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An Update on Overview of Cellulose, Its Structure and Applications

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Abstract

Cellulose ($C_6H_{10}O_5$)_n is one of the most ubiquitous organic polymers on the planet. It is a significant structural component of the primary cell wall of green plants, various forms of algae and oomycetes. It is a polysaccharide consisting of a linear chain of several hundred to many thousands of $\beta(1 \rightarrow 4)$ linked D-glucose units. There are various extraction procedures for cellulose developed by using different processes like oxidation, etherification and esterification which convert the prepared celluloses into cellulose derivatives. Since it is a non-toxic, bio-degradable polymer with high tensile and compressive strength, it has widespread use in various fields such as nanotechnology, pharmaceutical industry, food industry, cosmetics, textile and paper industry, drug-delivery systems in treating cancer and other diseases. Micro-crystalline cellulose in particular is among the most frequently used cellulose derivatives in the food, cosmetics, pharma industry, etc. and is an important excipient due to its binding and tableting properties, characterized by its plasticity and cohesiveness when wet. Bacterial cellulose's high dispersability, tasteless and odourless nature provides it with lot of industrial applications. Currently, about half of the waste produced in India contains about 50% cellulose which can be used productively. This chapter deals with the chemistry of cellulose, its extraction and its properties which help various industries to make the most of it.

Keywords: properties, chemistry, types, microcrystalline cellulose, cellulose nanocrystals, cellulose nanofibres, extraction, characterization, NMR, SEM, FTIR, BJH, biomedical applications, pharmaceutical applications, renewable energy applications, waste management, drug delivery, wound healing, scaffolding, implants, biofuels, consumables

1. Introduction

Cellulose is the most abundant biopolymer available in nature, since it is one of the major components of the cell walls of most of the plants [1]. It is a homopolymer of anhydroglucose, with the glucose residues linked in a β -1,4 fashion [2]. Cell walls of plant cells attribute their mechanical strength to cellulose. Cellulose owes its

structural properties to the fact that it can retain a semi-crystalline state of aggregation even in an aqueous environment, which is unusual for a polysaccharide [3, 4].

As far as cellulose based products are concerned, paperboard and paper are the most commonly used ones [5]. Smaller amounts of cellulose when processed under appropriate conditions, can be converted to a wide variety of derivatives, these can be used in manufacture of few commercial products like cellophane and rayon [6].

Since cellulose is a homopolymer of a glucose derivative, it is a great source of fermentable sugar. It is cultivated in the form of energy crops for the production of ethanol, ethers, acetic acid, etc. Besides energy requirements the industrial demands of cellulose are fulfilled by wood pulp and cotton crops [7].

Cellulose also fulfils the dietary requirements of some animals, particularly ruminants and termite, they can digest cellulose with help of symbiotic microorganisms present in their gut, while some organisms secrete a group of enzymes called cellulases to aid the degradation of cellulose molecules [8]. Human beings are unable to digest cellulose due to lack of cellulases, thus cellulose acts as a hydrophilic bulking agent for faeces and potentially aids in defecation [9].

2. Overview

Among the various raw materials which nature has placed at our disposal for industrial purposes, cellulose has from time immemorial occupied a prominent position. Its abundance is attributed to the constant photosynthetic cycles taking place in higher plants, which can synthesize around $10^{11} \pm 10^{12}$ tons of cellulose in a rather pure form. Since time immemorial it has served mankind either as a construction material or as a versatile starting material for chemical reactions for the production of artificial cellulose based threads and biofilms as well as for production of a variety of stable cellulose derivatives which are used for various industrial and domestic applications [10]. Cellulose was used for various biochemical conversions even before its polymeric nature was recognized and well understood. In the process of recognizing and understanding its polymeric structure, it led to the discovery of nitrocellulose, synthesis of organo-soluble cellulose acetate and the preparation of Schweizer's reagent (first cellulose solvent). Another area of great interest was nanocellulose, the nanostructure of cellulose has proven to be advantageous because of its applications in a variety of fields [11, 12].

Due to such great economical significance of tree cellulose, the current scientific focus is more towards cellulose biosynthesis as it is still not well understood [13]. Most of the recent findings concerning the molecular mechanism of cellulose biosynthesis in higher plants resulted from research in model herbaceous plants and fibre crops and have been reviewed recently. All these aspects trigger a researchers' curiosity and makes them want to dig deeper and unveil other properties and applications of cellulose.

3. Chemistry of cellulose

The Cellulose is made up of a D-glucose unit at one end and a C4-OH group, the non-reducing end, while the terminating group is C1-OH, the reducing end with aldehyde structure. Some technical celluloses contain extra carbonyl and carboxy groups, like the bleached wood pulp. The molecular structure is responsible for its significant properties: Chirality, hydrophilicity, degradability and chemical variability due to high reactivity from the donor group—OH. The superior hydrogen bonds add crystalline fibre structures to cellulose. **Figure 1** presents the four

