

Differentiation and Synonyms Standardization of Amorphous and Crystalline Cellulosic Products

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Abstract Different kinds of angstrometric- up to macrometric-scaled constructions can be synthesized from cellulose due to its hierarchical and multi-level organization. There are many commercial products can be obtained from cellulosic resources. Each cellulosic product may be known by several synonyms. Some of these synonyms may not define accurately such product. Accordingly, synonyms standardization is an urgent task to clear things up. We suggested dividing cellulosic products into seven scale categories based on their dimensional scale of their 3-D configurations, namely angstrometric, angstrometric/macrometric, nanometric, nanometric/macrometric, nanometric/micrometric, micrometric, and macrometric-scaled products. To distinctly differentiate the cellulosic products, they were classified based on their dimensions and aspect ratios and were distributed among the seven scale categories. Standardized synonyms of the commercial cellulosic products were suggested. In addition, an identification card (IC) of the cellulosic products was designed.

Keywords: *alpha cellulose, microcrystalline cellulose, nanocrystalline cellulose, nanofibrillated cellulose*

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1. Introduction

Cellulose is the most abundant renewable organic compound on Earth. The cell wall of higher plants consists of a mixture of polysaccharides, namely cellulose, hemicelluloses, lignin and pectin [1] and can be differentiated into primary and secondary walls. The differences between primary and secondary cell walls in chemical composition and structure are responsible for the biodiversity in the plant kingdom [2]. As seen from Table 1, the holocelluloses are the carbohydrates or polysaccharides found in a typical wood species and they are the total allocations of alpha cellulose and hemicelluloses together. Each of alpha cellulose, hemicelluloses, and lignin constitutes about 40-50%, 20-35%, and 15-35% of the total dry mass of wood, respectively (Table 1). Accordingly, alpha cellulose may constitutes about half of an oven-dried wood mass.

2. Angstrometric-Scaled Structure of Cellulose

2.1. Alpha, Beta-Glucose and Cellobiose

A single glucose unit (Figure 1a) is a hexose that takes on one of two forms, namely α -glucose (Figure 1b and Figure 2) or β -glucose (Figure 1c and Figure 2), depending on the position of the hydroxyl groups. Each

two glucose units are combined together to give one cellobiose unit as shown in Figure 1d [4].

When glucose is dissolved in water, the functional group grafted on its carbon atom (C_1) are encountering an internal arrangement to form one ring structure (α -glucose or β -glucose (Figure 2). The chemical mechanism of this transformation can be illustrated based on the higher electronegativity feature of the oxygen atom found on C_1 that attracts the electrons constituting the $-C=O$ bond. Accordingly, a partially negative charge is accumulated on the oxygen atom (O_1), while a partially positive charge is arisen on the C_1 . Due to the temporary unbalance in this region, the O_1 atom breaks its π -bond and borrow a proton from its aqueous solution to form a hydroxyl group which determines the type of glucose else α or β .

Table 1. Chemical components¹ of cell wall substance of a normal wood

Chemical component			Allocation %
Primary components	Polysaccharides (holocellulose)	Alpha cellulose	40-50
		Hemicelluloses	20-35
	Non-carbohydrates	Lignin	15-35
Secondary components	Tannins		10-15
	Volatile oils and resins		
	Gums-latex-alkaloids-dyes...etc		
	Ash or minerals		Usually <1%

¹ From Panshin and de Zeeuw [3].

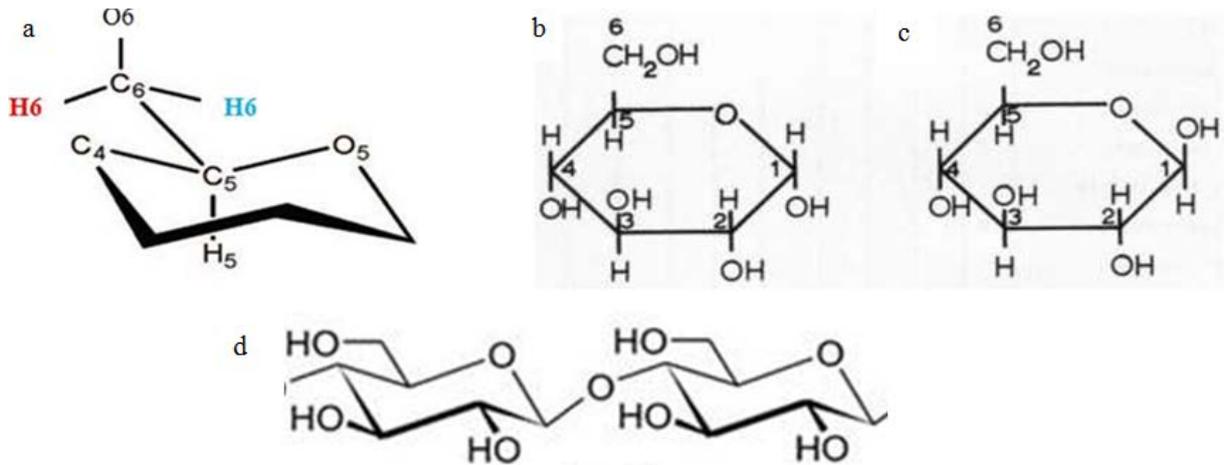


Figure 1. Angstromic-scaled structure of cellulose: a) A glucopyranose unit, b) Alpha glucose, c) Beta glucose, and A cellobiose unit

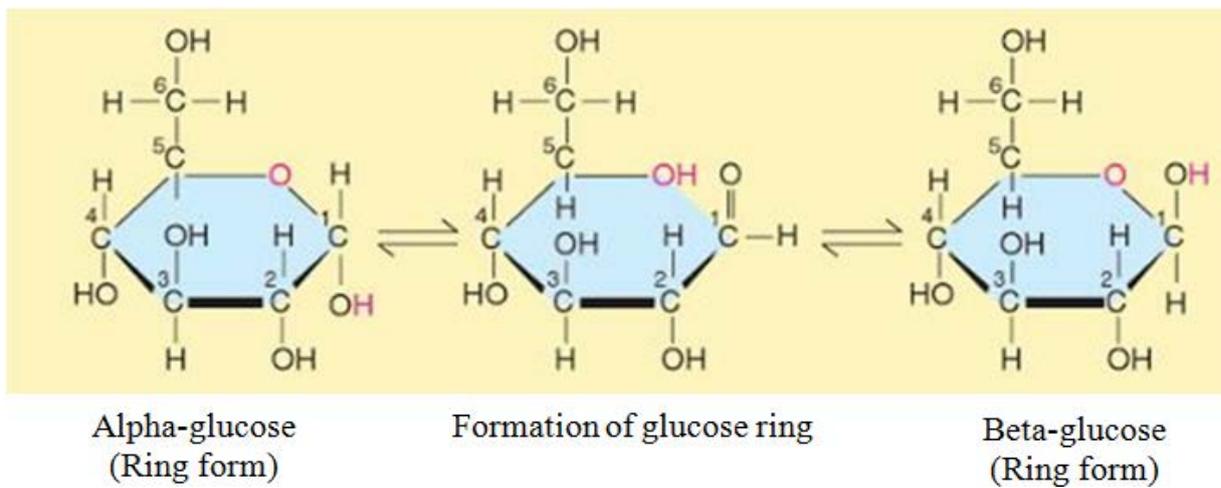


Figure 2. Formation of glucose ring in an aqueous solution [5]

