources of cellulose (Fig. 16.1), cotton and bacterial sources yield the purest forms of cellulose. In other biomasses, cellulose is present in combination with lignin and hemicellulose. The orderly region of cellulose due to hydrogen bonds forms the crystalline region and other parts constitute the amorphous region. The crystalline regions are very stable structures against hydrolysis, and they contribute to the stiffness and strength of cellulosic materials. The amorphous region contributes to the softness and flexibility of cellulosic materials. The presence of crystalline region in cotton fibers is the highest, and hence they exhibit better mechanical properties in comparison with other cellulosic fibers. Also, the degree of polymerization (number of glucose polymers in the linear chain of cellulose molecule) is very high (more than 10,000) in case of cotton compared to other agro-residues and forest biomass (less than 1000). These materials are being used for extracting the nanocellulose which is being discussed below.

Fig. 16.1 Various sources of cellulose

16.2 Nanocellulose

Nanocellulose is a natural nanomaterial extracted from the cellulosic biomass, having the size of any one dimension <100 nm. The nanodimension imparts very high specific strength, improved stiffness, high surface area, and thixotropic property to nanocellulose. In addition, in their basic structure, nanocellulose consists of a lot of –OH groups that could be available for surface modification for potential applications in pharmaceuticals, biomedical products, nanocomposites textiles, and so on (Phanthong et al. 2018). The use of cellulosic residues and other waste materials derived out of agricultural and industrial processes is increasing due to their widespread availability and renewable character (García et al. 2016). The schematic structural arrangements of cellulosic nanofibrils and nanocrystals inside the wood biomass and agro-residues are given in Fig. 16.2. The various cellulosic sources like agro-residues and forest biomass and their extraction methods for nanocellulose tried recently are summarized in Table 16.1.

Most of the nanocellulose production protocols involve the use of very strong chemicals like concentrated sulfuric acid or TEMPO oxidation and mechanical processes like high-pressure homogenization or friction grinding. They are either producing lot of effluent or requiring huge amount of energy, thereby reducing their widespread usage in various applications. The various types of classifications of

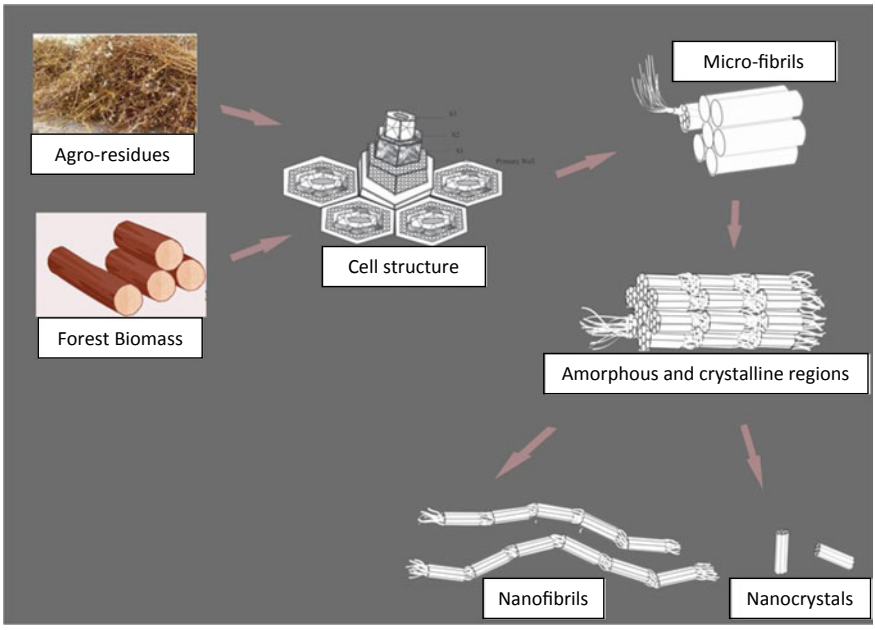

Fig. 16.2 Schematic of the structural features of cellulosic nanofibrils and nanocrystals being extracted from the agro-residues or forest biomass