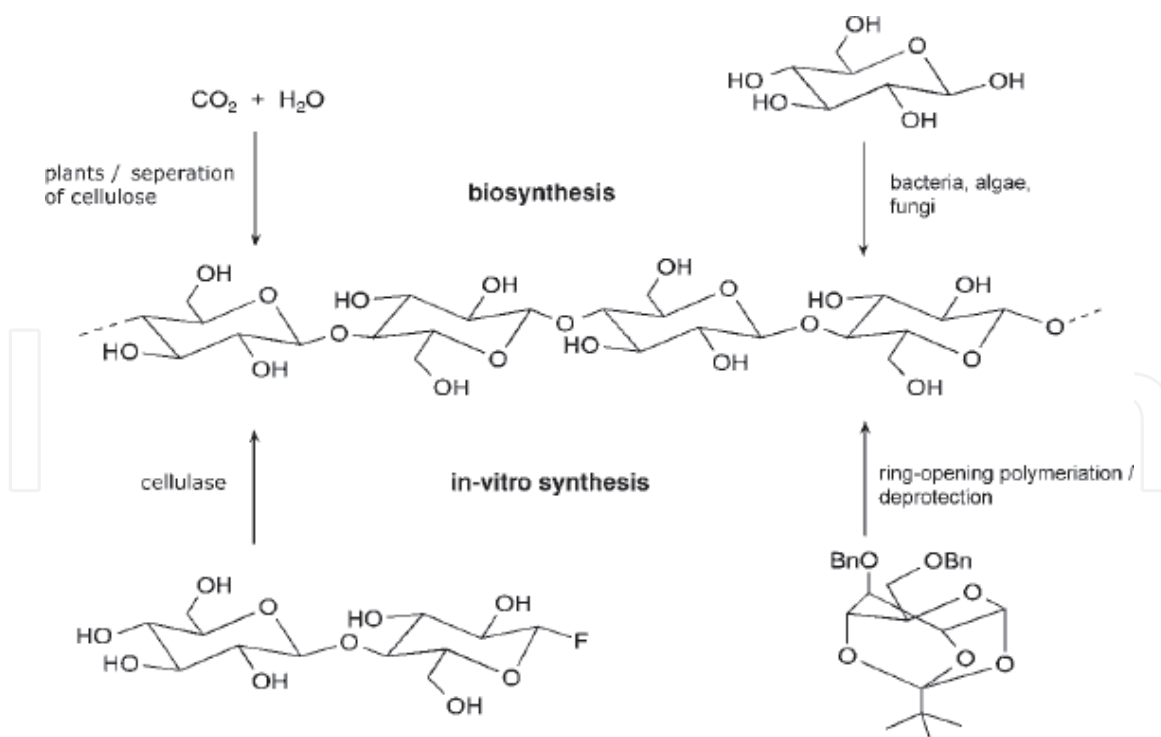


Figure 1.
 Major pathways of formation of cellulose [14].

different pathways which determine the major processing routes. The most famous and highly used pathway is the manufacture of cellulose from plants. It is established that cellulose is found in its purest form from the seed hairs of cotton. The wood cellulose, on the other hand forms a composite with lignin and other polysaccharides, which is further separated by large scale chemical pulping and purification processes. Cellulose can be derived from algae, some specific bacteria, and fungi, apart from most plants. The supramolecular structures are used for research on cellulose structures, reactivity, and crystallinity with further note on development of biomaterials and new substances. Cyanobacteria are known to biosynthesize cellulose for nearly 3.5 billion years [15]. The first synthesis of cellulose in vitro is reported as the cellulase—cellulose formation by catalyzed cellobiosyl fluoride and the chemosynthesis was processed in a ring opening polymerization of the D-glucose moieties [16]. A lot of research is ongoing in the field and study of cellulose over the past decade. The structure and properties of cellulose are quintessential to perform modifications and processing of cellulose on the whole.

4. Properties of cellulose

The structure of cellulose has been constantly a subject requiring intensive research as it is formed by the hydrogen bonds between the network of hydroxy groups [17]. The progress was for more than a 100 years of intensive development on structure analysis methods like electron microscopy, X-ray diffraction and high

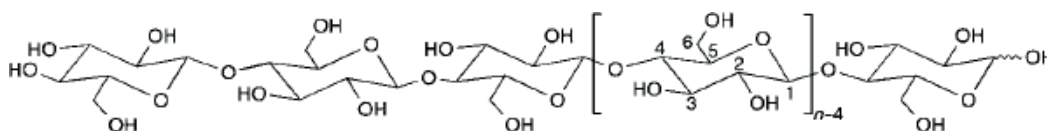


Figure 2.
 Molecular structure of cellulose ($n = DP$, degree of polymerization) [14].

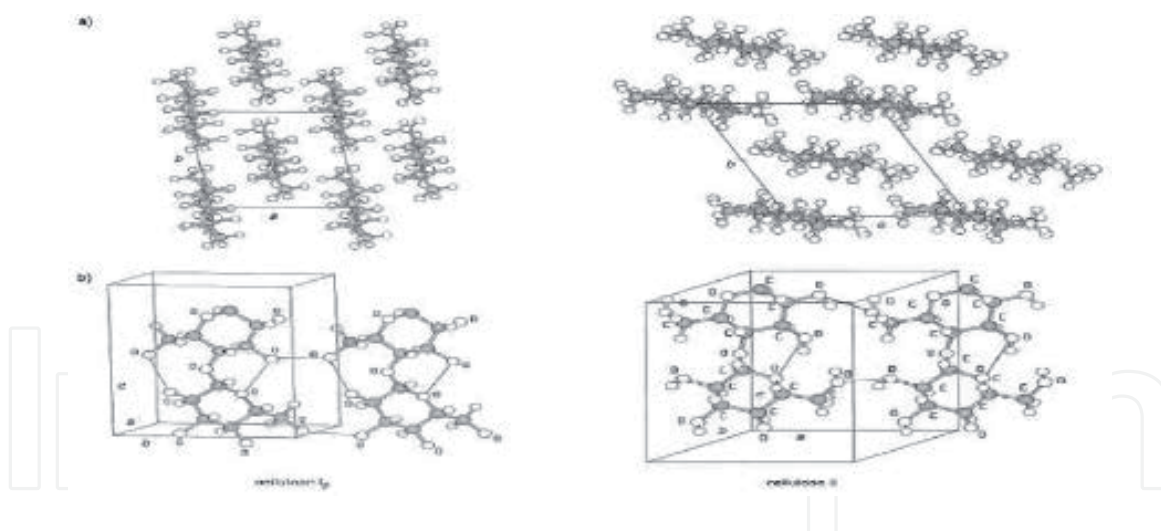


Figure 3.

The crystal structures of cellulose I and II: (a) projection of the unit cell along the a - b plane and (b) projection of UC parallel to (100) lattice plane, cellulose I and (010) lattice plane, cellulose II [14].

resolution solid state NMR spectroscopy. The complete detailed analysis is required for the procedures of synthetic reactions and cellulose based manmade products with extensive applications. The structure of cellulose as depicted in **Figure 2** consists of hydroxyl groups of β -1,4-glucan cellulose at C2, C3 and C6. The CH_2OH group is positioned relative to the C4 and C5 bonds along with a shear relativity with O5–C5 bonds. The solid state is equally likely to be represented in the crystalline (high order) and amorphous (low order). The crystal structure in particular is determined by the X-ray diffraction using a monoclinic unit cell which is made up of two cellulose chains in a parallel orientation and two fold screw axis [18]. The investigations with respect to the electron microbeam diffraction, combined X-ray and neutron diffraction have clearly indicated that the cellulose crystalline structures have a triclinic and monoclinic unit cell. The schematic representations of the I_β crystal structure, in **Figure 3**, indicate the two intramolecular chain-stiffening hydrogen bonds. The recent researches on the I_β crystal structure have different H-bonds and different conformations of neighbouring chains. The thermodynamically stable cellulose II can occur in other forms of crystal structures and is the most stable form of cellulose. The cellulose I can be treated with aqueous sodium hydroxide to form cellulose II.

5. Types of cellulose

5.1 Bacterial cellulose

Although cellulose is mainly produced by plants, many bacteria, especially those belonging to the genus *Gluconacetobacter* are involved in the production of a very peculiar form of cellulose with mechanical and structural properties that can be exploited in numerous applications. Bacterial cellulose are usually produced by *Gluconacetobacter hansenii* UCP1619 using the Hestrin-Schramm (HS) medium. But there are few limitations associated with bacterial cellulose like the production cost is high, use of expensive culture media, poor yields, downstream processing, and operating costs. Bacterial cellulose can also be produced by bacteria from genera *Sarcina*, and *Agrobacterium* [19]. Bacterial cellulose produced by aerobic bacteria has unique physiochemical properties compared to plant cellulose [20].