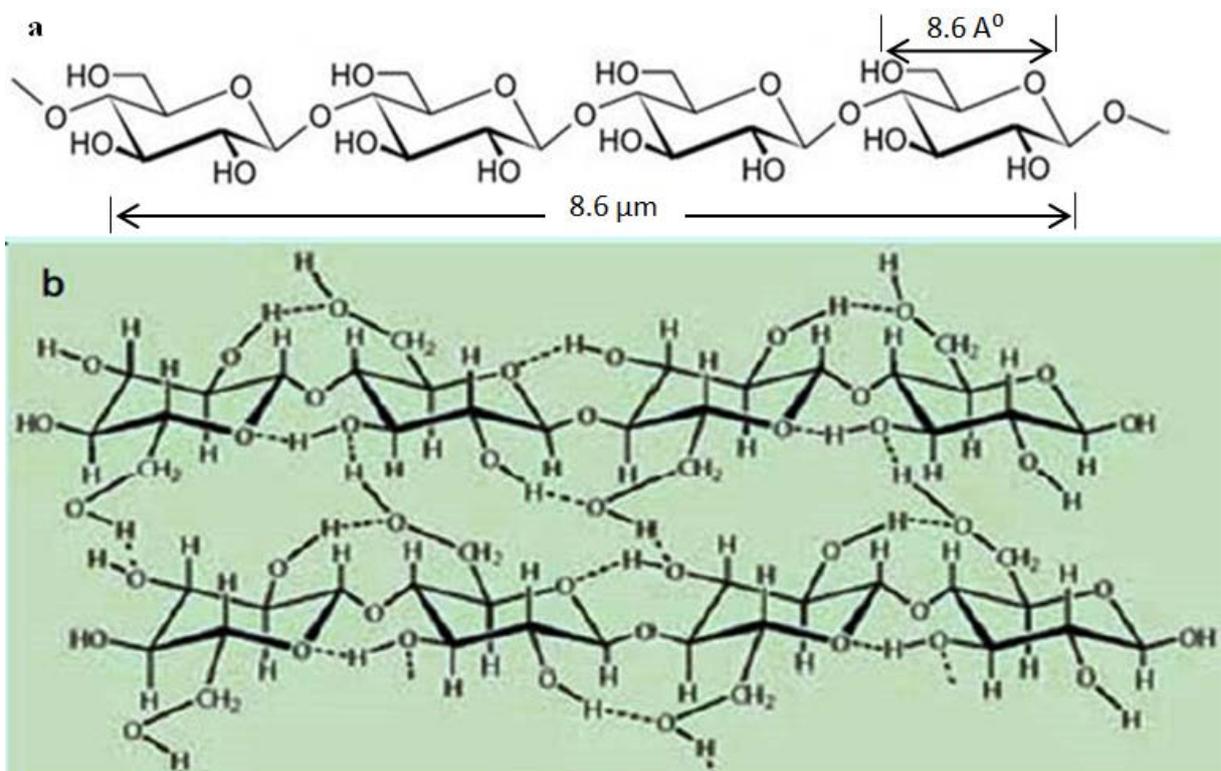


Figure 3. Schematic representative of cellulose: a) Glucan chain, and b) Two glucan chains conjugated by hydrogen bonding network [1]

2.2. Micro-/Angstrometric-Scaled Structure of Cellulose

2.2.1. Alpha Cellulose

The cellulosic chain termed as glucan chain is composed of poly 1 \rightarrow 4- β -D-glucopyranose [6] with a chemical formula of $(C_6H_{11}O_5)_n$. The width or diameter of a glucopyranose unit was estimated to be about 8.6 Å. Supposing that these units are polymerized up to 10,000 units, by multiplying the value of 8.6 Å \times 10,000, the glucan chain length will reach up to 8.6 μ m (Figure 3a). Accordingly, the width of the cellulose chain (Figure 3) lies within the angstrometric scale, while its length corresponds to the micrometric scale. Consequently, cellulose chain is assigned at the dimensional scale of micro-/angstrometric category.

2.2.2. Cellulose Allomorphs (Polymorphs): Celluloses I $_{\alpha}$, I $_{\beta}$, II, III $_I$, III $_{II}$, IV $_I$ and IV $_{II}$

There are seven polymorphs of cellulose, namely I $_{\alpha}$, I $_{\beta}$, II, III $_I$, III $_{II}$, IV $_I$ and IV $_{II}$ [7]. Native cellulose is the crystalline cellulose termed as cellulose I, while cellulose II refers to regenerated cellulose [7,8]. The cellulose I $_{\alpha}$ is dominant in algal, bacterial and tunicates, while both I $_{\alpha}$ and I $_{\beta}$ may present in higher plants. The I $_{\alpha}$ and I $_{\beta}$ are similar in their chains structure but they are different in their internal hydrogen bonding system [7,9] as shown in Figure 3b. The crystalline structure of cellulose I is made up of parallel chains [10,11], whereas that for cellulose II is antiparallel [10,12]. Cellulose II has additional hydrogen bonds per glucopyranose unit comparing to cellulose I that makes it is more thermodynamically stable [11].

Each of cellulose-I or II may be converted into the cellulose-III when treated with ammonia or various amine compounds [7]. At these conditions, cellulose-III $_I$ and III $_{II}$ can be produced irreversibly from their precursors (cellulose I and II, respectively). In addition, both cellulosic polymorphs of III $_I$ and III $_{II}$ can be reverted to their precursors at higher temperatures and humidity. The allomorphs IV $_I$ and IV $_{II}$ can be produced irreversibly by heating cellulose-III $_I$ or III $_{II}$, respectively up to 260°C in glycerol. Both cellulose-I and IV exist in several plant primary cell walls, while cellulose-II and III can be only produced artificially [7].

2.2.3. Alpha, Beta, and Gamma Celluloses

Alpha-cellulose is the pulp fraction that is resistant to 17.5% and 9.45% sodium hydroxide solution under conditions of the test. Beta-cellulose is the soluble fraction which is reprecipitated when acidifying the solution, while gamma-cellulose is the fraction that remaining in the solution after the above-mentioned circumstances [13].

The DP of cellulose is the number of β -D-glucopyranose monomers conjugated longitudinally along the cellulose chain axe. Cellulose precursors have different DPs according to their sources, delignification process, and their isolation scheme. DP values differed from 100 to 3000 or higher for commercial celluloses up to 20,000 for cotton fiber and is extended to reach about 44,000 for *Valonia* algae. Native cellulose generally has higher DP values than both regenerated cellulose and cellulosic pulp.