Table 16.1 Nanocellulose extraction from various cellulosic biomasses

S. No.	Agro-residues/ Forest biomass	Product	Methods	Dimension range	References
1	Sugarcane bagasse fibers and pith	Nanocellulose	High-pressure homogenization	10–20 nm diameter	Li et al. (2012)
		CNCs	Acid hydrolysis	69–117 nm length 6–7 nm diameter	Camargo et al. (2016), Oliveira et al. (2016), Wulandari et al. (2016)
2	Grape pomace	CNCs	Acid hydrolysis and ultrasound treatment	Lengths 307–323 nm and diameters 7–8 nm	Coelho et al. (2018)
3	Cotton and cotton stalk bleached pulps	NCC, CNF	Acid hydrolysis, TEMPO [(2,2,6,6-tetramethylpiperidin-1-yl) oxy radical]-mediated oxidation process	3–15 nm width and 10–100 nm length	Morais et al. (2013), Shamskar et al. (2016), Soni and Mahmoud (2015), Thambiraj and Shankaran (2017), Zhou et al. (2017)
		Ribbon-like CNC	cellulase enzymolysis	Length 250–900 nm and width 30–45 nm	Chen et al. (2019)
4	Corn stalks	NFC	(2,2,6,6-Tetramethylpiperidin-1-yl) oxyl (TEMPO)-mediated oxidation followed by high speed blending	10–25 nm width	Boufi and Chaker (2016), Cheng et al. (2018)
5	Seed fibers of Ushar (*Calotropis procera*)	CNC CNF	Acid hydrolysis TEMPO-mediated oxidation	Diameter of 14–24 nm and length of 140–260 nm Long fibrous structure with the diameter of 10–20 nm	Oun and Rhim (2016)
6	Brazilian satintail (*Imperata brasiliensis*) plant	CNs	Acid hydrolysis	Diameter from 10 to 60 nm and length in between 150 and 250 nm	Benini et al. (2018)

(continued)

Table 16.1 (continued)

S. No.	Agro-residues/ Forest biomass	Product	Methods	Dimension range	References
7	Softwood biomass	CNCs NC fibrils	AVAP® biorefinery technology	Width: 4.5 ± 1.5 Length: 222 ± 139 Width: 29 ± 18 nm Length:1627 ± 1252 nm	Kyle et al. (2018)
8	Eucalyptus pulp	Nanocellulose	High-pressure homogenization	20–100 nm diameter	Wang et al. (2017)
9	Saw dust	CNCs	chemically engineered hydrothermal process	~18–35 nm diameter range, lengths in the range of ~101–107 nm	Kalita et al. (2015)
10	Walnut shells	CNCs	Acid hydrolysis combined with sonication and homogenization	Diameter of CNCs was 130 nm	Hemmati et al. (2018)
11	Tomato peels	CNCs	Acid hydrolysis	average width 42 nm	Jiang and Hsieh (2015)
12	Pinecone of Jack pine (*Pinus banksiana*)	NCF	Chemical and mechanical treatment	Diameter range between 5 and 25 nm	Rambabu et al. (2016)

