A review on nanocellulosic fibres as new material for sustainable packaging: Process and applications

H.P.S. Abdul Khalil\textsuperscript{a,b}, Y. Davoudpour\textsuperscript{a}, Chaturbhuj K. Saurabh\textsuperscript{a}, Md. S. Hossain\textsuperscript{a}, A. S Adnan\textsuperscript{c}, R. Dungan\textsuperscript{d}, M.T. Paridah\textsuperscript{b,e}, Md. Z. Islam Sarker\textsuperscript{f}, M.R Nurul Fazita\textsuperscript{a}, M.I Syakira, M.K.M. Haafiz\textsuperscript{a}

\textsuperscript{a} School of Industrial Technology, Universiti Sains Malaysia, 11800 Pulau Pinang, Malaysia
\textsuperscript{b} Institute of Tropical Forestry and Forest Product, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
\textsuperscript{c} School of Medical Sciences, Universiti Sains Malaysia, 16150 Kota Bharu, Kelantan, Malaysia
\textsuperscript{d} Department of Life Sciences and Technology, Institut Teknologi Bandung, Gedung Labtex XI, Jalan Ganesha 10, Bandung 40132, West Java, Indonesia
\textsuperscript{e} Department of Forest Production, Faculty of Forestry, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
\textsuperscript{f} Department of Pharmaceutical Technology, Faculty of Pharmacy, International Islamic University Malaysia, Kuantan Campus, Bandar Indera Mahkota, Kuantan 25200, Pahang, Malaysia

Keywords:
Cellulose nano\textsuperscript{b}ber
Design process
Eco-friendly packaging
Natural fiber
Sustainable material

\textbf{Abstract}

The demand for exploring advanced and eco-friendly sustainable packaging materials with superior physical, mechanical and barrier properties is increasing. The materials that are currently used in packaging for food, beverage, medical and pharmaceutical products, as well as in industrial applications, are non-degradable, and thus, these materials are raising environmental pollution concerns. Numerous studies have been conducted on the utilization of bio-based materials in the pursuit of developing sustainable packaging materials. Although significant improvements have been achieved, a balance among environmental concerns, economic considerations and product packaging performance is still lacking. This is likely due to bio-based materials being used in product packaging applications without a proper design. The present review article intends to summarize the information regarding the potential applications of cellulose nano\textsuperscript{b}ber for the packaging. The importance of the design process, its principles and the challenges of design process for sustainable packaging are also summarized in this review.

Overall it can be concluded that scientists, designers and engineers all are necessarily required to contribute towards research in order to commercially exploit cellulose nano\textsuperscript{b}ber for sustainable packaging.
1. Introduction

The use of non-biodegradable and non-renewable materials (i.e., plastics, glass, and metals) in packaging applications has raised concerns about environmental pollution and thus there is demand for the safe management of such waste. Large amounts of packaging materials are produced every year with the intention of use and throw. Traditional methods for handling post consumer plastic wastes include incineration and land filling [1]. However there are some apprehensions related to these methods like during incineration of non-biodegradable packaging materials greenhouse gases generated which pose a threat to our health and environment [1,2]. Extensive research has been conducted to develop alternative packaging materials, with the emphasis on reducing the environmental impact of petroleum based packaging materials. Studies have reported that the use of bio-polymer based materials may minimize the generation of packaging waste and thus consecutively solve the waste disposal problem to some extent owing to its biodegradability [2–4]. One added advantage of synthetic plastics is that they are recyclable, however, thermo-setting plastics are not recyclable, contaminated plastics are not easy to recycle, recycling deteriorate the properties of plastics and recycling opportunities in many countries are not fully utilized. Thus due to concern over recycling procedure bioplastics has an added advantage over recyclable plastics. Nevertheless, one of the major limitation for wide spread commercial application of bioplastic is cost. However, recently cost of bioplastics per pound has dropped significantly for example PLA which cost $3/lb in 1990s has dropped to 90 cents/lb in 2010. Furthermore, the rise in oil price has made bio based plastics price comparable to the price of petroleum based thermoplastics. In terms of energy, production of bioplymer based plastics required less energy than conventional counter parts such as 1 kg of PLA need only 27.2 MJ of fossil fuel based energy. In contrast, polypropylene and high density polyethylene require 85.9 and 73.7 MJ/kg, respectively. Thus it can be concluded that bioplastics successfully address concerns regarding cost, energy consumption, sustainability and recycling procedure when compared to synthetic counter parts. However, poor mechanical and barrier properties of bio-polymer based packaging materials compared to those of non-biodegradable materials have limited their widespread application. For successful practical use of bio-polymer based film various methods have been proposed for improvement in properties like addition of plasticizer, chemical modification of polymer, gamma irradiation etc. One of the most frequently used method is the addition of nanomaterials especially cellulose nanofibers. Due to its nano scale size it interacts with material at the atomic, molecular, or macromolecular level thus affects functional behavior of biopolymer films.

Cellulose nanofibers from natural resources are recognized as the most abundant and renewable polymeric material as well as a key source of sustainable materials at the industrial scale. Because of their attractive properties, such as biocompatibility, biodegradability and chemical stability, cellulose materials have been utilized for more than 150 years as raw materials in the production of paper, pharmaceutical compounds, and textiles [5,6]. In recent years, nanocellulosic materials have attracted the interest of scientists for maximizing the mechanical and barrier properties of packaging materials. Use of cellulose nanofibers in packaging will minimize the costs of packed products due to their wide availability and low cost. It will also preserve the environment owing to its recyclability and reusability [7,8]. Cellulose nanofibres primarily consist of cellulose fibrils embedded in a learning matrix, and thus, these nanofibres may provide superior rigidity, tensile and flexural properties [9]. Therefore, an innovative approach with cellulose nanofibres can be a useful tool for the development of sustainable packaging with improved characteristics and for qualitative environmental management of packaging materials. An effective design of cellulose nanofibres for sustainable packaging may consist of qualitative and quantitative functioning of the product throughout its entire life cycle. Moreover, designing nanocellulosic materials will create a better experience for the end user and also allow for efficient manufacturing systems.

Functional products are produced by an engineering design process which is a methodical process. In general, the engineering design process is a key factor in developing effective manufacturing processes and technology for innovative products [10]. The utilization of the design process for the isolation of cellulose nanofiber will ensure product quality and the requirements of product packaging, such as safety, ergonomic, size, height, thickness and stress levels prior to being marketed, as well as its quantitative life cycle assessment and cost [10]. The primary role of a design process is to define the possibilities, limitations and suitability of cellulose nanofibres in the development of sustainable packaging [11]. In this paper, a systematic review is conducted on cellulose nanofibre, including its isolation, characterization, properties, simulation and its applicability towards sustainable packaging. The need of designing technologies for the production and processing of cellulose nanofibre as well as principles, importance and challenges in designing sustainable packaging are also discussed in this paper.

2. Production of nanocellulosic fibres

Nanotechnology is a multidisciplinary science that includes mathematics, physics, and chemistry for producing materials that have at least one dimension in nanoscale (10^-9 m) [12]. Extensive studies have been conducted on the isolation of cellulose nanomaterials from various sources and their applications in the development of value-added products [5,12,13].