Two techniques are commonly used to measure the DP of cellulose, namely viscometry and gel permeation chromatography (GPC) methods. Since cellulose is insoluble in all known traditional solvents due to its high molecular weight, intra- and inter-molecular hydrogen bonding, and its high crystallinity, it is dissolved in metal complex solutions or forming cellulose derivatives by nitration or tricarbanilation [14]. In addition, light scattering techniques are usually performed to determine absolute molecular weight of cellulose and subsequently DP estimation. For example, size exclusion chromatography (SEC) coupled with a multi- angle laser light scattering is used for the light scattering determination [14].

To differentiate between cellulose and hemicellulose, it is worth mentioning that hemicelluloses are the second primary components in plant cell walls. It is consisted of simple sugar monomers (glucose, galactose, mannose, xylose, arabinose and glucuronic acid). It has β -(1 \rightarrow 4)-linkages that link his monomers into a backbone in an equatorial configuration. Hemicelluloses are found in different compounds such as xylans, glucomannans, xyloglucans, mannans and beta-(1 \rightarrow 3,1 \rightarrow 4)-glucans. In nature, the structure of hemicelluloses differed widely according to species and cell types. Its interaction with the other biopolymers present in plant cell wall is an important biological task in forming the cross-links between cellulosic microfibrils [15]. Comparison to cellulose that is crystalline, strong, and resistant to hydrolysis, hemicellulose has a random and amorphous that makes it easily to be hydrolyzed by diluted acids and hemicellulase enzymes [1].

2.3. Nano-scaled Products

The nanometer range covers sizes bigger than several atoms and smaller than the wavelength range of visible light [16]. While the small fibrils isolated from natural fibers normally have a wide range of diameters, most of them are below 100 nm and the other are above this scale [17].

We have been noticing that many synonyms are referred to as nanocellulose (NC) in which we have a confusing with them such as nanocrystalline cellulose (NCC), cellulose nanocrystals (CNC), cellulose whiskers, cellulose nanowhiskers, nanofibrillated cellulose (NFC), cellulose nanofibrils (CNF), microfibrillated cellulose (MFC), carboxy-methylated cellulose (CMC), microcrystalline cellulose (MCC), cellulose microcrystals (CMC) and cellulose filaments, CF [18] ...etc.

By definition, nanocellulose is a nano-scale that having at least one dimension less than 100 nanometers in size. Two materials fit this definition: 1) cellulose nanocrystals (CNC), sometimes called nanocrystalline cellulose (NCC) or cellulose whiskers, and 2) cellulose nanofibrils (CNF), sometimes called nanofibrillated cellulose (NFC). The nanocellulose (NC) is a collective name for all types of nanocellulose and used for this material the last 7 years. The NC is derived from native cellulose and contains only crystalline regions [19].

Some of the materials in our alphabet soup are referred to as NC, but their sizes are not in the nanometric scale. A number of these micro-scale materials (e.g. microfibrillated cellulose and cellulose filaments) are often mentioned in

conjunction with nanocellulose, and are being offered for some of the same applications as CNC and CNF although they don't belong to the nanometric scale [18]. Nanofibrillated cellulose (NFC) is a new name started to be used 5-6 years ago, while cellulose nanofibrils (CNF) has been around for over 15 years, but poorly used [20].

Cellulosic colloidal nanorods or nanocrystals is another synonym for nanocrystalline cellulosic particles with length differed from 185 nm to 4 μm . They were synthesized from the hydrolysis of cellulose microfibrils (CMF) of cotton (CCN), bacterial cellulose (BCN) and Cladophora (ClacN) leading to aspect ratios differed from 13 to 160 [21].

2.3.1. Crystalline and Amorphous Cellulose

Spectroscopic investigation by Fourier transform infrared spectroscopy (FTIR) and x-ray diffraction (XRD) have confirmed consequence of crystalline and amorphous regions of the microfibrils [8]. The amorphous regions are randomly oriented constructions (spaghetti-like arrangements) with lower density compared to crystalline regions [12,22] as shown in Figure 4. Accordingly, the amorphous regions are susceptible to acid attack and may be eliminated leaving crystalline regions intact [19,22]. Most cellulosic materials is consisted of crystalline and amorphous regions, in different allocations, depending on their precursors. The physicochemical properties of cellulose are strongly influenced by the organization manner of the cellulose molecules. Most of the chemical reagents can penetrate only the amorphous regions and can react with the surface of the crystallites. The behavior of both regions has been extensively studied in view of the micro and macro as affected by thermal, hydrothermal and chemical treatments [23,24,25,26].

Due to the hierarchical and multi-level organization of cellulose, different types of nanoscaled cellulosic products can be obtained by hydrolyzing it [27]. The glucan chains are aggregated to form fibrils which are laterally stabilized by intermolecular hydrogen bonds [19,28]. Cellulose chains are arranged in a parallel manner and are organized in sheets stabilized by interchain hydrogen bonds, whereas the stacking of sheets is stabilized by both van der Waals dispersion forces and weak CH-O hydrogen bonds [29]. Accordingly, there are basically two families of nanosized cellulosic particles. The first one consists of cellulose nanocrystals and the second one is microfibrillated cellulose, MFC [29,30].

2.3.2. Cellulose Nano-Fibers (CNFs)

The CNF is also termed as nanofibrillated cellulose. It is a material containing fibrils with length in the micrometer scale and width in the nanometric range forming a network structure [31]. It contains both amorphous and crystalline cellulosic regions [32]. The

CNF can be prepared by mechanical methods using high pressure homogenizers, refiners, grinders, cryo-crushers, or microfluidizer [31] and sonication [33]. NFC can be produced from: a) cellulose I obtained from wood fibers, cotton floss, and agricultural residues, and b) cellulose II such as lyocell fibers using grinding, high pressure homogenization. Furthermore, NFC has a high aspect ratio in which the width is ranged from 10 to 100 nm, while its length extends up to tens of microns [33]. In addition, Chakraborty *et al.* [34] indicated that nanofibrils have at least one-dimensional at the nanometer scale (1-100 nm). The lengths of the CNC or nanowhiskers are shorter (100 to 1000 nm) than that for the cellulose nanofibrils (CNF) obtained through homogenization, microfluidization or grinding routes [35].

One of the important differences between NFC and CNC is that the former is produced by mechanical isolation processes, whereas the later is produced by acid or enzymatic hydrolysis. In addition, NFC contains both amorphous and crystalline regions with high aspect ratio. 4 to 20 nm in width, 500 to 2000 nm in length [36].

The CNF can be used as a replacement for conventional reinforcements such as glass fibers or inorganic fillers in composite products. The CNFs were used for reinforcing polyvinyl alcohol (PVA) matrix. The mechanical properties of the resulted composites were significantly influenced by the morphological features of these nanofibers [28].