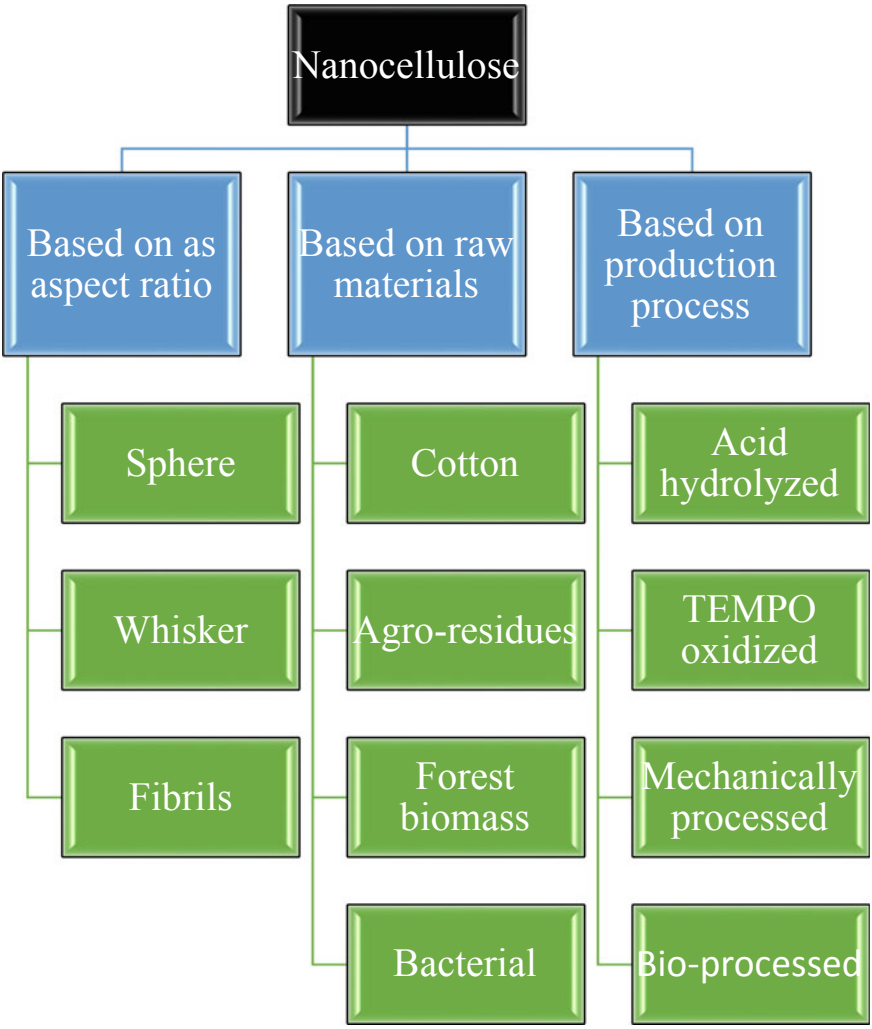

Fig. 16.3 Classification of nanocellulose based on different parameters

nanocellulose are given in the Fig. 16.3. They are classified based on their morphology, raw materials, or by the production protocol used. The type of required nanocellulose needs to be finalized based on the end-use applications.

Our research group at ICAR-Central Institute for Research on Cotton Technology, Mumbai is working on the production of nanocellulose from cotton linters and other agro-residues like banana fibers and sugarcane bagasse. Also, a pilot plant facility is installed with a capacity to produce 10 kg of nanocellulose per day for use in industrial trials for product development. The methodology being

used for production of nanocellulose preparation is a patented chemo-bio-mechanical process (Bharimalla et al. 2015, 2017; Vigneshwaran and Satyamurthy 2016; Vigneshwaran et al. 2015).

16.3 Characterization of Nanocellulose

Though basically made from the cellulosic substrate, the size, morphology, shape, surface charge and flow behavior vary greatly according to the source of raw material and the method of production. By considering the different applications of commercial interest, it is very much essential to carry out comprehensive evaluation of structure and other properties of nanocellulose. Normally, some of the characterization methods are used to analyze the sizes, shapes, and morphology of nanocellulose and others are used to obtain in-depth structural information. Figure 16.4 shows the overall methodologies being adopted for characterization of nanocellulose.

To understand the size dependent properties, following parameters need to be analyzed:

- Size, size distribution, shape, and aspect ratio
- Degree of aggregation and agglomeration
- Surface chemistry (zeta potential and surface functional groups)
- Crystal size and structure
- Optical properties
- Mechanical properties
- Rheological properties, and
- Electrical properties.