Cellulose nanofibres can be extracted from a wide range of cellulose rich sources, such as cotton, kenaf, banana, oil palm, bamboo, wheat, rice, and bagasse [5,9,14]. Selection of source is
dependent on the local availability of the fibre, chemical components for application and economic viability [9]. According to the literature, isolation of cellulose nanofibers can be conducted in 2 steps, namely, (i) pretreatment of cellulose fibres and (ii) production of cellulose nanofibre (CNF), as shown in Fig. 1 [5,15–17].

2.1. Pretreatments of cellulose fibres for the production of cellulose nanofibres

Table 1 shows various processes used for pretreatment of lignocellulosic fibres for the production of cellulose nanofibres. Typically, the delignification process is a necessary step in the isolation of nanocellulosic materials from lignocellulosic biomass. The delignification process primarily consists of pulping to depolymerise and eventually solubilise lignin and hemicelluloses, followed by bleaching with chemical agents [17]. During nanocellulose production there is a mechanical/chemical pretreatment step after bleaching. Mechanical pretreatments include refining and cryocrushing [17,18], and chemical pretreatments include acetylation [15], carboxymethylation [19], TEMPO oxidation [20], acid hydrolysis [21] and enzymatic hydrolysis [6]. In cryocrushing material is cool down to its brittleness point (below – 196 °C) in order to facilitate mechanical reduction. Acetylation and carboxymethylation refers to the process of substitution of an acetyl (resulting in an acetoxy group) or carboxymethyl group, respectively into a compound. Acidic or enzymatic hydrolysis requires acid or enzyme, respectively for the cleavage of chemical bonds by the addition of water. TEMPO oxidation is an aerobic oxidation of primary and secondary alcohols to aldehydes and ketones using TEMPO-CuCl as catalyst. Hydrolysis and TEMPO oxidation are the most common chemical processes that have been applied as a pretreatment for the isolation of cellulose nanofibres [20] (Fig. 1).

The reasons for performing these pretreatments are to [9,17,22]:

○ Decrease energy consumption in mechanical CNF extraction methods.

Cellulose includes both crystalline and amorphous regions (Fig. 2), which are bonded together by intra- and intermolecular bonds; thus, only the surface cellulosic chains are easily accessible to chemicals. The crystalline structure is conserved by hydrogen bonds and Van der Waals forces while amorphous structure consists of twists and torsions that can alter the ordered arrangement (Fig. 2). Therefore, the molecular structure of cellulose should be disrupted and depolymerised through pretreatment processes, prior to the isolation of cellulose nanofibre [62].

2.2. Isolation of cellulose nanofibres

Nanocellulose can be defined as a long, flexible and entangled network of microfibrils. Strands of spaghetti or strands of hair are two good examples for visualizing the structure of CNF. In fact, CNF includes both amorphous and crystalline regions and

![Fig. 1. Process for the isolation of nanocellulosic fiber from lignocellulosic biomass.](image-url)
possesses a high aspect ratio [4,63]. CNF can be isolated from cellulosic fibres using various mechanical or chemo-mechanical processes, including high-pressure homogenization, microfluidization, microgrinding, high-intensity ultrasonication, electrospinning, and steam explosion (Fig. 1). Each technology has its own advantages and disadvantages. Table 2 summarizes the benefits and drawbacks of various methods for the isolation of cellulosic nanofibres.

Recently, considerable attention has been devoted to cellulosic nanofibres because of their sustainable characteristics and their applicability in a wide variety of fields, such as composites, filtration, membranes, packaging, medical, industry, construction, cosmetics, and foods. Consequently, the isolation and analysis of the properties of nanocellulose have been the subjects of studies by many scholars. The chronological events that occur during CNF isolation processes are summarized in Table 3.

### 3. Properties and structure of cellulose

Cellulose is the most abundant natural biopolymer and is a linear homo-polysaccharide composed of β-D-glucopyranose units connected by β-1–4-linkages with a repeating unit of cellobiose [65], and it is considered an alternative for petroleum based materials for packaging [69]. Generally, cellulose consists of both crystalline and amorphous domains. There are three hydroxyl groups in a monomer of the cellulose structure that form hydrogen bonds, which play a vital role in the physical properties and crystalline packing of cellulose [113].

Cellulose does not exist as an individual molecule in nature. It can be found as assemblies of single cellulose chains, which form a fibre cell wall. The structure of cellulosic fibres is composed of cellulose, lignin and hemicellulose, ash and extractives are also present in varying amounts depending on their origin [114]. The hierarchical structure of cellulose is shown in Fig. 3. Naturally occurring cellulose (cellulose I) is crystalline and is composed of two polymorphs, named Iα (triclinic structure) and Iβ (monoclinic structure) [115]. Cellulose Iα, which appears as a metastable structure, can be converted into the Iβ form via an alkaline treatment. Cellulose Iβ, the most stable allomorph, has rarely been found in nature and it can be synthesized from cellulose I via mercerization or regeneration [115]. Other allomorphs of cellulose III and IV are also available and they can be produced by chemical treatment of either cellulose I or II.

Lignin is defined as a three dimensional complex polymer, and it is composed of propyl-phenol groups connected by C–C bonds and an ether group [116]. Generally, lignin leads to stiffening of cellulosic fibres which protect it against biological attack [14]. Hemicellulose is a low molecular weight amorphous and heterogeneous polysaccharide that consists of xyloglucans, xylans, mannans and glucomannans [14,117]. Hemicellulose acts as a compatibilizing agent, forming an interface between hydrophobic lignin and hydrophilic cellulose, and it links with cellulose and lignin in plant fibre cells [14]. Lignin and hemicelluloses typically constitute 15–25% and 20–30% (wt%), respectively of the total chemical composition of cellulosic fibres [118].

In general, cellulosic fibres are composed of single fibres linked by a middle lamella, which is rich in lignin (90%, w/w) and free of cellulose [22] (Fig. 3). Each single fibre consists of a cell wall and a central cavity called a lumen, as shown in Fig. 4 [119]. The volume of the central cavity in fibres (lumen) is approximately 0.2–0.4 cm³/g of fibres, and a larger lumen size leads to lower
strength and stiffness of plant fibres [120]. Basically, the cell wall in cellulosic fibres is not homogenous, and it is composed of a primary wall (thin outer layer) and a secondary wall, in which the secondary wall is composed of three layers namely S₁, S₂ and S₃ (Figs. 3 and 4).

The primary cell wall consists of 9–25% cellulose microfibrils, 25–50% hemicelluloses and 10–35% pectins; the secondary cell wall is a derivative of the primary wall and is composed of 40–80% cellulose, 10–40% hemicelluloses and 5–25% lignin [120]. The cellulose microfibril is an elementary structural constituent of cellulose, where each single microfibril has a diameter of approximately 2–20 nm [114]. Cellulose microfibrils are a helically wound framework, which have various directions in secondary cell wall layers and are randomly distributed in the primary cell wall. The highest content of cellulose is located in the secondary cell wall layer (specifically S₂) [69]. Essentially, rigid cellulose microfibrils