2.3.3. Cellulose Nanocrystals (CNCs)

The CNCs (Figure 5a-c) constitute a renewable nanosized raw material with a vast range of uses in cosmetics and medical devices. Furthermore, the CNCs can be used as fillers to improve mechanical and barrier properties of biocomposites [27].

The CNCs are produced by the acid hydrolysis that degrades the amorphous regions of cellulosic microfibrils found in cellulose-rich sources such as wood, microcrystalline cellulose, bacterial cellulose, algal cellulose termed as valonia, hemp, tunicin, cotton, ramie, sisal, date palm leaflets, seed floss of *Calotropis procera*, and sugar beet yielding highly crystalline nanoparticles.

The CNCs has an amazing property known as self-organization into a chiral nematic (cholesteric) liquid crystal phase with a helical arrangement. This wonderful character gives dried CNC film a photonic band gap in which it can be used for security papers and mirrorless lasing [38] and liquid crystal displays (LCDs and LEDs). Geometrical characteristics of the CNCs such as size, dimensions and shape depend on the nature of the cellulose precursors as well as the hydrolysis conditions such as time, temperature, ultrasound treatment, and purity of materials [29,39,40]. Above a critical concentration, the rod-like shape of the charged CNCs forms an anisotropic liquid crystalline phase [37,39].

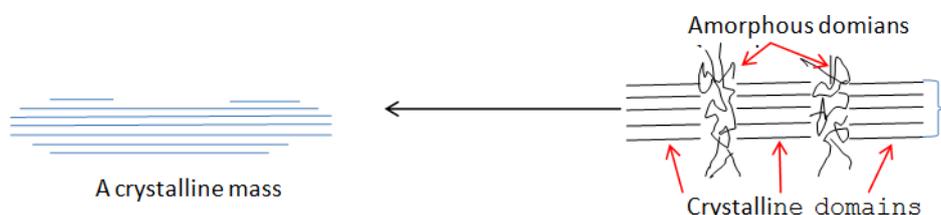


Figure 4. A schematic representative of the sulphuric acid-hydrolysis of cellulose

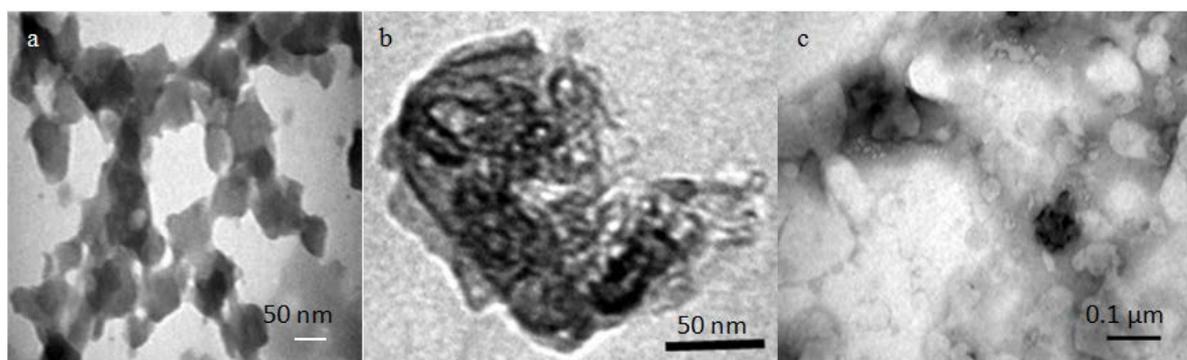


Figure 5. TEM micrographs of cellulose nanocrystals spherulites: a, b) In nanometric scale, and c) In micrometric scale as aggregated in bigger architectures, from Hindi [38]

Two different types of nanocellulose, cellulose nanocrystals (CNC) and cellulose nanofibrils (CNF), were isolated from cellulose of the seed floss of *Calotropis procera* using acid hydrolysis and TEMPO-mediated oxidation methods, respectively [41]. The CNC isolated from *Calotropis procera* showed needle shape with diameter of 14–24 nm and length of 140–260 nm, while the CNF exhibited web-like long fibrous structure with the diameter of 10–20 nm [41] as shown in Table 2. Furthermore, the crystallinity indices of CNC and CNF were 0.70 % and 0.59 %, respectively, and the onset temperature of thermal decomposition was 240 and 200 °C, respectively [41].

The Young's modulus of a pure CNCs ranged between 100 and 160 GPa [42]. Furthermore, when CNCs are assembled in a multiscale material, as in CNF, CNF-bundles or larger CNF-based structures, such high values of the Young's modulus can only be approached by careful control of orientation or alignment [43].

2.3.4. Cellulose Nanowhiskers

The nanowhiskers typically have a width of 2 to 20 nm and a length ranged between 100 to 600 nm [40,42]. Pan *et al.* [44] synthesized cellulose nanowhiskers (CNW) in the form of needle- or short rod-like nanoparticles with length of 199–344 nm and diameter of 11–33 nm. Furthermore, it was indicated using Fourier transform infrared spectroscopy (FTIR) and x-ray photoelectron spectroscopy (XPS), that some intramolecular hydrogen bonds and glycosidic linkages were destroyed due to hydrolysis of the cellulosic precursor used (microcrystalline cellulose). In addition, increasing the acid concentration from 20 to 60 wt % accelerated the breakages within the cellulosic molecules precursor, leading to narrower, less polydispersed nanoparticles accompanied with lower crystallinity index [44].

2.4. Micro-Nano-Scaled Products

2.4.1. Cellulose Micro/Nano Fibers (CMNF)

The CMNF is also known as micro/nanofibrils (MNF) and can be obtained by either chemical or mechanical process. The chemical method is done by strong acid hydrolysis which removes the amorphous regions of cellulose fiber. In addition, the mechanical method includes a high pressure refiner or a super grinder treatment [45], a microfluidizer [46], and a high-pressure homogenizer treatment [45,47]. As a reinforcing material for composites, the CMNF is becoming more and more

attractive for composite science because of its potential lightweight and high strength. The geometrical characteristics of the CMNF were investigated using optical microscopy and scanning electron microscopy (SEM), and their crystalline structure was investigated by wide angle X-ray diffraction (WAXD). Their mechanical properties were evaluated by tensile strength test and their morphological characteristics of the fracture cross sections were investigated with SEM [17].

The MNF isolated from natural fibers have higher mechanical properties, so that much attention have been paid in the past two decades to study its synthesis procedure and doping them with other polymers into nanocomposites [48].

2.4.2. Elementary Microfibril (Micelle)

Several cellulose chains can be arranged along their longitudinal axis to form crystalline regions called micelles or elementary fibrils. In addition, less ordered cellulose chains lie between micelles and around them to form paracrystalline regions. The single micelle can be constituted of about 100 cellulose chains. The diameter of a micelle is about 5 μm. Several micelles can assemble to form microfibrils whose diameter can range up to 30 μm.