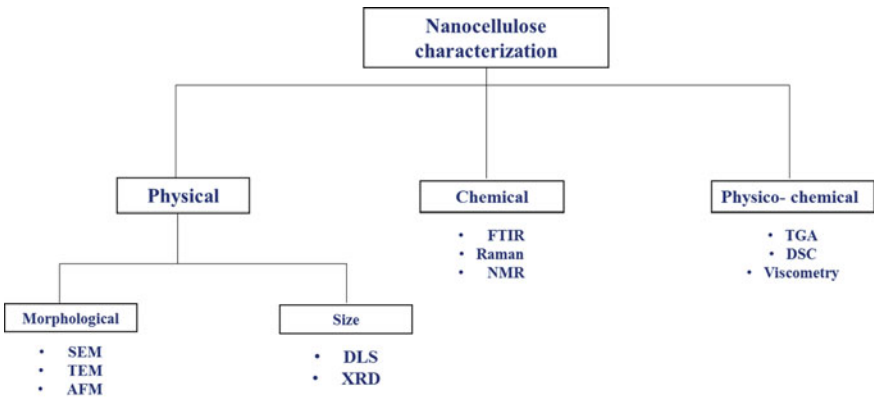

Fig. 16.4 Different analytical tools used for the NC characterization

16.3.1 FTIR Analysis

In practice, infrared radiation (400–4500 cm^{-1}) of successively increasing wavelength is passed through the sample and the percentage of transmittance is measured using an infrared spectrophotometer. Attenuated total reflection (ATR) is one of the accessories of FTIR to analyze the surface properties of solid film samples or thin film samples rather than analyzing their bulk properties. The characteristic peaks for the cellulose molecule (Oh et al. 2005; Satyamurthy and Vigneshwaran 2013) are hydrogen bond stretching at the wavenumber of 3299 cm^{-1}, OH bending of adsorbed water at 1644 cm^{-1}, the stretching of CH at 2921 cm^{-1}, the HCH and OCH in-plane bending vibrations located in 1430 cm^{-1}, CH deformation vibration at 1373 cm^{-1}, the COC, CCO, and CCH deformation modes and stretching vibrations in which the motions of the C-5 and C-6 atoms are at 850 cm^{-1}, and C–OH out-of-plane bending mode is located at 670 cm^{-1}. Mostly, cellulose will not change its chemical functionality after the conversion into nanocellulose because the changes are happening in its physical structure. However, some new functional groups may be added into the cellulose molecules which depend upon the nature of synthesis. For example, after the oxidation of cellulose, intensity of band at 1700–1750 cm^{-1} increases indicating an increase in quantum of carbonyl and carboxyl groups.

FTIR can also be used for comparative evaluation of cellulose crystallinity by measuring the relative height of two different peaks. A crystallinity index (CI) is the ratio of a particular peak related to crystallinity with respect to a peak that is not representing the crystallinity within the spectrum. The relative crystallinity index for the cellulose is determined by measuring the ratio of absorbance at 1428 cm^{-1} and at 900 cm^{-1}. This ratio indicates the relative amount of crystalline and amorphous portions in a cellulosic material.

16.3.2 Raman Analysis

Raman spectroscopy, a kind of vibrational spectroscopy, is used to find information about molecular vibrations and crystal structures with the help of a laser light source. On irradiation of the sample, an infinitesimal amount of Raman scattered light is formed that is detected and analyzed as a Raman spectrum. The characteristic fingerprinting pattern of a Raman spectrum of polymer makes it possible to detect polymorphs, crystallinity, orientation, and stress. Analysis of nanocellulose suspensions by Raman spectroscopy is very useful technique in nanocellulose characterization since the analysis can be carried out native hydrated state without special requirements. Numerous information can be obtained from the Raman spectra like estimation of crystallinity (in suspensions and freeze-dried states), measurement of accessibility, detection and quantitation of cellulose II polymorph in NCs, and effect of drying on the structure of NCs. Raman spectra of the NCs

contain bands that are associated with chemical functionalities usually present on the surfaces. Sulfate esters present on the surfaces of NC can be quantified by Raman spectroscopy. The index of crystallinity can be calculated from the ratio of the peak's height at 380 and 1096 cm^{-1}.