5.2 Cellulose acetate

Cellulose acetate is an important ester of cellulose. Cellulose acetate can be used for great varies of applications like for films, membranes or fibres, depending on the way it has been processed. A special field for using cellulose acetate is the synthesis of porous, spherical particles, so called cellulose beads [21].

5.3 Ethylcellulose

Ethylcellulose (EC) is a derivative of cellulose in which some of the hydroxyl groups on the repeating anhydroglucose units are modified into ethyl ether groups, largely called as non-ionic ethyl ether of cellulose. Ethylcellulose (EC) based microencapsulated drug delivery systems are being studied to achieve extended drug release and to protect the core substance from degradation [22].

5.4 Hydroxypropyl cellulose (HPC)

Hydroxypropyl cellulose (HPC) is one of the derivatives of cellulose which is soluble in both water and organic solvent. It can be used as a lubricant. It can also be used for the treatment of keratoconjunctivitis sicca, corneal erosions neuro-paralytic keratitis etc. It is also used as a lubricant for patients having artificial eye [23–25].

6. Extraction and characterization of cellulose

Cellulose is one of the most abundant biomass materials in nature possessing some promising properties. In our work, let us look into the various procedures involved in extracting cellulose from different sources. The sources available are many which can be broadly classified into Agro-waste, Domestic-waste (and other means such as wood, plant and paper). The processes involved include usual chemical procedures like alkaline extraction, bleaching, acid hydrolysis and chlorination. The final products can be characterized by using techniques like thermogravimetric analysis (TGA), infrared spectroscopy (FTIR), X-ray diffraction (XRD), differential scanning calorimetry (DSC) and scanning electronic microscopy (SEM). Purified cellulose can be obtained successfully using the above mentioned procedures. In our study, we will be concentrating on the extraction of cellulose from agricultural residues and plants [26–28] (**Figure 4**).

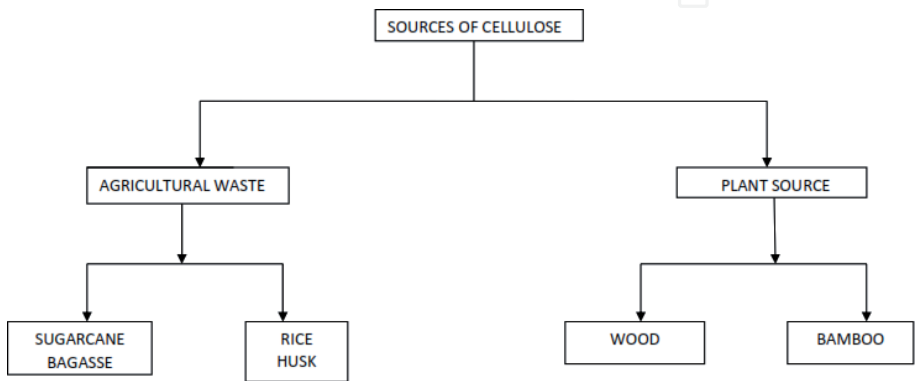


Figure 4.
Different sources of cellulose extraction.

6.1 Extraction of cellulose from agricultural residues

6.1.1 Extraction of cellulose from sugarcane bagasse

Sugarcane bagasse (SCB) is a key agricultural residue which has grown to be the point of interest in recent times. The extraction of cellulose from SCB was investigated using steam explosion and xylanase based environmentally friendly pre-treatment for reducing chemical bleaching and to determine the characteristics of cellulose from sugarcane bagasse. SCB is a low value agriculture residue and about 40–50% of bagasse is the glucose polymer cellulose. There are several approaches to pretreat lignocellulosic materials to extract cellulose such as steam explosion, solvent extraction and alkaline treatment.

6.1.1.1 Methodology

Cellulose is extracted from SCB by using steam explosion and xylanase pre-treatment and bleaching process. The dried SCB treated with steam explosion at a pressure 13 bar (195°C) for 15 minutes to obtain steam exploded SCB fibres. Then, the steam exploded SCB is treated with 20 µg of xylanase using fibre to liquor ratio of 1:10 for 1 hour at 50°C under constant agitation. Then, dried steam exploded SCB is treated with xylanase (fibre to liquor ratio of 1:10) and then bleached with 0.7% sodium chlorite (NaClO₂) adjusted to a pH of 4 by the addition of weak acetic acid at 70°C for 1 hour. Sodium chlorite and acetic acid at the same loading were added to the reaction every 1 hour till the cellulose turns white. The cellulose fibres thus obtained would then filtrated, washed with distilled water until the pH of water neutral and dried at 55°C for 24 hours. The steam explosion process includes saturating the dry material with steam at elevated pressure and temperature followed by sudden release of pressure, resulting in substantial resistance of degraded lignin fragments, facilitates the release of lignin, which is then readily available for further bleaching and thereby increases the efficiency of the bleaching process. Thus, the use of enzymes to treat pulp before applying chemical bleaching help to reduce chemical required in bleaching stage, breakdown of lignocellulosic structure, hydrolysis of the hemicelluloses fraction, depolymerization of the lignin components and defibrillization. In terms of bleaching treatments, chlorine-based chemicals were typically used for bleaching process resulting in chemical hazard released into environmental. Xylanases are glycosyl hydrolase that can catalyse the hydrolysis of β-1, 4-glycosidic bonds in xylan by means of double displacement mechanical reaction. This treatment improves accessibility of bleaching chemical to the pulp by decreasing diffusion [29] (**Table 1**).

6.1.2 Extraction of cellulose from rice husk

Rice is the most cultivated cereal crop in the world. Rice husk is a major agro-waste that is generated in huge quantities. It accounts for 20% of the 600 million tons of paddy produced worldwide. People often dispose the rice husk waste using open burning which is an environmental threat causing damage to the land and the surrounding area in which it is disposed. This rice husk can be put into best use by exploitation of its cellulose content. Rice husk comprises of 33% cellulose, 26% hemicellulose, and 7% lignin. Thus, the use of rice husk as the primary source for producing cellulose fibres and nanocrystals is efficient. The strategy is to extract cellulose fibres from the rice husk using alkali and bleaching treatments.

Fibres	α -Cellulose (in %)	Hemicellulose (in %)	Lignin (in %)
Untreated SCB	44.5	21.8	22.5
Steam-exploded SCB	65.7	9.9	18.3
Steam exploded with xylanase treated	66.3	8.8	18.6
Bleached fibre	89.3	4.3	1.5

Table 1.
Extraction and characterization of cellulose from sugarcane bagasse by using environmental friendly method [29].