<table>
<thead>
<tr>
<th>Year</th>
<th>Progress</th>
<th>CNF isolation technology</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1927</td>
<td>Production of board by wood CNF isolated using steam explosion</td>
<td>Steam explosion</td>
<td>[72]</td>
</tr>
<tr>
<td>1930</td>
<td>Formal introduced electrosprinning method</td>
<td>Electrosprinning</td>
<td>[73]</td>
</tr>
<tr>
<td>1962</td>
<td>Defibrillation of wood pulp by ultrasonication</td>
<td>High intensity ultrasonication</td>
<td>[74]</td>
</tr>
<tr>
<td>1983</td>
<td>Defibrillation the wood fibers to CNF</td>
<td>HP</td>
<td>[75]</td>
</tr>
<tr>
<td>2000</td>
<td>Isolation of CNF from potato tuber cells</td>
<td>HP</td>
<td>[76]</td>
</tr>
<tr>
<td>2004</td>
<td>Silylation of CNF from sugar beet pulp and its rheological characterization</td>
<td>HP</td>
<td>[77]</td>
</tr>
<tr>
<td>2005</td>
<td>Comparing the effect of grinding and high pressure homogenization on the properties of isolated CNF</td>
<td>Microgrinding</td>
<td>[78]</td>
</tr>
<tr>
<td>2006</td>
<td>Isolation of individualized CNF from never-dried cotton by TEMPO oxidation pretreatment</td>
<td>HP</td>
<td>[51]</td>
</tr>
<tr>
<td>2007</td>
<td>Preparation and characterization of CNF and strong gel from softwood pulp by enzymatic pretreatment and high pressure homogenization</td>
<td>Electrosprinning</td>
<td>[79]</td>
</tr>
<tr>
<td>2008</td>
<td>Evaluation of pressure and hardwood/water slurry concentration to isolate CNF for polyurethane based nanocomposites application</td>
<td>Microfluidization</td>
<td>[83]</td>
</tr>
<tr>
<td>2009</td>
<td>The effect of ultrasonic time on the properties of TEMPO oxidized wood CNF for nanocomposite applications</td>
<td>High intensity ultrasonication</td>
<td>[85]</td>
</tr>
<tr>
<td>2010</td>
<td>Comparison between the thermal stability of CNF prepared by atomization, oven and freeze-drying methods</td>
<td>Electrospraying</td>
<td>[86]</td>
</tr>
<tr>
<td>2010</td>
<td>The impact of moisture on the thermo-mechanical and morphological characteristics of electrosprun rami CNW/poly(vinyl alcohol)/(PVA) composite nanofibers</td>
<td>Electrospraying</td>
<td>[56]</td>
</tr>
<tr>
<td>2011</td>
<td>Isolation and characterization of pineapple leaf CNF prepared by steam explosion</td>
<td>Steam explosion</td>
<td>[71]</td>
</tr>
<tr>
<td>2012</td>
<td>Preparation of sugarcane bagasse CNF by high pressure homogenization</td>
<td>HP</td>
<td>[95]</td>
</tr>
<tr>
<td>2012</td>
<td>Preparation of CNF from by microfluidization process to produce nanofiber</td>
<td>Microfluidization</td>
<td>[96]</td>
</tr>
<tr>
<td>2013</td>
<td>Optimization of refining-microfluidization process to isolate CNF from bagasse and rice straw and nanofiber preparation</td>
<td>Microfluidization</td>
<td>[97]</td>
</tr>
<tr>
<td>2013</td>
<td>Preparation of CNW from by microfluidization process to produce nanocellulose</td>
<td>Microfluidization</td>
<td>[98]</td>
</tr>
<tr>
<td>2013</td>
<td>Preparation of CNW by ultrasonication from microcrystalline cellulose to reinforce polyvinyl alcohol (PVA) film</td>
<td>High intensity ultrasonication</td>
<td>[95]</td>
</tr>
<tr>
<td>2013</td>
<td>Influence of various bacterial CNW concentration on the properties of ethylene vinyl alcohol (EVOH)/CNW composite nanofibers</td>
<td>Electrospraying</td>
<td>[100]</td>
</tr>
<tr>
<td>2014</td>
<td>Dynamic rheological behavior of wood CNF produced by ultrasonication as a function of fiber/water slurry concentration</td>
<td>High intensity ultrasonication</td>
<td>[102]</td>
</tr>
<tr>
<td>2015</td>
<td>Preparation of banana CNF by steam explosion method</td>
<td>Steam explosion</td>
<td>[70]</td>
</tr>
<tr>
<td>2015</td>
<td>Preparation and properties analysis of wheat straw CNF obtained by steam explosion-high pressure homogenization</td>
<td>HP</td>
<td>[94]</td>
</tr>
<tr>
<td>2015</td>
<td>Comparison between bleached and unbleached kenaf bast CNF isolated by grinding</td>
<td>Microcrystalline</td>
<td>[88]</td>
</tr>
<tr>
<td>2015</td>
<td>Isolation and characterization of sludge CNF by grinding</td>
<td>Microcrystalline</td>
<td>[99]</td>
</tr>
<tr>
<td>2015</td>
<td>Optimization of redefining-microfluidization process to produce isolated CNF from bagasse and rice straw and nanofiber preparation</td>
<td>Microfluidization</td>
<td>[97]</td>
</tr>
<tr>
<td>2015</td>
<td>Preparation of jute CNF by high pressure homogenization and nanofiber preparation</td>
<td>Microfluidization</td>
<td>[97]</td>
</tr>
<tr>
<td>2015</td>
<td>Preparation of jute CNW/electrospun nanofiber membrane using immersion-drying method for filtration applications</td>
<td>Microfluidization</td>
<td>[104]</td>
</tr>
<tr>
<td>2015</td>
<td>Isolation of CNF by steam explosion pretreated with ultrasonication</td>
<td>Steam explosion</td>
<td>[105]</td>
</tr>
<tr>
<td>2015</td>
<td>Controlling pressure and shear force in microenvironment to homogeneous preparation of bagasse CNF by dynamic microfluidizer</td>
<td>Microfluidization</td>
<td>[106]</td>
</tr>
<tr>
<td>2015</td>
<td>Comparison between bleached and unbleached kenaf bast CNF isolated by grinding</td>
<td>Microcrystalline</td>
<td>[107]</td>
</tr>
<tr>
<td>2015</td>
<td>Effect of grinding time on the characteristics of CNF</td>
<td>Microcrystalline</td>
<td>[108]</td>
</tr>
<tr>
<td>2015</td>
<td>Isolation of softwood CNF by NaOH/urea/thiourea pretreatment and ultrasonication</td>
<td>High intensity ultrasonication</td>
<td>[109]</td>
</tr>
<tr>
<td>2015</td>
<td>Electrospraying of cellulose/cotton CNW with different CNW loading percentages for tissue engineering applications</td>
<td>Electrospraying</td>
<td>[110]</td>
</tr>
<tr>
<td>2015</td>
<td>Isolation of eucalyptus CNF by enzymatic pretreatment-microfluidization</td>
<td>Electrospraying</td>
<td>[111]</td>
</tr>
<tr>
<td>2015</td>
<td>Electrospinning of cotton and wood fiber in TFA and application of the resultant drug loaded CNF for biomedical applications</td>
<td>Electrospraying</td>
<td>[112]</td>
</tr>
<tr>
<td>2015</td>
<td>The impact of moisture on the thermo-mechanical and morphological characteristics of electrosprun rami CNW/poly(vinyl alcohol)/(PVA) composite nanofibers</td>
<td>Electrospraying</td>
<td>[56]</td>
</tr>
<tr>
<td>2015</td>
<td>Preparation of sugarcane bagasse CNF by high pressure homogenization</td>
<td>HP</td>
<td>[95]</td>
</tr>
<tr>
<td>2015</td>
<td>Preparation of CNW from by microfluidization process to produce nanofiber</td>
<td>Microfluidization</td>
<td>[96]</td>
</tr>
<tr>
<td>2015</td>
<td>Preparation of CNW by ultrasonication from microcrystalline cellulose to reinforce polyvinyl alcohol (PVA) film</td>
<td>High intensity ultrasonication</td>
<td>[95]</td>
</tr>
<tr>
<td>2015</td>
<td>Influence of various bacterial CNW concentration on the properties of ethylene vinyl alcohol (EVOH)/CNW composite nanofibers</td>
<td>Electrospraying</td>
<td>[100]</td>
</tr>
<tr>
<td>2015</td>
<td>Dynamic rheological behavior of wood CNF produced by ultrasonication as a function of fiber/water slurry concentration</td>
<td>High intensity ultrasonication</td>
<td>[102]</td>
</tr>
<tr>
<td>2015</td>
<td>Comparison between bleached and unbleached kenaf bast CNF isolated by grinding</td>
<td>Microcrystalline</td>
<td>[88]</td>
</tr>
<tr>
<td>2015</td>
<td>Effect of grinding time on the characteristics of CNF</td>
<td>Microcrystalline</td>
<td>[108]</td>
</tr>
<tr>
<td>2015</td>
<td>Isolation of softwood CNF by NaOH/urea/thiourea pretreatment and ultrasonication</td>
<td>High intensity ultrasonication</td>
<td>[109]</td>
</tr>
<tr>
<td>2015</td>
<td>Electrospraying of cellulose/cotton CNW with different CNW loading percentages for tissue engineering applications</td>
<td>Electrospraying</td>
<td>[110]</td>
</tr>
<tr>
<td>2015</td>
<td>Isolation of eucalyptus CNF by enzymatic pretreatment-microfluidization</td>
<td>Electrospraying</td>
<td>[111]</td>
</tr>
<tr>
<td>2015</td>
<td>Electrospinning of cotton and wood fiber in TFA and application of the resultant drug loaded CNF for biomedical applications</td>
<td>Electrospraying</td>
<td>[112]</td>
</tr>
<tr>
<td>2015</td>
<td>The impact of moisture on the thermo-mechanical and morphological characteristics of electrosprun rami CNW/poly(vinyl alcohol)/(PVA) composite nanofibers</td>
<td>Electrospraying</td>
<td>[56]</td>
</tr>
<tr>
<td>2015</td>
<td>Preparation of sugarcane bagasse CNF by high pressure homogenization</td>
<td>HP</td>
<td>[95]</td>
</tr>
<tr>
<td>2015</td>
<td>Preparation of CNW from by microfluidization process to produce nanofiber</td>
<td>Microfluidization</td>
<td>[96]</td>
</tr>
<tr>
<td>2015</td>
<td>Preparation of CNW by ultrasonication from microcrystalline cellulose to reinforce polyvinyl alcohol (PVA) film</td>
<td>High intensity ultrasonication</td>
<td>[95]</td>
</tr>
<tr>
<td>2015</td>
<td>Influence of various bacterial CNW concentration on the properties of ethylene vinyl alcohol (EVOH)/CNW composite nanofibers</td>
<td>Electrospraying</td>
<td>[100]</td>
</tr>
<tr>
<td>2015</td>
<td>Dynamic rheological behavior of wood CNF produced by ultrasonication as a function of fiber/water slurry concentration</td>
<td>High intensity ultrasonication</td>
<td>[102]</td>
</tr>
</tbody>
</table>
are embedded in a soft matrix that consists of lignin and hemicelluloses [69].