16.3.3 Dynamic Light Scattering (DLS) Analysis

Dynamic light scattering (DLS) is a valuable technique used for size analysis of nanocellulose and other nanomaterials. The analysis of scattered light helps to determine particle size, molecular weight, and zeta potential. Nanocellulose in dispersion are in constant Brownian motion due to the thermal energy. The speed of the Brownian motion of the particles is measured from their scattered light by a technique known as photon correlation spectroscopy or DLS. The observed intensity of scattering dependents on the particle size and reduces with the reduction in particle's cross-sectional area. Sample preparation either by filtration or centrifugation is critical to remove dust and artefacts from the suspension. The hydrodynamic diameter is obtained based on dynamic light scattering and autocorrelation principle. The mean diameter of particles is calculated from Brownian motion via Stokes–Einstein equation (Edward 1970).

$$d_{\mathrm{H}} = \frac{kT}{3\pi\eta D}$$

where
d_{H} = hydrodynamic diameter (m)
k = Boltzmann constant (J/K = kg m^2/s^2 K)
T = temperature (K)
η = solvent viscosity (kg/m s)
D = diffusion coefficient (m^2/s).

The stability of colloidal material is analyzed through their zeta potential. Zeta potential is an indirect measurement of the surface charge and it can be obtained by evaluating potential difference between the outer Helmholtz plane and surface of shear. Low-angle zeta potential analysis by electrophoretic light scattering can be used for the analysis of surface charge. The magnitude of the zeta potential gives an indication of the potential stability of the colloidal system. If all the particles have higher zeta potential, they will repel each other which will maintain dispersion stability. If particles have lower zeta potential, then there is no force to prevent the particles coming together and it induces the instability in the dispersion.

16.3.4 Wide-Angle X-Ray Diffraction (XRD)

XRD is one of the most essential tools used in characterization of the crystal structures. Evaluation of crystal structure is very much important even for nanoscale materials. Though a material's properties may be affected by structures on the nanometer scale, its crystal structures are determined by arrangement of atoms. The principle of XRD is based on the well-known Bragg's law ($\lambda = 2d\sin\theta$). Cellulose exists in several crystalline allomorphs: cellulose I_α and I_β (native forms), cellulose II (prepared regeneration or sodium hydroxide treatment), and cellulose III (prepared by liquid NH_3 treatment). Evaluation of these allomorphs of cellulose can be done by determining positions of the important diffraction peaks in XRD of cellulose. The crystalline domain diameter (D) or grain size is obtained from XRD peaks using the Scherrer's equation (Monshi et al. 2012).

$$D = K * \lambda/\beta * \cos\theta$$

where λ is the wavelength of the incident X-ray beam; θ is the Bragg's diffraction angle; β is the width of the X-ray pattern line at half peak—height in radian and the dimensionless shape factor (K) has a typical value of 0.89 but varies with the actual shape of the crystalline. It is expected to get broader peaks in XRD once the material is converted into bulk form to nanoform due to reduction in the grain size.

The determination of XRD crystallinity implies use of a two-phase model, i.e., the sample is composed of crystals and amorphous and no regions of semi-crystalline organization. The diffraction profile is divided in two parts, i.e., peaks are related to diffraction of crystallites and broad scattering alone is related to the amorphous scattering.