2.5. Micrometric-Scaled Structure of Cellulose

2.5.1. Microfibrils

Upon wood formation, cellulosic microfibrils or so-called microfibrils are precipitated in the secondary cell wall into three consecutive layers (S_1 , S_2 , S_3). Within each layer, the cellulose microfibrils are highly ordered and parallel, while the microfibril angle is oriented differently from one layer to another [49,50]. The microfibril has a diameter of 0.1–1 μm and a length ranged from 5 to 50 μm [35], while nanofibrils (NFs) have at least one-dimensional at the nanometer scale (1–100 nm). While the small fibrils isolated from natural fibers normally have a wide range of diameters in which most of them are below 100 nm and the other are above 0.1 μm [51].

2.5.2. Microcrystalline Cellulose (MCC)

Microcrystalline cellulose (MCC) or so-called cellulose microcrystals (CMC) shown in Figure 6 can be synthesized using different procedures such as reactive extrusion-, enzyme mediated- [52], the steam explosion- and acid hydrolysis processes [53,54]. The acid hydrolysis

process is preferred due to its shorter reaction duration comparing to the other processes. Furthermore, it can be applied by a continuous process rather than a batch-type process and it uses limited quantity of acid and produces finer particles of the MCC [55]. The MCC can be obtained

commercially from wood as well as non-woody lignocellulosic materials.

Nine MCC products differing in their particle size can be separated from the crude MCC powder by standard sieves (Table 2).

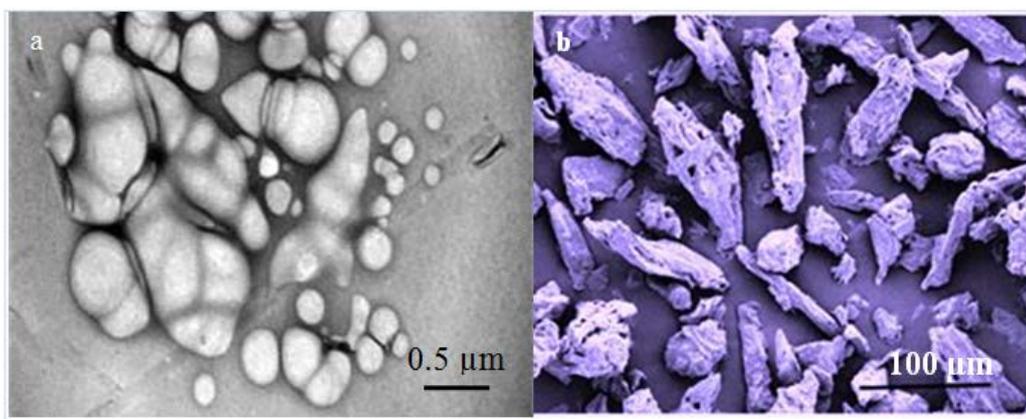


Figure 6. TEM micrograph of oven-dried SCNCs: single, di- and multi-spherulites and CNCs-spherulites once liberated from their parent microfibrils

Table 2. Models of microcrystalline cellulose (MCC) based on their particle size

MCC Type	Particle Size (micron)	Utilization
PH 101	50	For pharmaceutical utilizations such as a tableting agent by direct compression tableting, wet granulation, spheronization and capsule filling.
PH 102	100	Like PH-101 but with higher flow capability due to its larger particle size.
PH 103 PH-113	50	For moisture sensitive pharmaceutical active ingredients due to its lower moisture content (3%).
PH 105	>50	The most compressible MCC type for direct compression due to it has the smallest particle size.
PH 112	100	For moisture sensitive pharmaceutical ingredients.
PH 200	180	For reducing weight variation and enhancing uniformity in pharmaceutical formulations due its large particle size.
PH 301	50	Useful for making smaller tablets and in capsule filling excipient.
PH 302	90	

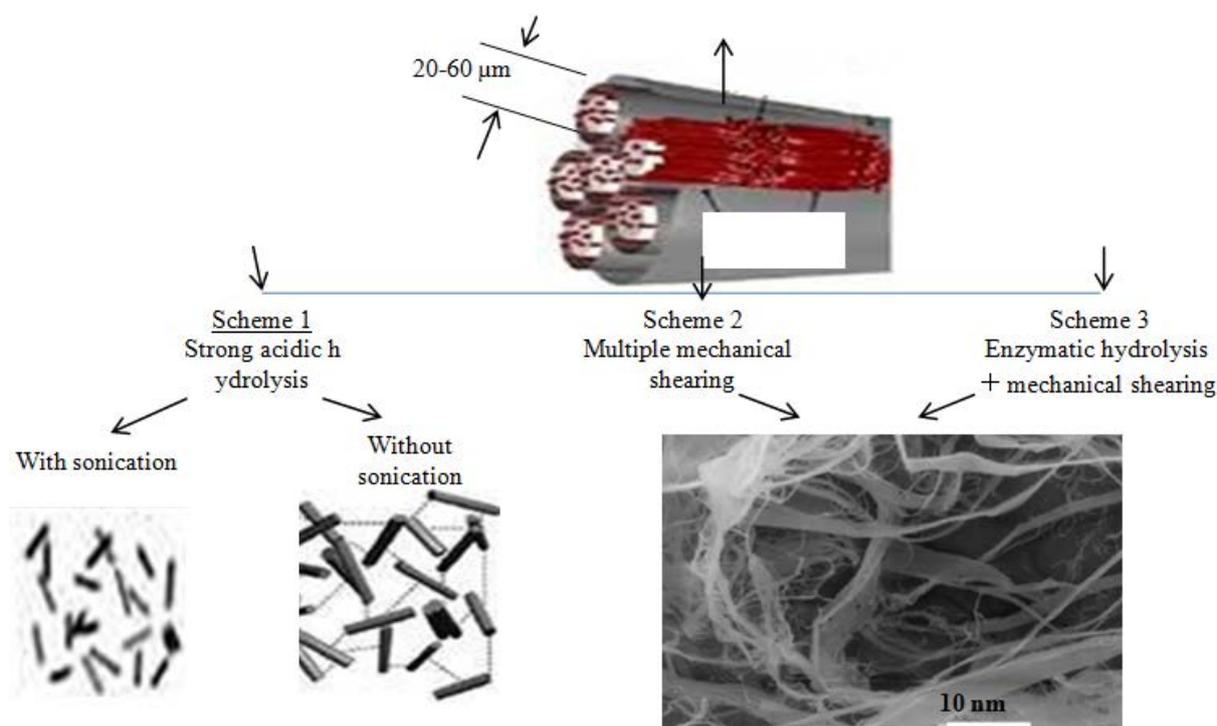


Figure 7. Schematic representative of synthesis schemes of: a) Whiskers, and b) Microcrystalline fibril bundles, from Paakko *et al.* [57] and c) Microfibrillated cellulose, from Nakagaito and Yano [48]

2.5.3. Microfibrillated Cellulose (MFC) or Microfibrillar Cellulose

Microfibrillated cellulose is the original name since the 1980's. The MFC is cellulose in which the outer layer of the fibers is peeled and stripped away by mechanical shearing. The resultant MFC has a web-like structure and are thinner than the parent precursor.