4. Cellulose nanofibres in packaging applications

Because of their promising characteristics, nanofibrillated cellulose fibres have been widely utilized in a variety of applications in various fields, including medical [71], packaging [63], paper and coating [103], electronics [121] and membranes [14]. The past decade has witnessed significant advancements in the development of biodegradable plastic packaging, particularly from renewable cellulose based biomaterials. These advancements are focused on obtaining improved food quality and safety through packaging with the move towards globalization. The use of such renewable and biodegradable material will also contribute to environmental sustainability by reducing waste disposal and greenhouse gas balances. Various research and development activities have been performed by researchers to promote the use of biodegradable and eco-friendly packaging materials to replace existing conventional packaging materials available in the market, such as conventional plastic or glass packages [122]. De Moura et al.
suppliers, and this company produces Pure-Pak™ NatureFlex™ films, released NatureFlex™ a cellulose film that offers an excellent barrier to gas and moisture. These improved properties have allowed it to be used in a wide range of food categories such as dry food products, frozen or liquid foods, beverages and fresh foods [138]. The primary functions of food packaging are to protect and preserve the food, maintain its quality and safety, and reduce food waste [140]. The most commonly used cellulose based food packaging is cellophane, which is also known as regenerated cellulose in film. A number of cellulose derivatives such as carboxymethyl cellulose, methyl cellulose, ethyl cellulose, hydroxypropyl cellulose, hydroxyethyl cellulose and cellulose acetate are used in the preparation of cellulose based films. Cellulose acetate is also widely used as a rigid wrapping film along with cellulose triacetate than other derivatives, since they have low gas and moisture barrier properties [141]. In 2008, a company from the United States, Innovia FibreForm D6400) and Australian (AS4736) norms for compostable packaging. These standards are designed to ensure that the materials are biodegradable and compostable, and that they meet certain quality and performance criteria.

4.1. Foods and beverages

Cellulose fibres have traditionally been used in packaging for a wide range of food categories such as dry food products, frozen or liquid foods, beverages and fresh foods [138]. The primary functions of food packaging are to protect and preserve the food, maintain its quality and safety, and reduce food waste [140]. The most commonly used cellulose based food packaging is cellophane, which is also known as regenerated cellulose in film. A number of cellulose derivatives such as carboxymethyl cellulose, methyl cellulose, ethyl cellulose, hydroxypropyl cellulose, hydroxyethyl cellulose and cellulose acetate are used in the preparation of cellulose based films. Cellulose acetate is also widely used as a rigid wrapping film along with cellulose triacetate than other derivatives, since they have low gas and moisture barrier properties [141]. In 2008, a company from the United States, Innovia FibreForm D6400) and Australian (AS4736) norms for compostable packaging. These norms are designed to ensure that the materials are biodegradable and compostable, and that they meet certain quality and performance criteria.