Total intensity = $I_a + I_b$

I_a = Intensity of crystalline phase (020 plane)

I_b = Intensity of amorphous crystalline phase

$$\text{Degree of crystallinity} = \frac{I_a}{I_a + I_b}$$

16.3.5 Small-Angle X-Ray Scattering

Small-angle X-ray scattering (SAXS) helps in the evaluation of sizes of small particles ranges from several to 100 nm by analyzing the scattered intensity of the X-rays in an angular range from 0.1° to 3°. In contrast to XRD, SAXS can be applied not only to the crystalline materials but also for amorphous materials. The SAXS intensity mainly depends on electron density and the form factor [$F(q)$]: $q = 4\pi\sin\theta/\lambda$, where θ is scattering angle and λ is wavelength of X-ray of the particle and the structure factor [$S(q)$]. The basic application of SAXS is the

evaluation of particle size, shape, orientation, and size distribution in dilute dispersions, where the particle–particle correlation factor, $S(q)$, is negligible.

16.3.6 Electron Microscopy (TEM, SEM)

Electron microscopy uses electrons having shorter wavelengths thereby allowing the observation of matter down to atomic resolution. Two categories of electron microscopes are popularly used. In the scanning electron microscope (SEM), the electron beam is scanned over surface of an object to analyze the scattered electrons. The electron beam is generally scanned in a raster scan and the beam's position is merged with detected signal to produce an image. SEM can achieve resolution down to 1 nm. Specimens can be observed in vacuum or in ambient condition as in the case of ESEM. Transmission electron microscopy techniques (TEM) provide imaging, diffraction, and spectroscopic information of the specimen with an atomic and sub-nanometer spatial resolution. The sample preparation for TEM is tedious and time-consuming due to its requirement to be ultra-thin for electron transmittance. High-resolution TEM imaging in combination with the nanodiffraction and atomic resolution is very important to the fundamental studies of importance to nanotechnology. For TEM characterization, the nanoparticles dispersion is deposited onto the surface of grids and dried. For organic materials like nanocellulose, after dispersion, they needed to be fixed using a negative staining material (uranyl acetate).

16.3.7 Atomic Force Microscopy

AFM is ideally suited for characterizing many types of nanomaterials and it offers the capability of 3D visualization and semi-quantitative information on most of the physical properties like size, morphology, surface texture, roughness, and elasticity. The major advantage of AFM in comparison with other techniques is its ability to work in ambient air, vacuum, and under liquid environment. With an SEM/TEM, the images measured are only in two dimensions while the images from an AFM represent data in three dimensions, so that it is possible to measure the height or depth of the nanosurfaces. With an AFM, the mechanical characterization of nanomaterials is possible as the probe is in very close interaction with the sample while that is not possible in case of SEM or TEM. With neatly prepared samples (clean, with no excessively large surface features), resolution in the x–y plane ranges from 0.1 to 1.0 nm and in the z-direction is 0.01 nm. AFM requires neither a vacuum environment nor any tedious sample preparation techniques. With these advantages, AFM has significantly impacted various fields like materials science, chemistry, biology, physics, and semiconductors. The radius of AFM tip is around

5–50 nm and hence, it can probe extremely small interaction area with high sensitivity to small forces. These probes are suspended on a very soft spring made of silicon or silicon nitride beams thus allowing forces in pico-Newton range to be measured. This corresponds to the magnitude of forces that are required to break a single hydrogen bond. In the imaging mode, the cantilever having probe is scanned over the surface while in "force spectroscopy," the cantilever is moved directly toward the sample until contact and retracted again, while their interaction is measured.

16.3.8 Physico-Chemical Methods

Thermo analytical methods like differential thermal analysis (DTA) and thermogravimetric analysis (TGA) provide information about various physical and chemical changes, accompanied by heat of enthalpy. In thermal analysis nanocellulose, we can understand the sorption desorption, oxidation, and thermal decomposition properties. Differential scanning calorimetry (DSC) of typical cellulose shows an endotherm ranging from 360 to 385 °C with a peak at 372 °C corresponding to depolymerization of cellulose with the formation of flammable gases like pyro-glucosan and levo-glucosan. At this temperature, pyrolytic degradation of cellulose takes place with a rapid cleavage of the glucosidic bond. The shifting of this endothermic peak along with increase in intensity for nanocellulose was observed due to increase in amount of crystalline region (Satyamurthy and Vigneshwaran 2013).