6.1.2.1 Methodology

Sodium hydroxide (99% purity) is used for alkaline treatment. Sodium chlorite, acetic acid and NaOH are used as bleaching agents while sulphuric acid is used for hydrolysis.

6.1.2.2 Preparation of cellulose nanocrystals from rice husk

- 1. Treatment with alkali:** Cellulose is purified by treating with Alkali to remove lignin and hemicellulose on or after rice husk grits. The pulverised rice husk is preserved through an alkali solution (4% by weight of NaOH). The combination is poured into a plump bottom flask and action is performed at reflux temperature intended for 2 hours. The solid is formerly filtered and carry away numerous times by means of distilled water. This treatment is frequent thrice.
- 2. Bleaching process:** Subsequent the alkali action, bleaching progression is completed by totalling a buffer solution of acetic acid, aqueous chlorite (1.7% by weightiness) and purified water at reflux (by means of a silicon emollient soak at 100–130°C) for 4 hours. The assortment is then permitted to cool and the additional distilled liquid is filtered. The bleaching procedure is performed four periods.
- 3. Acid hydrolysis:** The acid hydrolysis action is performed on the fibres subsequently alkali action and decolourising at a temperature of 50°C by means of 10.0 mol L⁻¹ of preheated sulphuric acid intended for 40 minutes underneath non-stop stirring. The fibre content varieties from 4 to 6% by heaviness. The hydrolysed substantial is eroded by centrifugation at 10000 rpm at 10°C for 10 minutes. This centrifugation stage is repeated many times before the suspension is dialyzed in contradiction of purified water for several days until persistent pH in the range of 5–6 is attained. The subsequent suspension is formerly sonicated for 30 minutes previously it is frozen for additional use [30].

6.2 Extraction of cellulose from plants

6.2.1 Extraction of cellulose from bamboo

This extraction method involves use of Bamboo fibres as a raw material for cellulose extraction. The chemicals used to produce cellulose nanofibres are toluene, ethanol, hydrogen peroxide, acetic acid glacial, titanium (IV) oxide, and sodium hydroxide. All the chemicals used here are of analytical grade.

6.1.2.3 Methodology

1. **Bamboo fibre preparation:** Green bamboo Culm of 1 m length is prepared. It is then ground using a planner machine to produce small chips and powder form excluding the internodes. This chips and powder mixture is put into an oven at 70°C for 72 hours to dry. The oven dried sample is ground and then sieved using 600 µm size sieve. The 600 µm mesh size fibres are used for the synthesis of cellulose fibre. This sample is then labelled as green bamboo fibre (GBF).
2. **Preparation of cellulose from bamboo fibre and de-waxing of bamboo fibre:** The 400 mL toluene and 200 mL of ethyl alcohol are filled into a round flask to produce toluene-ethanol of ratio 2:1. The round flask is placed on a heating element. A Soxhlet extractor is placed on top of the boiling flask and fixed firmly using a retort stand. About 10 grams of GBF is scooped into a membrane tube and placed into the extraction thimble. A Liebig condenser is placed on top of the extractor and then fixed firmly. The temperature of the heating element is observed using a digital thermometer and it is maintained at 250°C. The extraction process is continued till the colour mixture disappears. The process takes 2 hours with approximately 10–12 cycles of extraction. The extraction thimble is taken out using tweezers. The product is transferred into a beaker and stirred using a glass rod while adding toluene-ethanol mixture. The final product is filtered using a filter paper placed on a funnel. It is then distributed evenly using glass rod on a filter paper. It is then placed in an oven set to temperature 70°C for drying overnight and is kept for delignification processes. The dried sample is identified as dewaxed bamboo fibre (DBF).
3. **Delignification of bamboo fibre:** The delignification solution is prepared using 82.3 g of 35% by weight of hydrogen peroxide (H_2O_2) and 106.2 g of 99.8% by weight of acetic acid (CH_3COOH) in the present of titanium (IV) oxide as catalyst. Thirty grams of dry DBF sample is weighed and immersed into delignification solution contained in a round bottom flask. The flask is placed on the heating element and heated to 130°C. After 2 hours, the heater is switched off and cooled to room temperature. The treated product is then filtered using Buchner flask and rinsed with de-ionized (DI) water until the pH level reaches 7 and dried at 70°C for 1 day. The dried sample is placed in a bottle and kept in a cool and dark place for alkaline treatment. The sample so obtained is delignified bamboo fibre (DLBF).
4. **Mercerization:** DLBF is finally immersed in an alkaline solution in order to dissolve the pectin and hemicelluloses. 6% by weight of sodium hydroxide is used to treat the DLBF in a flask at room temperature. The mixture is stirred using auto shaker at 150 rpm, heated to 80°C for 2 hours, and stopped after 8 hours of proper stirring. The mixture is then rinsed continuously with de-ionized water until the product reaches pH 7. The treated product is finally filtered using Buchner flask, rinsed with de-ionized water until the pH level reaches 7, and freeze-dried at –85°C for 2 days [31].

6.1.2.4 Characterization of cellulose extracted from bamboo

After extraction of cellulose, it is generally characterized by using the following techniques:

1. **Fourier transform infrared spectroscopy (FTIR):** The infrared spectra obtained using a FTIR Spectrometer model IRAFFINITY-1 CE. The spectra were to be taken at a resolution of 4 cm^{-1} , with a total of 60 scans for each sample. The transmittance range of the scans was $600\text{--}4000\text{ cm}^{-1}$. The composition changes in GBF were investigated by FTIR spectroscopy (**Figure 5**).
2. **Scanning electron microscopy (SEM):** The bamboo fibre samples was vacuum-dried for 24 hours at 70°C , pressed onto a carbon tape adhered to a sample holder surface, and sputtered with titanium. Imaging of each sample was done using Hitachi M-3030 scanning electron microscope. All images were taken at an accelerating voltage of 5 kV with a magnification of 1500 time [33].
3. **Barrett-Joyner-Halenda (BJH) analysis:** In order to do BJH analysis the bamboo fibre sample is dried for 24 hours at 70°C and inserted into a capillary tube. The outgas had an approximately 7 hour duration with final outgas temperature of 350°C . After outgas process, the sample was analysed using Nova Quantachrome 4200e automated gas sorption instrument for 1.5 hours across a wide range of relative pressures at constant temperature (77 K) using liquid nitrogen (**Figure 6**).
4. **Thermogravimetric analysis (TGA):** Dynamic thermogravimetric measurements were performed using a Shimadzu DTG 60H instrument. The temperature programs for dynamic tests was run from ambient temperature $25\text{--}700^\circ\text{C}$. All measurements was made under a nitrogen flow (20 mL/min), while keeping a constant heating rate of $10^\circ\text{C min}^{-1}$ and using an aluminium crucible with a pinhole (**Figure 7**).