4.1. Foods and beverages

**Table 4** Lignocelluloses fibers utilized in packaging of food and non-food materials.

<table>
<thead>
<tr>
<th>Cellulosic</th>
<th>Application</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>Food packaging</td>
<td>[51]</td>
</tr>
<tr>
<td>Wood pulp</td>
<td>Food packaging</td>
<td>[89]</td>
</tr>
<tr>
<td>Sago starch</td>
<td>Pharmaceutical and Industrial packaging</td>
<td>[124]</td>
</tr>
<tr>
<td>Sterculia urens</td>
<td>Food and medical application</td>
<td>[125]</td>
</tr>
<tr>
<td>Wood</td>
<td>Agricultural packaging</td>
<td>[126]</td>
</tr>
<tr>
<td>Bagasse</td>
<td>Food packaging</td>
<td>[127]</td>
</tr>
<tr>
<td>Empty fruit bunch</td>
<td>Food packaging</td>
<td>[96]</td>
</tr>
<tr>
<td>Cassava</td>
<td>Food packaging</td>
<td>[128]</td>
</tr>
<tr>
<td>Corn</td>
<td>Food packaging</td>
<td>[129]</td>
</tr>
<tr>
<td>Rice straw</td>
<td>Industrial and food packaging</td>
<td>[130]</td>
</tr>
<tr>
<td>Wood Pine</td>
<td>Food packaging</td>
<td>[131]</td>
</tr>
<tr>
<td>Esparto grass</td>
<td>Food packaging</td>
<td>[132]</td>
</tr>
<tr>
<td>Pinus radiata</td>
<td>Industrial packaging</td>
<td>[133]</td>
</tr>
<tr>
<td>Phormium tenax</td>
<td>Food packaging</td>
<td>[134]</td>
</tr>
<tr>
<td>Curauá</td>
<td>Food packaging</td>
<td>[135]</td>
</tr>
<tr>
<td>Ramie</td>
<td>Food packaging</td>
<td>[136]</td>
</tr>
<tr>
<td>Sweet potato</td>
<td>Food packaging</td>
<td>[11]</td>
</tr>
<tr>
<td>Mulberry</td>
<td>Food packaging</td>
<td>[137]</td>
</tr>
<tr>
<td>Poplar</td>
<td>Food packaging</td>
<td>[90]</td>
</tr>
<tr>
<td>Canola straw</td>
<td>Food packaging</td>
<td>[138]</td>
</tr>
<tr>
<td>Wheat</td>
<td>Industrial packaging</td>
<td>[139]</td>
</tr>
</tbody>
</table>

functions as a liquid barrier. These cartons are used to protect milk, juices and other liquid foods and to reduce food wastage as much as possible. The design and structure of the cartons enable the customer to squeeze the packaging more effectively thereby reducing the amount of remaining product [143].

4.2. Medical and pharmaceutical products

Over the past few years the pharmaceutical packaging market has continuously increased with the increasing demands of personal lifestyles, chronic diseases, ageing population and increasing incomes in developing countries. Packaging for pharmaceuticals provides reliable and rapid solutions that deliver a combination of product protection, quality, identification, information, convenience and security needs [144]. Papers that are composed of cellulose fibre networks are suitable for use as raw materials in medical and pharmaceutical packaging. These papers are used to prepare the outer containers, such as boxes, cartons, envelopes, blisters and strips for tablets, suppositories and capsules that are packed in board cartons [145]. Cartons are mostly used in pharmaceutical packaging because of certain factors such as increasing the display area, providing a better display of stock items and providing physical protection particularly for items such as metal collapsible tubes. Cellulose has also been used to modify the release of drugs from tablet and capsule formulations. It also helps in tablet binding, thickening and rheology control agents for film formation, water retention, improving adhesive strength and act as suspension and emulsifying agents [146].

4.3. Industrial packaging

Compared to other packaging applications, industrial packaging applications are slowly evolving with a few large corporations, including Honeywell, Mitsubishi Gas and Chemical, Bayer, Triton Systems and Nanocor which are currently acting as pioneers in CNF based packaging applications [130]. In 2012, Unisource Company introduced a compostable, bamboo moulded fibre packaging that is used to ship laptops around the world. They received a LUXE PACK in Green Award in recognition of their innovative products that replace up to 80% of the plastic used in traditional blister packs. Such packaging are produced using technology used by the paper pulp industry but are reported to be cheaper than polystyrene trays with the advantage of being completely biodegradable [147]. BASF introduced ecovio®, a thermoformed packaging produced from corn starch. This material is a very tough sheet that wraps around very well and suitable for single and multi-layered sheeting. Additionally, it is also being used as shopping and waste collection bags [148]. According to Nomikos et al. [149], industrial packaging is gaining popularity and importance in the graphic arts and print media industries.

4.4. Other potential uses

Packaging is currently at the centre of intensive research among scientists concerning new technologies that include the development of environmental friendly packaging materials that interact well with foods in terms of preservation. To provide a positive impact on consumer health, the packaging is designed by incorporating functional ingredients in the structure of the packaging with the added food products [113]. New developments in packaging technology have been fuelled by developments in materials engineering, electronics and processing technology which involve some key areas including high barrier materials, active packaging, intelligent packaging, nanotechnology, tagging applications and digital print for packaging that are important for the growth of packaging industry [149]. Most challenging aspect of...
packaging research is to develop and promote the use of renewable and biodegradable “bio-plastic” which can commercially replace petroleum based plastics and thus help in reducing waste disposal problem. However, biopolymers based packaging has relatively poor mechanical and barrier properties than non-biodegradable counterparts which currently limit their industrial use. Various chemical and physical methods have been proposed in past to improve the mechanical and barrier properties of biopolymer based packaging. Researchers currently suggest that the inherent limitations of biopolymer-based packaging materials may be overcome through nanocomposite technology [150]. There are two types of nanomaterials used in polymer based nanocomposite film: inorganic and organic. Organic nanoparticle is edible and highly compatible with biopolymer. These advantages give organic nanoparticle an edge over inorganic nanoparticle in bio based films. Starch and chitosan based nanoparticle is used in biopolymer based plastic with special emphasis on cellulose based nanofibers [151].

Although extensive research is being undertaken, the nanotechnology approach for packaging applications is still in the development stage. The main focus is to examine the complete life cycle of the packaging (raw material selection, production, analysis of interaction with food, use and disposal) while integrating and balancing cost, performance and impact on health and environment. According to Youssef et al. [130], there is a possibility to produce packages with stronger mechanical, barrier and thermal properties by adding an appropriate nanoparticle in food packaging. Beside improvement in properties of food packaging nanomaterials will also prevent the invasion of bacteria and microbes into packed food products through packaging. Some examples of antimicrobial immobilization into cellulose nanofibers are shown in Table 5. Embedded nanosensors in the packaging will also alert the consumer if a food has spoiled. Liu et al. [152] also reported that the preparation of composites with nanoscale fillers has been considered a promising method for improving the gas barrier and mechanical properties without affecting transparency for packaging applications. Polymers incorporated with clay nanoparticles were among the first polymer based nanocomposites to emerge on the market with improved materials for food packaging and are already used in packaging for carbonated drinks and in thermoformed containers for industrial purposes [153]. Polymers with cellulose fibre/nanoclay based hybrid materials would provide high barrier, short life, easy disposal and environmentally compatible properties for food packaging materials. Active and intelligent packaging includes advances in delayed oxidation and microbial growth rate, and controlled respiration and moisture migration rate. Intelligent packaging also includes time-temperature indicators, ripeness indicators, biosensors and radio frequency identification [154].

A recent study by Vargas et al. [156] explored the potential of cereal straws (oats, maize, rapeseed, barley and wheat) to be used in biodegradable packaging applications. The process used to obtain cellulose pulp was having high yields. The yield of wheat straw was (70%) was highest than other cereal trawls. Starch is the most widely used polysaccharide for the preparation of biodegradable films. Yan et al. [157] extruded a corn starch based film to investigate the effects of extrusion and glycerol content on the properties of the starch film. They found that extrusion did not impact the starch films, whereas the glycerol content had an apparent effect on the mechanical and barrier properties of the film. Moreover, Blick et al. [158] developed biodegradable films for fruit bagging from cassava starch and poly (butylene adipate-co-terephthalate) (PBAT) by extrusion process. Salmieri et al. [159] demonstrated the strong antimicrobial potential of films prepared by using poly (lactic acid) (PLA) containing cellulose nanocrystals (CNC) coated with nisin as a promising bioactive packaging for protecting fresh food products against foodborne pathogens. The film was prepared using the compression moulding method. Lopez et al. [160] developed packaging bags from thermo-compressed films of thermoplastic corn starch containing talc nanoparticles. The mechanical properties of the film were found to increase with talc at concentrations higher than 3% (w/w) of thermoplastic starch.