16.4 Application of Nanocellulose for Pulp and Paper Products

The major types of nanocellulose applications in paper industries are discussed below and depicted in Fig. 16.5.

16.4.1 Coating Additive

In paper coatings, the quality of final printing is dictated by coating uniformity, pore structure, and chemical nature of the surface. Nanocellulose, due to its size range and rheological behavior, could be a potential substitute for the natural and synthetic co-binders, including modified starch, carboxymethyl cellulose (CMC), and polyacrylic thickeners. The nanocellulose additives are reported to operate as water-binding gel-forming components rather than the flocculating thickening

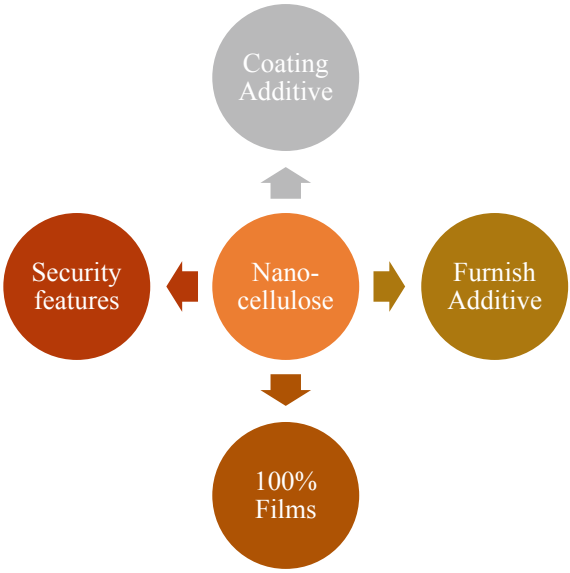

Fig. 16.5 Areas of applications of nanocellulose in paper industry

action of CMC. Immobilization of color in presence of nanocellulose is identified as a point of gel–water entrapment rather than the traditional stick–slip particle–particle interlocking mechanism predominating in traditional flocculant thickener formulations (Dimic-Misic et al. 2013). In another study, the impact of nanocellulose on rheological behavior of paper coatings were comparatively evaluated and showed that nanocellulose prepared by sulfuric acid hydrolysis and TEMPO oxidation exhibited very large dimensions, limited negative surface charge, and hence poor stability in their aqueous suspensions, while the FCN aqueous suspension displayed the highest viscoelastic modulus due to the formation of highly entangled network. And, sulfuric acid hydrolyzed nanocellulose exhibited strong interactions with pigments and immobilized water molecules, in comparison with other two types of nanocellulose evaluated (Liu et al. 2017).

Different processes like extrusion, curtain, size press, bar, and dip coatings are routinely used for coating of various additives on the surface of paper. The creation of bio-based nanocomposite coatings on the paper provides the opportunity to maintain a combination of favorable barrier properties toward low oxygen and water vapor permeability (Rastogi and Samyn 2015). Medical application of the NFC coated paper was also reported (Liu et al. 2015) wherein, the paper coated with triclosan-loaded NFC demonstrated excellent antibacterial activity against *E. coli* in addition to improving their tensile index (18.0%) and tear index (26.45).

16.4.2 Furnish Additive

NFC is always used as a furnish additive to improve the mechanical properties of the paper. In an earlier report, the eucalyptus pulp was reinforced with NFC and the best mechanical and physical results were reported with 6–9 wt% of NFC. But, the use of NFC resulted in drainage difficulties. At 3 wt% of NFC, it was possible to reduce the intensity of beating without affecting the final quality of paper (González et al. 2012). Another study reported that addition of 9 wt% of CNF (produced by TEMPO oxidation followed by mechanical homogenization) increased the tensile index of paper by around 95%, equivalent to that produced by the PFI refining at 1600 revolutions. This did not affect the paper machine runnability (Vallejos et al. 2016). It was also demonstrated to decrease the absorption of water to about 23.1% by the addition of acetylated NFC to non-acetylated pulp in addition to improving the mechanical properties like tensile and burse strength (Mashkour et al. 2015). In addition to these studies, there are other reports on the potential use of nanocellulose for reinforcing for paper (Kajanto and Kosonen 2012; Osong et al. 2014; Sun et al. 2015).