6.1.2.5 Characterization of cellulose extracted from rice husk fibres

The chemical conformation of rice husk at individual phase of action is originate to be giving to the approaches conveyed by the Technical Association of Pulp and Paper Industry (TAPPI). The cellulose and hemicellulose contents are retrieved conferring to TAPPI standard T203 OS-74 though the lignin content is restrained according to TAPPI normal T222 OS-83. The silica ash content is calculated by

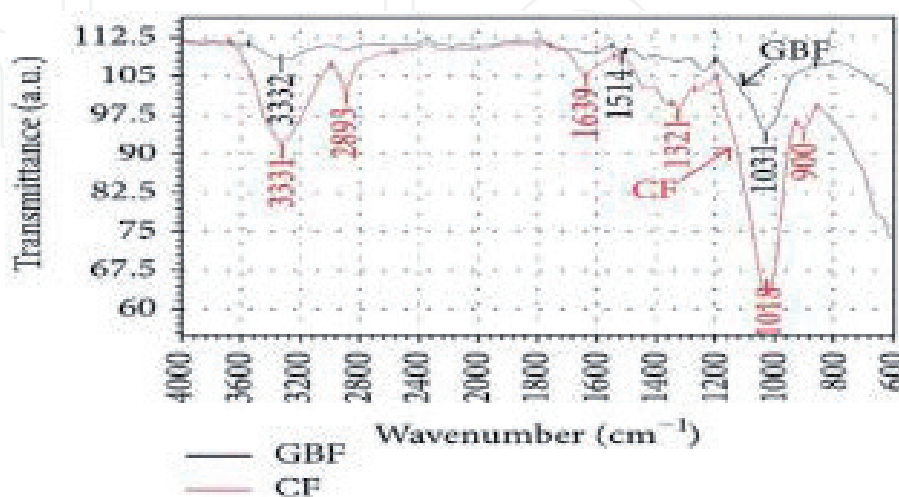


Figure 5. Comparative differences of FTIR peaks into green bamboo fibre (GBF) and cellulose fibre (CF). The peak intensity at 1514 cm^{-1} from the spectrum of the GBF is credited to the $\text{C}=\text{C}$ stretching vibration in the aromatic ring of lignin. Yet, the cellulose fibre did not show the $\text{C}=\text{C}$ stretching at that region. This is an indication that the lignin was well removed by chemical process [30, 32].

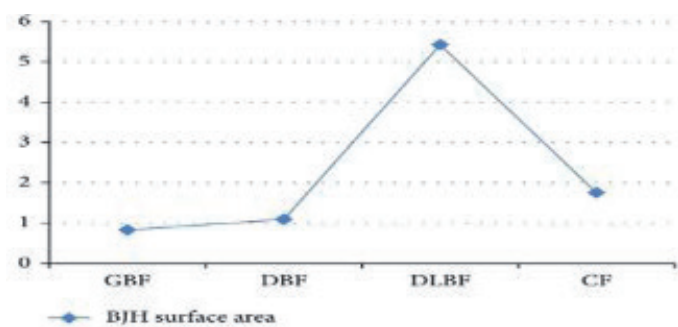


Figure 6. BJH surface area for four samples. It was noted that there was an increase in the BJH surface area of GBF and a decrease after DLBF. The decreased surface area of cellulose fibre might be a result of the mechanical grinding process that creates smaller cellulose fibre thus reduced the surface area. This result also indicates that mechanical grinding should be avoided to obtain higher BJH surface area. The final cellulose fibre showed that BJH surface area is two times greater than the initial green bamboo fibre [30, 32].

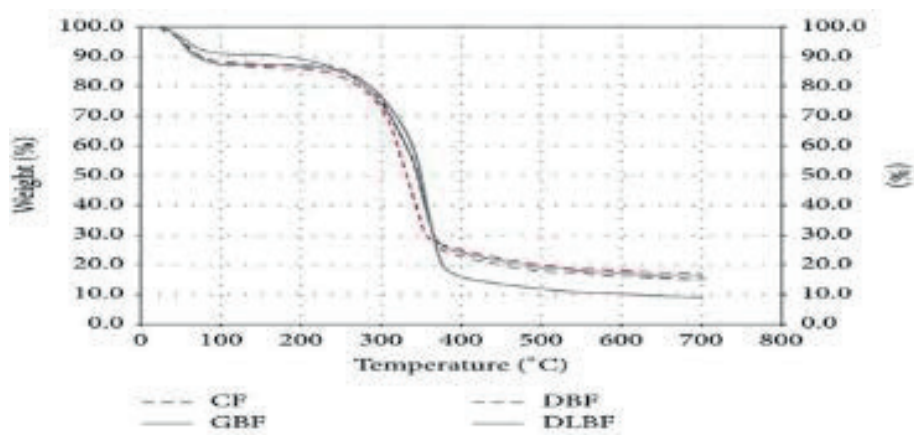


Figure 7. The thermogravimetric analysis of (GBF, DBF, DLBF and CF) green bamboo fibre, dewaxed bamboo fibre, delignified bamboo fibre and cellulose fibre, respectively. The weight loss rate was obtained from the derivative thermogravimetric (DTG) data. The intersection of tangents drawn from thermogravimetric curve, one before inflection caused by the degradation and another from the cellulose degradation step indicates the onset degradation temperature [30].

means of the thermogravimetric examination (TGA) data. The arrangement of silica ash was found at temperatures 900°C as the residual ash at this point can be credited to the silica ash [30, 33, 34].

6.1.2.6 Scanning electron microscopy (SEM)

It is utilized to detect the superficial morphology of the rice husk fibres. The effect of the numerous chemical treatments is evaluated using an assessment of the raw, alkali treated, and bleached fibres. Rice husk fibres is reserved on the aluminium stub and raised in the oven at 60°C. The samples are then covered with gold by means of a vacuum sputter coater (model SC 500). The width of the gold layer is approximately 0.01–0.1 µm. The fast-tracking voltage is 15 kV. Transmission electron microscopy (TEM) is used to regulate the proportions of the cellulose nanocrystals attained from the rice husk fibres. A drop of a diluted suspension (1% by weight) is placed on the superficial of a clean copper grid and covered through a thin carbon film. As for contrast in TEM, the cellulose nanocrystals are undesirably stained in a 2% by weight solution of uranyl acetate for 10 seconds then carried away by means of 50% by weight of sieved alcohol. Later sample is dehydrated at ambient temperature before TEM examination is approved out through an accelerating voltage of 80 kV (Figure 8).