5. Sustainable packaging

Sustainable packaging is the development of packaging film by utilizing recyclable materials and it involves the use of life cycle assessments and life cycle inventories to minimize the ecological footprint and environmental impact of the packaging. The Sustainable Packaging Coalition (http://www.sustainablepackaging.org, accessed 10 December 2011) defines sustainable packaging as packaging that is:

- Beneficial, safe and healthy for individuals and communities throughout its life cycle;
- Meeting market criteria for both performance and cost;
- Sourced, manufactured, transported and recycled using renewable energy;
- Optimizing the use of renewable or recycled source materials;
- Manufactured using clean production technologies and best practices;
- Produced from materials that are safe in all probable end of life scenarios;
- Physically designed to optimize materials and energy;
- Effectively recovered and used in biological and/or industrial closed-loop cycles.

According to Valdes et al. [161], packaging waste accounted for 29.5% of the total municipal solid waste (MSW) in 2009 in the USA and 25% of the total MSW in Europe in 2006. Packaging waste is currently disposed by landfilling, recycling, incinerating and composting; therefore, there is still much work has to be done to

<table>
<thead>
<tr>
<th>Antimicrobial agent</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnO incorporated into the cellulose acetate nanofiber.</td>
<td>Exhibited strong antibacterial activity against the S. aureus, E. Coli and Citrobacter.</td>
</tr>
<tr>
<td>Silver nitrate (particle size ranging from 10–20 nm) incorporated into the cellulose acetate nanofiber.</td>
<td>Very strong antimicrobial activity against S. aureus, K. pneumoniae, E. coli and P. aeruginosa.</td>
</tr>
<tr>
<td>Silver nanoparticles (average size of 21 nm) incorporated into the cellulose acetate nanofiber.</td>
<td>Excellent antibacterial action against Gram-positive S. aureus and Gram-negative E. coli, K. pneumonia and P. aeruginosa.</td>
</tr>
<tr>
<td>Silver nanoparticles incorporated into bacterial cellulose nanofibers.</td>
<td>Strong antimicrobial potential against E. coli and S. saureus bacteria.</td>
</tr>
<tr>
<td>T4 bacteriophage incorporated into core/shell electrospun fibers of poly(ethylene oxide) (PEO), cellulose diacetate (CDA), and their blends.</td>
<td>Prevent bacterial growth on contaminated food surfaces.</td>
</tr>
</tbody>
</table>
significantly reduce packaging waste present in MSW. A variety of laws have been implemented by governments worldwide to limit the use of plastics and to reduce the amount of packaging waste. In Europe, the Packaging and Packaging Waste Directive (94/62/EC amended by 2004/12/EC) is the tool that is used to reduce packaging waste and to encourage the recovery and recycling of the materials [162]. Currently, consumers are increasingly aware of environmental issues and prefer packaging that is produced from sustainable materials. Many countries have already begun to integrate bio-materials based packaging into their markets. Packaging manufacturers, brand owners and food retailers are becoming more concerned and appreciating the value of high-quality packaging to protect their products [148]. Leading retailers in industries, such as Unilever, are committed to promoting sustainable packaging by designing products that are suitable for waste management practices and minimizing the use of PVC in their packaging products. They are also working to develop strategies to ensure that all paper for the manufacturing of packaging comes from sustainable sources. Billerud, a company from Sweden, is a leading supplier of primary fibre based packaging paper. They are continuing to develop various types of bio-based packaging as alternatives to conventional plastic packaging. By working with natural and renewable materials, Billerud helps to create sustainable development of the earth’s resources [148].

5.1. Principles of sustainable packaging

Sustainable packaging is a complex concept that requires analyses and documentation to evaluate the package design, material selection, processing and lifecycle [163,164]. The objective of sustainable packaging is to incorporate functional and innovative materials in packaging that promote economic and environmental health. Packaging sustainability is often considered to be a marketing tool for promoting and distinguishing a new packaging material [163]. However, packaging sustainability is a highly specialized topic and a considerably more serious and complex concept. Several organizations including Sustainable Packaging Coalition (SPC) in United States and Sustainable Packaging Alliance (SPA) in Australia have attempted to define “sustainable packaging” based on the literature and a survey of key stakeholders. The feedback of the survey highlighted the need and importance of a balance between social, environmental and commercial drivers [165]. Fig. 5 shows the four principles of sustainable packaging identified by the SPA.

The first principle of sustainable packaging is functionality of the packaging materials. The materials designed for the packaging must support sustainable development while effectively protecting the quality of the products. Typically, materials for sustainable packaging are designed to meet regulatory requirements, critical cost, material performance and market demand [166]. The design starts with the selection of materials, clear understanding of the performance of materials on protecting product quality and impact on the life cycle of materials [166]. The second principle of sustainable packaging is recovery of materials to minimize the generation of packaging waste. The effective recovery of packaging materials is a challenge for the development of sustainable packaging [2]. In this context, effective recovery implies significant collection of the packaging materials which is economically viable. There are various methods available for the potential collection and recovery of packaging materials such as biological recovery (composting), technical recovery (recycling) and energy recovery (waste to energy) [2,166]. The third principle of sustainable packaging is that the materials used for packaging should be cycled continuously with minimal material degradation. According to McDonough and Braungart [167], materials designed for packaging should be durable such that they can be continuously recycled and reused or remanufactured. Moreover, it must be ensured that the recovered packaging materials do not contaminate. The fourth principle of sustainable packaging is that the materials used in packaging should be clean and safe such that they do not pose any hazard to human or ecosystem. The basic requirements of sustainable packaging are to eliminate or minimize the hazards associated with the materials used in packaging along with the life cycle assessment of the packaging materials [164]. Packaging materials may contain certain chemicals or harmful substances which can be released and pose hazardous during collection and recycling [74].

5.2. Impact of cellulose nanofibres in sustainable packaging

Cellulose nanofibre has been considered as a remarkable engineering material because of its high abundance, low weight, high strength, stiffness and biodegradability [9,65]. The use of cellulose nanofibre adequately enhanced the mechanical and barrier properties of cellulose fibre based products (e.g., papers, biocomposites). Cellulose nanofibres are derived from natural resources (wood or plant) thus they are almost inexhaustible, renewable and globally abundant [9]. Moreover, cellulose nanofibre neither interferes with the human food chain nor uses petrochemical components for its functionality. Therefore, nanocellulosic fibres have been utilized in a wide range of applications. Packaging sector could be one of the area were cellulose nanofibres can be used for sustainable and green packaging. Studies have demonstrated that the use of nanocellulosic based materials as reinforcing elements in various bio-based polymeric composites enhanced the mechanical and functional properties of the composite, such as their biodegradability, transparency, gas barrier properties, specific surface area and heat stability [93,106]. The key features of cellulose nanofibres in packaging applications for satisfying the sustainable packaging principles and strategies are presented in Table 6.