There are many procedures for production of the MFC (Figure 7), namely electro-spinning, bacterial, non-wood, high shear, grinding and a combination of enzyme hydrolysis, shear and homogenization. Homogenization is widely used as a single production technique. The MFCs are used in foods, cosmetics, paints, paper, nonwoven textiles, oils field, medicine and as a reinforcing agent for nanocomposites [27].

2.6. Macro-Nano-Scaled Products

2.6.1. Cellulose Filaments (CF)

The CFs are very thin filaments measuring about 80 to 300 nm wide and up to a millimeter long, which is comparable to the length of the parent wood fibers (Figure 8a,b). The CF has the highest aspect ratio in the cellulosic materials market. This biomaterial has high strengthening capability, extreme flexibility with light weight that is useful for preparation of nanocomposites. In addition, the CFs are light with high surface area having a unique bonding capacity that makes them an ideal reinforcing additive and rheological modifier for composites [57].

Cellulose filaments (CF) can be synthesized from the CNF-hydrogels through wet-spinning process. Hydrogel viscosity and spinnability, as well as orientation and strength of the spun filaments were strongly affected by the osmotic pressure. Remarkable values of tensile strength, Young's modulus and degree of orientation of the CF-filaments were found to be 297 MPa, 21 GPa and 83%, respectively [59].

2.6.2. Bacterial/Microbial Cellulose/ Biocellulose

It was reviewed by Yuwawech *et al.* [33] that cellulose nanofibers (CNF) including nanofibrillated cellulose (NFC) and bacterial cellulose (BC) have attracted high interests as reinforcement fillers due to their outstanding mechanical characteristics, higher aspect ratios, higher crystallinity indices, and lower coefficients of thermal expansion when compared to the micrometric-sized cellulosic fibers. In addition, the BC can be produced by fermentation of sugar by the Gram-negative bacteria such

as *Acetobacter xylinum* and *Gluconacetobacter xylinus* with an average width of 25-200 nm. The BC was found to have high effective modulus (79–114 GPa) due to its higher crystallinity index approaching to 138 GPa for the crystal modulus of cellulose I [33]. Accordingly, NFC and BC are regarded as the next generation of renewable reinforcement materials for high performance biocomposites.

2.7. Macrometric-Scaled Products

2.7.1. Prosenchyma Cells

Prosenchyma cells (PCs) are a plant tissue consisting of elongated narrow cells with tapering ends and thick walls (Figure 9). There are three types of the PCs, namely tracheids (in softwoods) as shown in Figure 9a, and vessels and fibers (in hardwoods) as presented Figure 9b and Figure 1c, respectively. Due to their thick walls, they contain more cellulose than cells with thin walls such as parenchyma cells. The PCs offer fluid conduction and reinforcement for plant tissues.

The anatomical components of wood that arranged longitudinally are presented in Table 3, and Table 4 and Figure 9a for softwood and Table 3, and Table 5 and Figure 9b for hardwood. It is clear that softwoods possess fewer types of cells and a uniform of arrangement of the cells giving a simpler microstructure than those for hardwoods. In addition, the woody tissue of softwood is consisted mainly of tracheid cells (about 90%), while that of hardwood is constituted essentially from both vessels and fiber cells as indicated in Table 3, and Table 5.

2.7.2. Pulp

Pulp is a cellulosic material (Figure 9c) isolated generally from wood, recycled cellulosic materials, agricultural wastes, and non-woody materials such as bagasse, cereal straw, bamboo, reeds, esparto grass, jute, flax, and sisal [60]. The cellulosic isolation can be done by delignifying the lignocellulosic precursor mechanically, chemically, or by both techniques.

2.7.2.1. Mechanical Pulp

Mechanical pulping permits separating fibers from each other releasing them as fragments, single or bundles units. Most of the parent lignin in the cellulosic precursor is retained giving higher yield (80-95%) with acceptable strength properties and brightness for the isolated fibers [60].

Table 3. Longitudinal anatomical elements found in softwoods and hardwoods [3]

Anatomical element		Softwoods	Hardwoods
Tracheid	Longitudinal tracheid	Present	Absent
	Strand tracheid	Present	Absent
	Vasicentric tracheid	Absent	Present
	Vascular tracheid	Absent	Present
Vessels		Absent	Present
Fibers	Fiber tracheid	Absent	Present
	Libriform fibers	Absent	Present
Parenchyma	Axial	Present ¹	Present
	Fusiform	Absent	Present
	Epithelial cells	Present	Present

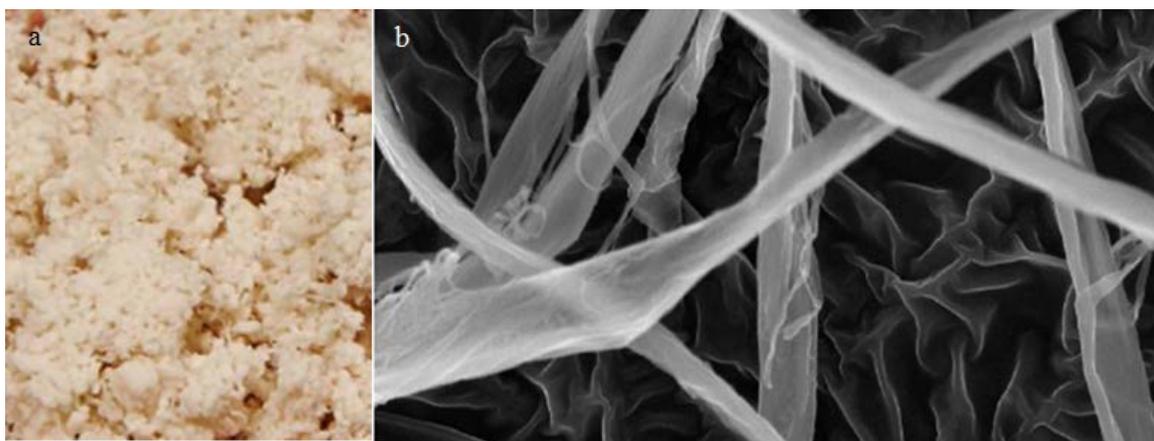
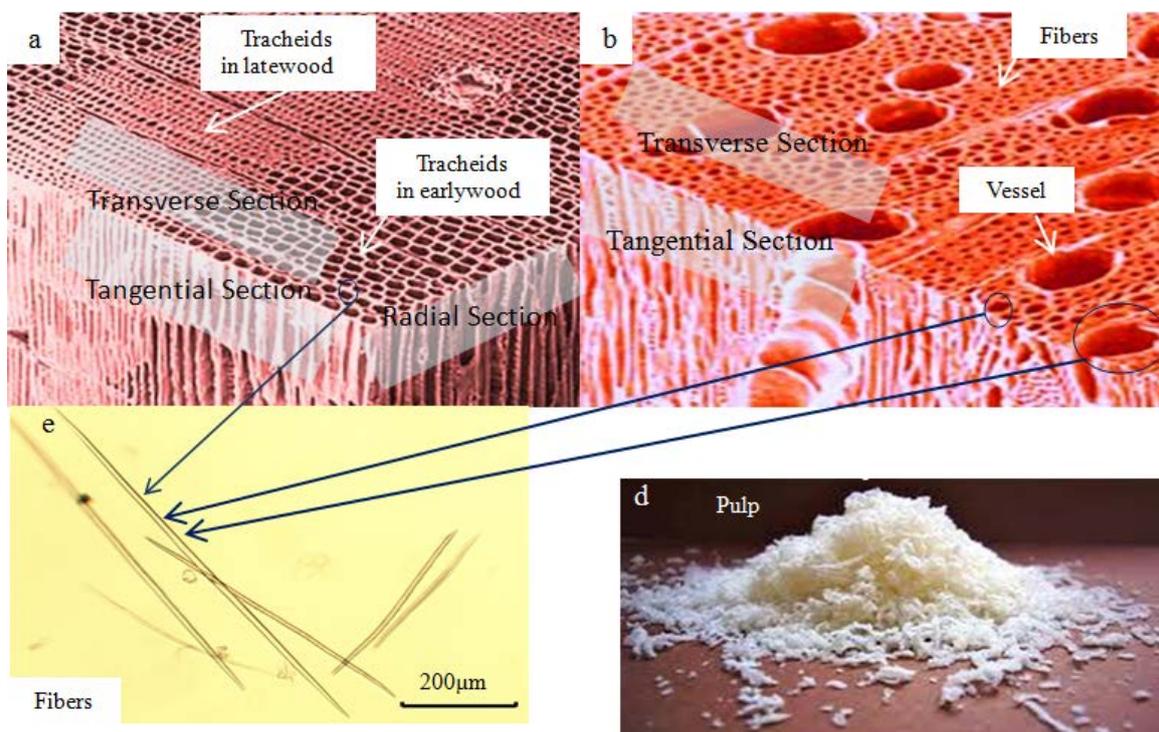
¹ Except for the species of pine, spruce, larch, hemlock, Araucaria and Agathis.