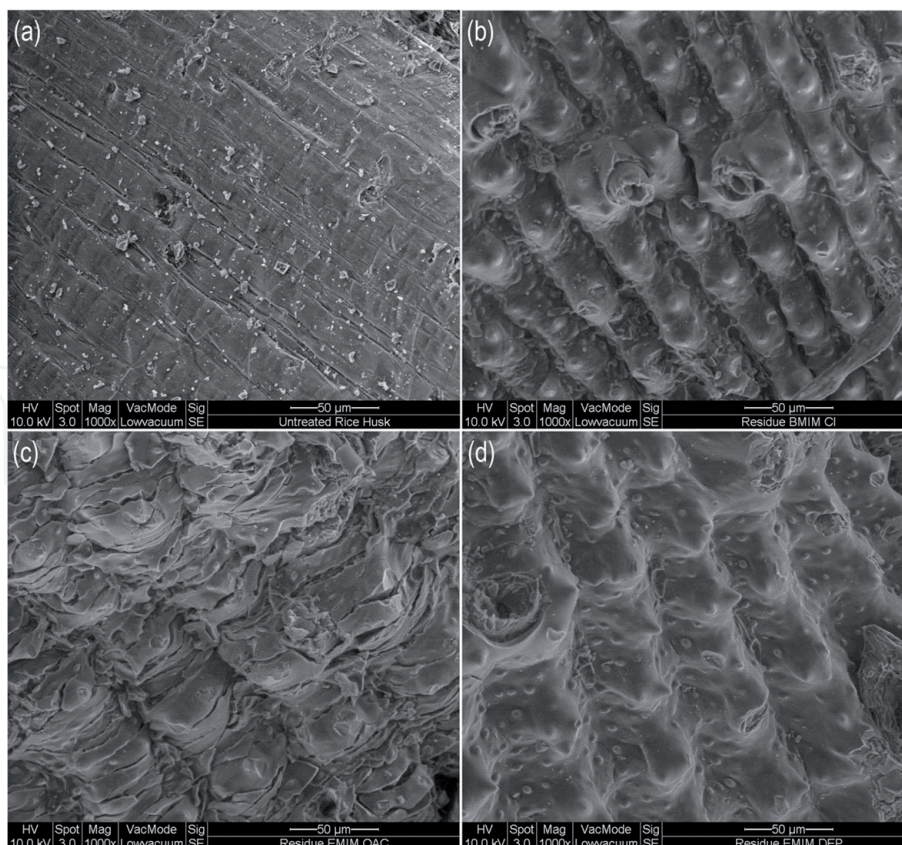


Figure 8. SEM images of (a) untreated rice husk and rice husk residues of (b) [BMIM]Cl, 1-butyl-3-methylimidazolium chloride; (c) [EMIM] OAc, 1-ethyl-3-methylimidazolium acetate; and (d) [EMIM] DEP, 1-ethyl-3-methylimidazolium diethyl phosphate pretreatments [34].

6.1.2.7 Fourier transform infrared (FTIR) spectroscopy

Fourier transform infrared spectra are noted with the assistance of a Perkin-Elmer FTIR spectrophotometer. Un-treated, alkali-treated, blanched, and acid-hydrolysed rice husk fibres models are examined. Models are excellently crushed and mixed with potassium bromide. The combination is then flattened to pellet form. FTIR spectral investigation is achieved inside the wave number range of $400\text{--}4000\text{ cm}^{-1}$ (**Figure 9**).

6.1.2.8 X-ray diffraction (XRD)

X-ray diffraction is applied to identify the crystallinity of rice husk grits after numerous extraction methods. Each sample/material in the arrangement of milled powder is set aside on the sample vessel and levelled to attain complete and unvarying X-ray exposure. The trials are examined with the assistance of an X-ray diffractometer at room temperature (RT) by means of a monochromatic $\text{CuK}\alpha$ energy source ($\lambda = 0.1539\text{ nm}$) in the step-scan approach with a 2θ angle extending from 10 to 50°C with a stage of 0.04 and scanning period of 5 minutes. To characterize the crystallinity of the several samples, the crystallinity index CrI, is created based on the mirrored intensity data (**Figure 10**).

6.1.2.9 Thermogravimetric analysis (TGA)

The thermal stability of the different samples is determined by TGA measurements performed using a Mettler Toledo thermogravimetric analyser. The quantity

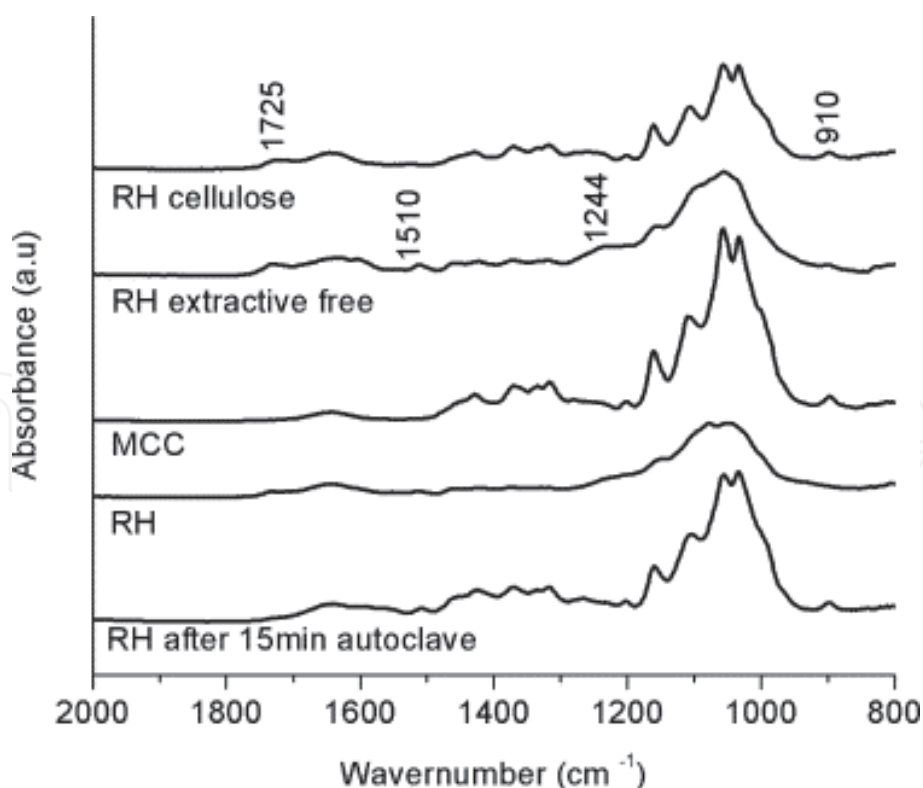


Figure 9.

FTIR spectra for RH (rice husk), RH extractive-free, alkaline treated RH (RH after 15 minutes autoclave), RH cellulose (after 30 minutes bleaching) and commercial microcrystalline cellulose (MCC) in the range from 2000 to 800 cm^{-1} [34].