5.3. Design process for sustainable packaging

Design in engineering and product manufacturing is introduced as a problem solver. Designing plays a role to obtain a goal more quickly and efficiently. An engineering design process is a methodical series of steps [168]. Although the methodical steps tend to be articulated, subdivided, and/or illustrated in a variety of ways, they generally reflect certain inherent principles regarding the fundamental concepts and respective sequence and inter-relationship. The design process may be iterative because it may require repeating the experimental procedure to obtain a highly effective product. The key input of a design process is the early
5.3.1. Define the problem

The first stage of a design process is defining the problem [170]. The definition typically includes detailed information on nanocellulosic production from natural fibre and its limitation towards packaging applications. In a later step, relevant information on existing materials other than nano-cellulose from natural fibre should be collected to develop a problem statement. The problem statement should specifically address the limitations of existing packaging for food and non-food products with a wide range of alternative solutions. The final stage of defining the problem is Establish Criteria for Success [170]. In this stage, possible solutions for the problem statement of nanocellulosic materials for packaging applications should be drawn to provide direction for obtaining desirable output. However, the design should be conducted using the following criteria to produce nanocellulosic materials for packaging applications:

- The process must be cost effective: Recently, American Process Inc, a bio-refinery technology development company headquartered in Atlanta, Georgia, has announced a low cost production of cellulose nanofibrils and cellulose nanocrystals with biofuels using AVAP biorefinery technology.
- The process must be environmental friendly: In 2015 in India with the help of World Bank ICAR-CIRCOT started a nanocellulose pilot plant based on patented energy efficient and eco-friendly technologies.
- The process should be simple to operate with minimal human effort. JeNaCell has now developed an automated production technology for bacterial nanocellulose in a continuous loop without interfering in fermentation.
- The produced cellulose nanofibre should have high tensile, flexural and chemical properties; Currently there is one process that stands out in terms of achieving high mechanical performance is hydrodynamic alignment by flow focusing concept.
- The product should be biodegradable and renewable: Beside impressive mechanical properties and reinforcing capabilities the most appealing properties of cellulose nanofibres are that they are inherently biodegradable and renewable.

It can be observe from above points that attempt has been made to tackle a specific problem at a time. However, there is a need for cumulative effort to address all the challenges like economic viability, eco friendliness, automation, product properties etc. simultaneously for nanocellulose production.

5.3.2. Gather pertinent information to minimize uncertainty

The desired physical, mechanical and chemical properties of the nanocellulosic materials for packaging vary based on the types of materials (i.e., food, non-food, medical, consumer specified product, etc.) to be packed [9]. Therefore, an engineering design for nanocellulosic material for packaging applications is uncertain because designing is often performed with inadequate knowledge.

Packaging plays a significant role in bringing products to consumers in a safe and wholesome manner without compromising product quality [3,130]. Interactions between packaging materials and the packed product might contribute in changing the product quality. It is therefore important to consider several factors (i.e., raw materials, experimental procedure as well as rigidity, tensile strength, flexural and chemical properties of the packaging materials) to develop efficient packaging for products. In this case, multiple sets of design procedures can be conducted with various raw materials and treatment processes of nanocellulosic fibres.
Subsequently, the produced nanocellulosic materials would be tested based on the aforementioned criteria of success.

5.3.3. Simplicity of the design methodology

The purpose of the simplicity of the design methodology is to decide which design procedure will be more suitable for minimizing the uncertainty of the design producer in a simple way to address the product packaging requirements [171]. In this stage, design methodologies on the isolation of nanocellulosic materials for packaging applications would be analysed in terms of the criteria of success. It may be conceptual, but it is important to note the likely behaviour and the promising mechanisms of deformation and failure. Subsequently, a design procedure will be decided based on the likely output of the studied design procedures, the criteria of success and simplicity. A recent study successfully demonstrated a simple freeze drying procedure for nanocellulose production for high performance air filters [172]. However simple methodology of nanocellulose production for sustainable packaging application is yet to be explored.

5.3.4. Optimization of the design procedure

Optimization is an effective tool for minimizing or maximizing a design function. Optimization in engineering has been applied for the past century. Linear optimization and linear least squares optimization methods have been widely used in a substantial number of application areas, including production planning, transportation, design and data fitting. Optimization in engineering design enables problems to be solved more efficiently.

Numerous factors, including cost, safety, productivity, renewable and sustainability of isolated nanocellulosic materials for packaging applications must be optimized to minimize the risks involved with the design procedure. In addition, the optimization process could be applied in the treatment process for the production of cellulose nanofibres from bioresources, such as pulping, bleaching, hydroxylation and nanofabrication processes. However, the optimization could be conducted either mathematically or statistically. In recent years, one of the statistical processes, namely, “Design of Experiments (DoE)”, has been widely used for optimizing the process parameters in various engineering fields [173].

5.3.5. Implementation of the design procedure

Implementation of a design procedure is very crucial. If a design procedure is not implanted safely and if it does not satisfy the criteria of success then the design will not be valid [171]. Thus it will be necessary to review and repeat the design procedure either completely or partially. The methodology used throughout the design process can be applied to ensure that a defensible and robust design has been decided. There is often misconception in engineering design analysis due to minimal validity analyses with input data and failure criteria. If the input information is inadequate the conception of the design will be incorrectly formulated. Thus the validity analysis of the design model must be conducted.

5.4. Importance of designing cellulose nanofibres for sustainable packaging

Innovative approaches using cellulose nanofibres can be a useful tool for the development of sustainable packaging and for the qualitative environmental management of the packaging materials. An effective design of cellulose nanofibre for sustainable packaging may consist of the product quantitatively and qualitatively functioning throughout its entire life cycle [174]. Moreover, designing nanocellulosic materials for sustainable packaging will create a better experience for the end user and also allow for efficient manufacturing systems. Cellulose nanofibre is considered to be a promising natural material and thus it is attractive for the packaging of food, medical, pharmaceutical products and also for other industrial applications. Moreover, the application of cellulose nanofibre in packaging has the tendency to overcome resource efficient challenges by minimizing packaging waste generation due to its recyclability and sustainability [2,74]. The engineering design approach for cellulose nanofibres for packaging will ensure product safety, packaging material sustainability, its quantitative life cycle assessment and cost [165]. An engineering design will help researchers to define the possibilities, limitations and suitability of nanocellulosic fibres for packaging applications [165]. Moreover, a successful engineering design will determine the effective manufacturing process and technology for the production of cellulose nanofibre and its application in packaging. One of the important factors for packaging is to provide a quality product to market. An engineering design will evaluate the product quality and the requirements for product packaging such as level of safety, ergonomics, size, height, thickness and stress levels prior to being marketed. Products that fail the assessment will return to be redesigned.

5.5. Challenges of engineering design for sustainable packaging

A key strategy of engineering design for sustainable packaging is optimizing the employed bio-based materials while ensuring maximum product quality. Availability and price of the bio-based materials, manufacturing process and packaging performance might influence the feasibility of incorporating these materials into a sustainable packaging design. There are various factors that are needed to be considered to incorporate the engineering design of nanocellulosic materials for sustainable packaging applications including durability properties, suitable technology, target market, price, recyclability and sustainability [175]. The quality of recycled materials is of prime concern to the end user in packaging applications due to the concerns over the physical performance, quality, appearance and contamination [156]. Therefore, the engineering design of nanocellulosic materials for packaging applications can be considered successful if the product packaging quality, physical performance and durability properties are higher than those of other types of commercially available packaging materials.