16.4.3 100% Films

The films made up of 100% nanocellulose, also called as self-standing films, are being used as a substrate for flexible electronics and sensors (Hu et al. 2013). The ample opportunities for surface modification of cellulosic molecules in addition to their strength and biodegradability make them an ideal material for the substrates of nanosensors. The periodate oxidation of nanocellulose results in films with an elastic modulus of 11 GPa followed by ozone treatment that induces conversion of aldehyde into carboxyl functionalities. The crystalline cellulose "Janus" film is suggested as an interfacial component in biomaterial engineering, separation technology, or in layered composite materials for the tunable affinity between the layers (Nypelö et al. 2018). Another study reported that the periodate-based nanocellulose films showed very high tensile strength (130–163 MPa) and modulus (19–22 GPa) and also superior oxygen barrier properties (as low as 0.12 cm^3 μm/(m^2 d kPa) at 50% relative humidity) (Sirviö et al. 2014). Another research group demonstrated to control the oxygen permeability of highly hydrophilic nanocellulosic film at elevated humid conditions with a simple surface modification strategy by the APTES-chemistry. Such modification resulted in a very thin layer with the nanometer-range thickness and hence proved very efficient (Peresin et al. 2017).

16.4.4 Security Features

Counterfeiting of important certificates, land documents, and currency notes is a serious issue in various countries. This results in increased focus by various researchers to develop novel anti-counterfeiting materials using nanotechnology. The use of a nanocellulose latex blend as an ink for security printing was reported wherein the inks are recognized as being special in its diffuse reflection, if polarizers are inserted between the light source and the paper and, also, between paper and the observer (Chindawong and Johannsmann 2014). Ink made using nanocellulose appears peculiar as it scrambles the polarization from background without being a strong scatterer itself. This application requires a dark background; applied to black paper, the contrast strongly depends on whether the printed area is viewed with polarizers being parallel/crossed.

Rapidly responsive and flexible photonic papers are manufactured by co-assembly of nanocellulose and waterborne polyurethane latex for fully utilizing the advantage of the chiral nematic structure of nanocellulose and the flexibility of the latex polymer. The resulting composite papers exhibit not only tunable iridescent colors, but also instant optical responses to water, ascribed to the easy chain movement of the elastomeric latex that does not restrict the fast water absorption-induced swelling of nanocellulose (Wan et al. 2018). Apart from security applications, this methodology will be of immense use in sensors and photonic circuits. Another research reported a family of new amino resin–cellulose nanocrystal composites. Owing to the chiral nematic order of the nanocellulose embedded in amino resin polymer, the materials appear highly iridescent and their color could be manipulated by the addition of salts. Also, the colored chiral nematic patterns could be permanently recorded in a composite film, suggesting their potential application in security features and sensors (Giese et al. 2013).

16.5 Conclusion

Lignocellulosic biomass is the most abundant and renewable polymer on Earth and its conversion would produce the novel material, nanocellulose. This adds value to the forest biomass and agricultural residues. To meet the ever-increasing demand for high-quality paper without any additional cost, nanocellulose offers a hope for such production. Apart from the use of nanocellulose in pulp and paper industries, it can be used as substrate for immobilization of chemical, microbial and enzyme catalysts. Also, the synthesis of synthetic rubbers, bioplastics, and pharmaceutical molecules from nanocellulose would be a quantum leap in nanocellulose industry (Lee et al. 2014). The nanocellulose, being renewable, organic and degradable in nature, will not leave the carbon footprint in nature.

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