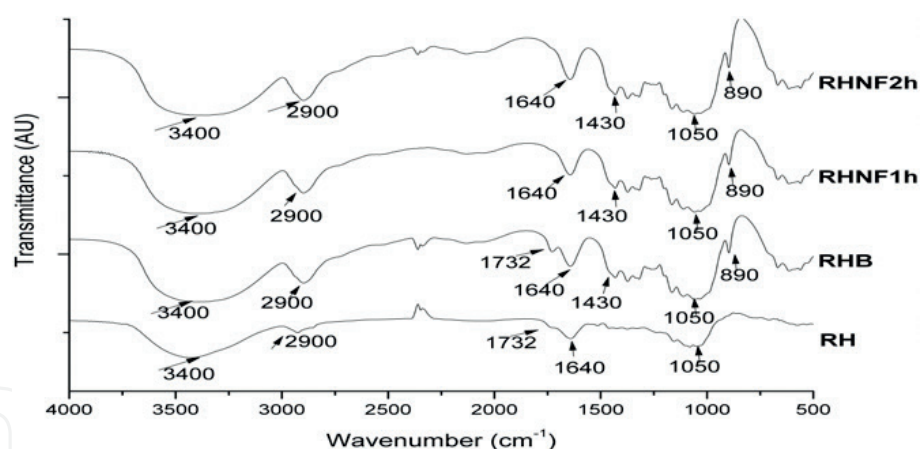


Figure 10.

X-ray diffractograms of rice husk (RH), bleached rice husk (RHB), rise husk nanofibrin after 1 and 2 hour of bleaching (RHNF1h and RHNF2h, respectively) [34].

of sample involved for individual measurement remained approximately 1 mg. Each measurement is achieved under a nitrogen based generated atmosphere through a gas flow of 10 mL min^{-1} by means of heating the substantial from room temperature to 900°C at a heating rate of 10°C min^{-1} [34].

7. Applications of cellulose

Cellulose is the most richly found organic polymer, as it is a major structural component of the primary cell wall of green plants, several algae and oomycetes. Cellulose is found in large quantities in frequently used materials like cotton (90%),

Wood (50%) and dried Hemp (57%). It has numerous applications in various fields, but it is most frequently used in the manufacturing of paper and cardboard or in derivative products like cellophane and rayon. It is also a major component of textiles made from cotton or linen. Further, its use is seen in the pharmaceutical industry as inactive fillers in drugs, in the form of powdered cellulose and micro-crystalline cellulose. However, one of the most important uses of cellulose is in the production of biofuel and in the food Industry. This will be elaborated further in the following sections [33].

7.1 Use of cellulose in renewable energy

7.1.1 Biofuel

A drastic increase in the population of the world coupled with an exponential increase in technological advancements and need of the people, fossil fuels are being rapidly depleted. At such an hour, the term sustainable development comes into play. In order to develop sustainably, it is important to switch to a fuel that is more clean, green and more cost-effective. One such alternative, is cellulose derived biofuel. There are numerous advantages of using biofuel, the first and foremost being cost-effective. Recent studies have shown that due to increase in demand, the cost of biofuel is decreasing as ethanol costs lesser than petrol and diesel. Further, there is a significant reduction in the carbon emission. The raw material used for biofuel is simply a substrate that has cellulose in it. Since cellulose is so widely abundant, the cost is significantly lower.

The ethanol obtained from cellulose is used as an alternative substrate in the production of biofuel. It is considered a superior source due to its high energy efficiency and low cost as compared to other sources. This is a very good source for renewable energy as it is found most abundantly in stalks, leaves and stem of green plants. Other sources for ethanol include, feedstocks, including wheat straw, rice straw, sawdust, forest thinning and grasses perennial grasses and switch-grass. Cellulose can be broken down into fermentable sugars by using the fungus *Trichoderma reesei* or by using acid to convert them first into sugars and then into gas. The gut of termites also can be utilized for this purpose. Further, a group of bacteria collectively referred to as methanogens have the ability to digest cellulose and produce carbon di oxide and methane, which is further processed. One group of such bacteria called methanobacteria grow anaerobically on cellulosic matter and degrade it to produce methane. They are also found in the rumen of cattle and the dung of cattle. As is seen from this, it is quite easy to obtain a substrate for biogas production especially by using waste cellulosic material. Therefore, it is important that to utilize even the apparent waste material to ensure a reduction in wastage and optimum usage of its potential [34, 35].

7.2 Use of cellulose in consumables

Cellulose has numerous applications in the field of pharmaceuticals and food technology. Modifying the structure of cellulose with other chemical groups results in the production of structures that have better bio-compatibility, flexibility, stability, emulsifying effects. Further, cellulose being indigestible by human beings, tend to have zero calorific value and can thus have been added in food to serve several purposes. Compounds like HPMC, sodium carboxymethyl cellulose, hydroxyethyl cellulose and others are commonly utilized in the pharmaceutical industry and food technology industry. Some of these uses are enumerated below:

7.2.1 *Hydroxypropyl methylcellulose*

HPMC is widely utilized in the pharmaceutical industry not only because it is safe and nontoxic but also because it does not get engrossed orally and does not upsurge the energy of foods. It is utilized as a film-forming agent, thickener, blocker, sustained-release agent, blending agent and suspending agent in many dosage forms, thus forming the numerous pharmaceutical preparation consistently discrete, tough short of being wrecked due to sustained release effects or steady emulsion without stratification. It is regularly used as a matrix, adhesives, frame ingredients, the film creating material or in the creation of sustained or controlled release microcapsules and pellets [36].

7.2.2 *Sodium carboxymethyl cellulose*

It used as an emulsion stabilizer in injections, adhesion and film-forming materials which have proved to be effective in controlling wound infections and can reduce postoperative oedema and wound stimulation phenomena. Animal experiments have shown that sodium carboxymethyl cellulose is a safe and reliable carrier of anticancer drugs [37].

7.2.3 *Hydroxyethyl cellulose*

In ice cream, frozen milk drinks, it is added as a stabilizer to extend the storage life and improve the overflow property. It is also used as the stabilizer of beer foam.

7.2.4 *Food*

Due to its unique physical and chemical properties and its behaviour in water, it is today being increasingly used a food additive to improve the bulk and fibre content of foods without having a major impact on the flavour of the food. Since it is indigestible by humans, it has no caloric value and is thus used in excessive amounts in diet foods to create a sensation of fullness both physical and physiology without having consumed too many calories. It is also widely used an emulsifier and a thickening agent in whipped cream, sauces and ice cream [38].