Table 4. Volumetric composition (VC) of some softwood species [3]

Species	VC of softwood (%)	
	Longitudinal tracheid	Total ray parenchyma
<i>Pinus cembra</i>	89.8	9.24
<i>Juniperus excels</i>	91.5	8.26
<i>Pinus strobus</i>	93	6
<i>Cupressus sempervirens</i>	94.2	5.58

Table 5. Volumetric composition (VC) of some hardwood species [3]

Species	VC of hardwood (%)			
	Vessels	Fibers	Ray parenchyma	Axial parenchyma
<i>Carya ovata</i>	6.5	65.5	20	8
<i>Populus deltoides</i>	33	53.1	13.7	0.2
<i>Prunus serotonia</i>	41.4	41.4	17.2	0
<i>Liquidamber styraciflua</i>	54.9	26.6	18.8	0.2

**Figure 8.** Cellulose filaments (CF): a) The oven-dried product, and b) SEM micrograph, from anonymous [59]**Figure 9.** Macro-structure of a) Softwood, b) Hardwood, and c) Macerated cellulose fibers (pulp)

2.7.2.2. Chemical Pulp

More purely cellulose fibers can be removed from lignocellulosic precursors using chemical reagents with lower yield (45-55%) than the mechanical pulp. The

chemical pulps are made by digesting the lignocellulosic materials, using the kraft (sulfate) method which is the most dominated process and the sulfite processes. In the case of Kraft pulp the active chemical reagents are NaOH

and Na₂S [61]. For both pulping processes, the obtained pulp is bleached with peroxides such as hydrogen peroxide or sodium hypochlorite and hydrosulfites to remove the remaining lignin after cooking [60].

The objectives of this work are:

- Calculation of aspect ratio of a cellulosic product (ARCP) based on cited results.
- CDesigning dimensional scale for cellulosic products
- CDesigning the identification card (IC) of cellulosic products

3. Materials and Methods

3.1. Calculation of Aspect Ratio of a Cellulosic Product (ARCP)

The ARCP of a cellulosic product describes the proportional relationship between its length (L) and width (W) expressed by one number resulting from the division process. It was calculated by the following equation:

$$\text{ARCP} = L / W$$

Where L and W are average values taken from cited literatures.

3.2. Designing Dimensional Scale for Cellulosic Products

We suggest dividing cellulosic products into seven scale categories based on their dimensional scale

of their 3-D configurations, namely angstrometric-, micro-/angstrometric-, nanometric-, micro-/nanometric-, micrometric-, macro-/nanometric-, and macrometric-scaled products. The cellulosic products were classified and distributed among the seven scale categories. In addition, cellulosic precursor, delignification technique of the cellulosic precursor, production procedure of the cellulosic product, molecular weight of the cellulosic products and the URL of the material safety data sheets (MSDS) were suggested to be conjugated to its scale division.

3.3. Designing the Identification Card (IC) of Cellulosic Products

Identification data of a cellulosic product is a crucial part of either research and/or marketing. This makes it possible to simultaneously simplify researchers, producers and customers for accurate identification and specifying of each cellulosic product.

The IC card typically must include the information about cellulosic precursor, namely delignification process as well as for the cellulosic product such as dimensions (length, width, and aspect ratio), dimensional scale, molecular weight, drying technique, utilization and the URL of material safety data sheet (MSDS) of the product.

4. Results and Discussion

The cited synonyms of the commercial products of cellulose were collected and presented in Table 6.

Table 6. A list of the high frequency synonyms of cellulose products (CP)

No.	CP	Synonyms of CP	Reference
2	Angstrometric	Glucopyranose rings Cellobiose	[7]
1	Angstrom-/ Macrometric	A glucan chain, or cellulose chain	[7]
3	Nanometric	Fibrils Elementary fibrils Nanofibers Cellulose nanocrystals (CNC) Nanocrystalline cellulose (NCC) Crystallites Whiskers Nanowhiskers (CNW)	[62] [62] [63] [32,36,64] [30,40] [20,65] [20,65] [19,45]
	Nano-/macrometric	Bacterial NanoCellulose (BNC), Microbial cellulose/ Biocellulose Cellulose filaments (CF)	[20,65] [18]
4	Nano-/micrometric	Cellulose Micro/Nano fibers (CMNF) Rod-like cellulose microcrystals Nanofibrillated cellulose (NFC) Cellulose nanofibrils (CNF)	[66,67] [20,65] [20] [20]
5	Micrometric	Microfibrils Cellulose nanofibrils (CNF) Cellulose nano-fibers(CNF) Nanofibrillar cellulose (NFC) Nanofibrillated cellulose (NFC) Microfibrillated cellulose (MFC) Microfibrillar cellulose (MFC) Cellulose microcrystals (CMC) Microcrystalline cellulose (MCC)	[1] [36] [28] [32] [64,68] [63] [69] [61] [56,70]
6	Macrometric	Tracheids Vessels Fibers Pulp Cellulose powder (flour) Amorphous cellulose Alpha cellulose Cellulose allomorphs (polymorphs)	[3] [3] [71] [72] [73] [74] [75] [7]