Overall limited research has been conducted at the lab scale on the utilization of nanocellulosic fibre in packaging applications. A successful design process for the production of sustainable packaging materials using nanocellulosic materials depends on defining and solving the existing problem of product packaging. Therefore it is important to conduct lab-scale research on the utilization of nanocellulosic materials in sustainable packaging. Moreover, the present review article strongly recommends conducting lab-scale studies with the collaboration of two or more areas of expertise, including scientists, designers and engineers, where scientists can investigate and propose new formulas for the problems encountered, designers can bring unique skills in design research and engineers will produce accurate use of appropriate technology.

Another important aspect for sustainable packaging is the life cycle assessment of packaging material. However, many industries have not done any impact assessment because of the inherent complexity. Another technical shortcoming is that life cycle assessments are largely confined to existing products and there is a lack of techniques to analyze the environmental impact of new products [176].
6. Conclusion

There is an increasing urgency to define environmental friendly materials and advanced technology to develop sustainable packaging. The use of non-biodegradable and non-renewable materials in packaging applications has raised concerns over environmental pollution. In recent years, cellulosic nanomaterials have attracted the interests of scientists for use in product packaging materials. Cellulose nanofibres are recognized as the most abundant renewable polymeric materials. Thus, the utilization of cellulose nanofibres in packaging would minimize the costs of product packaging and reduce environment pollution. An effective design of cellulose nanofibre can be a useful tool for the development of sustainable packaging and for qualitative environmental management of the packaging materials. The designing is a methodical process for producing innovative products while ensuring product quality and the requirements of product packaging. The primary role of designing is to define the possibilities, limitations and suitability of nanocellulosic fibres for the development of sustainable packaging. However, sustainable packaging is a complex concept that requires analyses and documentation to evaluate the package design, selection of materials, processing and life cycle. The objective of sustainable packaging is to incorporate functional and innovative materials in packaging that promote economic and environmental health. A design process will help researchers to determine the effective manufacturing process and technology for the production of cellulose nanofibre and its application in packaging. A successful design process for the production of sustainable packaging materials using nanocellulosic materials depends on defining and solving existing problems of product packaging. Therefore, it requires conducting lab-scale research on the utilization of cellulose nanofibres in sustainable packaging with the collaboration of two or more areas of expertise including scientists, designers and engineers.

Acknowledgement

The authors are gratefully acknowledged Universiti Sains Malaysia, Penang, Malaysia for providing Research University Grant (RUI-1001/01EKKIND/814255), and Ministry of Education for the Fundamental Research Grant Scheme (FRGS-203/01EKKIND/6711323).

References

[44] Vu THM, Pakkanen H, Alen R. Delignification of bamboo (Bambusa protera acher): Part I. Kraft pulping and the subsequent oxygen delignification to
Yousef M, et al. All-cellulose nanocomposite

Yang Q, Lue A, Zhang L. Reinforcement of ramie

Flisberg P, Rönnqvist M, Nilsson S. Billerud optimizes its bleaching process

Gutiérrez MC, De Paoli M-A, Felisberti MI. Cellulose acetate and short curauá

Jayaramudu J, et al. Structure and properties of poly (lactic acid)/Sterculia


Gladiere M, et al. All-cellulose nanocomposite film made from bagasse cel-

Müller CM, Laurindo JR, Yamashita F. Effect of cellulose fibers on the crys-
tallinility and mechanical properties of starch-based films at different relative

Neo YP, et al. Evaluation of gallic acid loaded zein sub-micron electrospun fiber

Youssef AM, El-Samahy MA, Rehim MHA. Preparation of conductive paper

Khatn V, et al. ZnO-modified cellulose fiber sheets for antibody immo-

Sanchez-Garcia M, Gimenez E, Lagaron J. Morphology and barrier properties of solvent cast composites of thermoplastic biopolymers and purified cellu-

Small AC, Johnston JH. Novel hybrid materials of magnetic nanoparticles and cellu-

Fortunati E, et al. Investigation of thermo-mechanical, chemical and de-
gradative properties of PLA-limonene films reinforced with cellulose nano-

Gutierrez MC, De Paoli M-A, Felisberti MT. Cellulose acetate and short curauá
fibers biocomposites prepared by large scale processing: reinforcing and
reinforcement of solvent cast composites of thermoplastic biopolymers and

Youssef H, et al. Comparative study of paper and nanopaper properties
prepared from bacterial cellulose nanofibers and fibers/ground cellulose

Mora L. Starch-based biodegradable materials suitable for thermoforming

Bradley EL, Castle L, Chaudhry Q. Applications of nanomaterials in food
packaging with a consideration of opportunities for developing countries.

Paunonen S. Strength and barrier enhancements of cellophane and cellulose

Flisberg P, Rönquist M, Nilsson S. Billerud optimizes its bleaching process

Harms RW, Freamon BK, Bliht DW. Indian ocean slavery in the age ofabo-

Zaduha N, et al. Recent trends and future of pharmaceutical packaging

Reddy N, Yang Y. Biofibers from agricultural byproducts for industrial


Kosior E, Braganca RM, Fowler P. Lightweight compostable packaging: lit-

Mullhaupt R. Green polymer chemistry and bio-based plastics: dreams and


Liu H, Yang S, Ni Y. Effect of pulp fines on the dye–fiber interactions during

Siqueira G, Bras J, Dufresne A. Cellulosic biocomposites: a review of

Restuccia D, et al. New EU regulation aspects and global market of active and
intelligent packaging for food industry applications. Food Control 2010;21

Rezaei A, Nasipour A, Fathi M. Application of cellulose nanofibers in food
science using electrosprinning and its potential risk. Compr Rev Food Sci Food

Vargas F, et al. Cellulose pulps of cereal straws as raw material for the

Yan Q, et al. Effects of extrusion and glycerol content on properties of oxi-
dized and acetylated corn starch-based films. Carbohydr Polym 2012;87

Blick AP, et al. Efficacy of some biodegradable films as pre-harvest covering

Salmieri S, et al. Antimicrobial nanocomposite films made of poly (lactic acid)/cellulose nanocrystals (PLA–CNC) in food applications: Part A—effect
of nisin release on the inactivation of Listeria monocytogenes in ham. Cellulose

López OV, et al. Food packaging bags based on thermoplastic corn starch

Valdés A, et al. Natural additives and agricultural wastes in biopolymer

Guzman A, Gnutke N, Janik H. Biodegradable polymers for food packing-
factors influencing their degradation and certification types—a comprehen-

Yam KL, Lee DS. Emerging food packaging technologies: principles and
practice. 80 High Street, Sawston, Cambridge CB22 3HJ, UK: Elsevier; 2012.

Zhang HC, et al. Environmentally conscious design and manufacturing: a

Lewis H, Verghese K, Fitzpatrick L. Evaluating the sustainability impacts of
packaging: the plastic carry bag dilemma. Packaging Technol Sci 2010;23

Ljungberg LY. Materials selection and design for development of sustainable

McDonough W, Braungart M. Cradle to cradle: remaking the way we make
things. 19 Union Square West, New York 1003, United States: MacMillan;
2010.

Poole S, Simon M. Technological trends, product design and the environment.


Benavides EM. Advanced engineering design: an integrated approach. 80
High Street, Sawston, Cambridge CB22 3HJ, UK: Elsevier; 2011.

Nemoto J, et al. Simple freeze-drying procedure for producing nanocellulose


Restuccia D, et al. New EU regulation aspects and global market of active and
intelligent packaging for food industry applications. Food Control 2010;21

Rezaei A, Nasipour A, Fathi M. Application of cellulose nanofibers in food
science using electrosprinning and its potential risk. Compr Rev Food Sci Food