7.3 **Biomedical and pharmaceutical applications of cellulose**

Cellulose, with its properties, as discussed in previous sections of this manuscript, is extensively used in the field of biomedicine and pharmaceuticals. The cost of several pharmaceutical products is extremely high due to production factors such as high cost, difficulty in procuring the material, complicated processing steps etc. These problems can be remedied by the use of cellulose, which is found abundantly in nature. The most productive use of cellulose would be the utilization of plant based waste materials which are produced in bulk by many industries such as the sugar production industry as well as in minor quantities by households. The applications highlighted below could be brought to mainstream commercial use with the appropriate optimization techniques and novel modifications to the various steps of the production and processing of cellulosic material.

7.3.1 *Cellulose in coating of solid dosage forms and compressibility enhancers*

Solid dosage forms including pills, tablets, granules, pellets, microcapsules and spherules can be coated, usually with the aim to protect the drug from adverse environmental factors such as humidity, oxygen, enzymatic or acidic degradation.

Coating may also be used to facilitate drug delivery systems with altered release mechanisms such as delayed release, extended release, step-by-step release, pulsatile release and sustained release. Derivatives of cellulose such as esters and ethers are also extensively used as coating materials. In the process of solid dosage form manufacture by direct compression, a problem that frequently occurs is low compactability of the drug, this is more seen more frequently when the amount of drug in the formulation exceeds 30%. Many attempts are being made to reduce the price of the final product by experimenting with various starting materials and test conditions [39].

7.3.2 Cellulose in drug delivery

From the advent of novel drug delivery systems, cellulose based models seemed like strong candidates due to their projected benefits. Since then various advances have been made with the aim to bring its use to common practice. There are still many hurdles to cross before this becomes a reality. Cellulose based drug delivery is an important step in green and sustainable pharmacy which focuses on toxicity reduction, biodegradability and less hazardous synthesis with respect to drugs and drug delivery systems. A very brief overview of the primary ways in which it is used is provided here. Cellulose nanocrystals (CNCs) have the potential to acquire a negative charge during hydrolysis. This coupled with their large surface area allow them to bind ionizable drugs such as tetracycline and doxorubicin permitting optimum dosing control. Sites for surface modification for multiple chemicals are provided by the multitude of surface hydroxyl groups. This is used in case of non-ionized or hydrophobic drugs which do not generally bind to cellulose. The open pore structure and high surface area of CNC based aerogels provide increased drug loading capacity and drug bioavailability. Extremely porous aerogel scaffolds were reported to attain sustained drug release [40].

Cellulose derivatives have also been researched in terms of drug delivery. For instance, cellulose acetate has been successfully used in several HIV drugs, five flavonoids, one pain reliever and two antibiotics among others. Hydroxypropyl methylcellulose has been used in oral drug delivery formulations [41].

7.3.3 Cellulose in scaffolding

Scaffolds are materials that have been engineered to cause desirable cellular interactions to contribute to the formation of new functional tissues for medical purposes by providing the microenvironment required by cells to proliferate, migrate and differentiate. It contributes the geometrical basis and building blocks to provide cell attachment. *Gluconacetobacter xylinus* sourced nanocellulose is an emerging biomaterial for this purpose. Bacterial nanocellulose has a very high affinity for water and therefore displays properties similar to those of hydrogels which provides an ideal environment to host cells. Studies have confirmed that human smooth muscle cells, bone forming osteoblasts and fibroblasts and human embryonic kidney cells can grow in the presence of bacterial cellulose scaffolds. The main challenge in the production of these scaffolds seems to be biodegradability as the cellulose, the enzyme required to breakdown cellulose is not present in humans. This property was reported to be enhanced by periodate oxidation [42].

7.3.4 Cellulose in biomedical implants

BNC is specifically nondegradable under physiological conditions and has been shown to be biocompatible. These properties further impart durable mechanical properties and long-term chemical stability which make it an exciting candidate for application in this field:

- **Cardiovascular implants:** Bacterial cellulose has an important application in artificial blood vessels. Compared to the material generally used for vascular grafts, these materials show less thrombosis and occlusion. Heparin hybridized bacterial nanocellulose scaffolds with anticoagulant properties have potential use in vascular tissue engineering. Potential use of BC in the production of heart valve replacements has been explored [43, 44].
- **Bone and connective tissue repair:** Nanocellulose are promising materials for the culture of various cells including osteoblasts and chondroblasts indicating that they have potential for bone tissue regeneration and healing. A membrane of BC and hydroxyapatite was developed as biomaterial for potential bone regeneration, which delivered prone growth of osteoblast cells, high level of alkaline phosphatase activity and greater bone nodule formation. It was also found that HAp crystals are partially substituted with carbonate resembling natural bones [45–47].

8. Conclusion

From the chapter we can conclude that cellulose is a highly versatile polymer which is easy to manufacture and extract. Its application in multiple fields has been discussed above. With increasing population, demand and technological innovations, renewable energy is gradually becoming imperative aspect of resource conservation and overall environmental health. Although various other polymers can be utilized for consumables, biomedical and pharmaceutical applications, the marked advantage of cellulose is that it is a biodegradable and environmentally friendly material. The intensive research on the chemistry of the compound, has resulted in the production of a wide variety of biodegradable products with a plethora of applications. An improved information of the many structural levels in which cellulose partakes will allow us to understand better practise of this exceptional and metastable molecular assembly produced by plant metabolic pathways. We have placed emphasis on the diverse applications of cellulose to promote more innovations that aim to bridge the gap between the amounts of cellulosic waste and its optimum utilization. Large amounts of cellulose based wastes are produced in every community across the world, which remain a largely untapped resource. Research that involves the conversion of this perceived waste into a widely used commodity would have the dual benefit of organic waste management and sustainable innovations.

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List of abbreviations

DP	degree of polymerization
NMR	nuclear magnetic resonance
HS	Hestrin-Schramm
CMC	carboxymethyl cellulose
PKC	palm kernel cake
EC	ethylcellulose
HPC	hydroxypropyl cellulose
MCC	microcrystalline cellulose
TGA	thermogravimetric analysis
FTIR	Fourier transform infrared spectroscopy
XRD	X-ray diffraction
DSC	differential scanning calorimetry
SEM	scanning electron microscopy
SCB	sugarcane bagasse
GBF	green bamboo fibre
DBF	dewaxed bamboo fibre
DI	deionized
DLBF	delignified bamboo fibre
AmimCl	1-allyl-3-methylimidazolium chloride
IL	ionic liquid
DMSO	dimethyl sulfoxide
BJH	Barrett-Joyner-Halenda analysis
DTG	derivative thermogravimetric
CNC	cellulose nanocrystal
HIV	human immunodeficiency virus
ER	extended release
BNC	bacterial nanocellulose
BC	bacterial cellulose
HAp	hydroxyapatite
GTR	guided tissue regeneration

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