Table 7. Calculated aspect ratio of cellulosic products

Ordinary name of cellulosic product	Cellulosic Precursor	Dimensions			Calculated Aspect Ratio
		Length	Width	Reference	
Cellulose chain (Glucan chain)	Wood	8 μm	8 A ⁰	[75] and calculated	10000
Micelle		2 μm	3-5 nm	[1]	571.2
Nanofibrillated cellulose (NFC)	Wood	0.5 to 2 μm	4 to 20 nm	[36]	100-250
Cellulosic colloidal nanorods (CCNR)	Wood	n.d.	n.d.	[21]	13-160
Nanocrystalline cellulose (NCC)	Tunicate	n.d.	n.d.	[76]	148 \pm 147
		2 μm	20 nm	[77]	100
	Bark	400–500 nm	25–40 nm	[78]	16-40
		190–660 nm	17 nm	[79]	11.2-38.8
	Wood	n.d.	n.d.	[76]	23 \pm 12
		420 \pm 190 nm	11 \pm 4 nm	[80]	38.2
	Ramie	100–250 nm	3–10 nm	[81]	25-33.3
	MCC	112 \pm 26 nm	10 \pm 3 nm	[82]	11.2
<i>Calotropis procera</i> seed floss	140–260 nm	14–24 nm	[42]	10-10.3	
Cotton	40–100 nm	5–10 nm	[83]	8-10	
Cellulose Nanowhiskers	Microcrystalline cellulose	199-344 nm	11-33 nm	[44]	18.1-10.4
Microcrystalline cellulose	Wood	n.d.	n.d.	[84]	1.8 to 6.4
Microfibrils or Microfibers		5-50 μm	0.1-1 μm	[34,75]	50
Tracheid cell		3-4 mm	30-40 μm	[85]	100
Vessels		0.5-1.5mm	20-300 μm		25-50
Fibers		1-2 mm	10-20 μm		100-

Table 8. The ordinary and standardized names of cellulosic products

Ordinary name	Standardized name	Dimensional scale
Glucose	B-D-glucopyranose	Angstrometric
Cellobiose	Cellobiose	Angstrometric
Cellulose chain (CC) Glucan chain (GC)	Cellobiose chain (CC)	Angstro-/macrometric
Cellulose nanocrystals Cellulose nanowhiskers Cellulose nanorods Cellulosic colloidal nanorods	Nanocrystalline cellulose (NCC)	Nanometric
Cellulose filaments (CF) Bacterial/Microbial cellulose/ Biocellulose	Nanocrystalline Cellulose filaments (NCCF)	Nano-/ macrometric
Nanofibrillated cellulose (NFC) Cellulose nanofibrils (CNF)	Nanosemicrystalline cellulose (NSCC)	Nano/micro-metric
Cellulose Micro/Nano fibers (CMNF)		
Cellulose microcrystals (CMC)		
Microfibrillated cellulose (MFC) Microfibrillar cellulose (MFC)	Microcrystalline cellulose (MCC)	Micrometric
Microfibril or Microfiber	Microfibril	
Tracheids Vessels Fibers Pulp	Prosenchyma cells (PC)	Macrometric

4.1. Aspect Ratio of the Cellulosic Products

Aspect ratio is very important property that determines behavior of cellulosic products for a certain chemical/physical. Cellulosic products with high aspect ratio are more suitable for reinforcing nanocomposites.

The calculated aspect ratio of the most important cellulosic products are presented at Table 7. It is obvious that the crude cellulose chain has the highest aspect ratio that was calculated assuming that the degree of polymerization of cellulose is 10,000 units followed by micelle (571.2).

4.2. Synonyms Standardization of Cellulosic Products

The suggested cellulosic synonyms are presented in

Table 8. For the glucan chain synonym, it is based on conjugating the adjacent glucopyranose units together to form its chain without put any imagination about their linkages (β -D-glucosidic linkage). On the other hand, since the cellobiose synonym express conjugating two glucopyranose units by the β -D-glucosidic linkage, the cellobiose chain give an overall and integrated meaning for cellulose chain.

Scientifically, a fiber synonym is one of the three types of the prosenchyma cells, but commercially it extends to cover all the three synonyms. Accordingly, the suggested standardized name of the macerated cellulosic cells is prosenchyma cells (PC).

4.3. Design of an Identification Card of Cellulosic Products

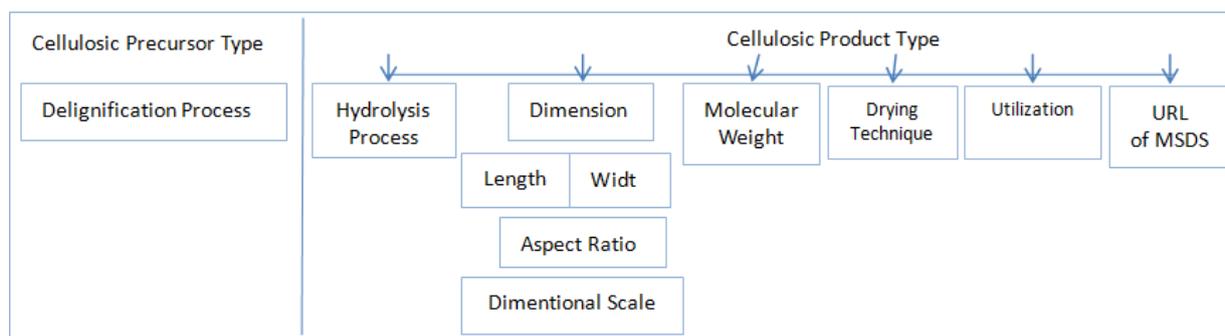


Figure 10. The suggested identification card for a certain cellulosic product

5. Conclusion

- Cited dimensional values of cellulosic products particles were collected and aspect ratios were calculated.
- Cellulosic products were distributed among seven scale categories based on their dimensional scale and aspect ratios.
- The seven dimensional scale categories suggested are angstrometric-, angstrom/macrometric-, nanometric-, nano/macrometric-, nano/micrometric-, micrometric-, and macrometric-scaled products.
- To distinctly differentiate the cellulosic products, they were classified and distributed among the seven scale categories.
- Standardized synonyms of the important cellulosic products were suggested.
- An identification card of the cellulosic products was designed.
- The identification card was suggested to include information about cellulosic precursor such as its type and delignification process as well as the cellulosic product.
- For such a cellulosic product, hydrolysis process, dimensions, molecular weight, drying technique, utilization, and uniform resource locator of its material safety data sheet were suggested to be included in the identification card.

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