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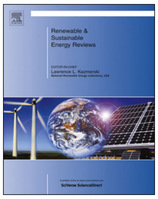

A review on nanocellulosic fibres as new material for sustainable packaging: Process and applications

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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 cellulosic nanofiber 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 nanofiber for sustainable packaging.

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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, thermosetting 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 90cents/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 biopolymer 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 matter at the atomic, molecular, or macromolecular level thus affects functional behavior of biopolymer films.

Cellulose nanofibres 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, cellulosic 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 cellulosic nanofibres 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 level of safety, ergonomics, 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 cellulosic 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

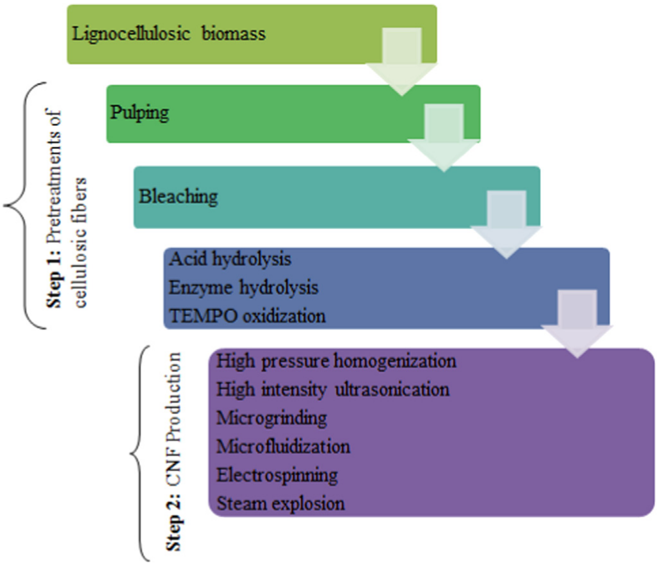

Fig. 1. Process for the isolation of nanocellulosic fiber from lignocellulosic biomass.

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 depolymerisation and eventually solubilises 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]:

- Facilitate the disintegration of CNF,
- Increase the efficiency of the nanofibrillation process,
- Produce highly purified cellulose,
- Remove noncellulosic constituents such as hemicelluloses and lignin,
- Change the surface from hydrophilic to hydrophobic,
- Reduce the size of the fibres to prevent clogging of nanocellulose isolation instruments,
- Decrease energy consumption in mechanical CNF extraction methods.

Table 1
Various pretreatment processes for the production cellulosic nanofiber from cellulosic fiber.

Fiber	Pretreatment process	References
Finnish spruce	Pulping	[23]
Wood	Pulping	**[24]**
	TEMPO oxidation	**[25]**
	Enzymatic hydrolysis	**[26]**
Pine and Spruce	Pulping	[27]
Date-Palm leaves	Pulping	[28]
Date-Palm tree	TEMPO oxidation	[29]
Corn stover,	Pulping	[30]
Wheat straw	Pulping	[30]
Tobacco stalks	Pulping	[31]
Softwood	Pulping	[32]
	TEMPO oxidation	[33]
	Acid hydrolysis	[34]
Eucalyptus	Pulping	[35]
Kenaf stem	Pulping	[36]
Bagasse	Pulping	[30,37]
	Acid hydrolysis	[38]
	Bleaching	[39]
	Enzymatic hydrolysis	[40,41]
Rice straw	Pulping	[42]
Bamboo	Pulping	[43]
	Enzymatic hydrolysis	[6]
	Bleaching	[44]
Corn stalks and Kash	Pulping	[45]
Rice straw	Pulping	[46]
	Acid hydrolysis	[38]
	Enzymatic hydrolysis	[40]
Oil palm empty fruit bunch	Pulping	[16]
	Acid hydrolysis	[34]
	Acid hydrolysis	[16]
Birch chips	Pulping	[47]
Kenaf	Pulping	[21]
Sisal	Pulping	[48]
Spruce	Pulping	[49]
	Enzymatic hydrolysis	[40,50]
	TEMPO oxidation	[51]
Eucalyptus	Pulping	[35]
	Bleaching	[52]
	Acid hydrolysis	[53]
Hardwood	Bleaching	[54]
	Enzymatic hydrolysis	[55]
Cotton	Bleaching	[56]
	Acid hydrolysis	[57]
	TEMPO oxidation	[51]
	Enzymatic hydrolysis	[40]
Jute	Acid hydrolysis	[58]
Rice Hulls	Acid hydrolysis	[59]
Sisal	TEMPO oxidation	[60]
Hemp	TEMPO oxidation	[61]

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

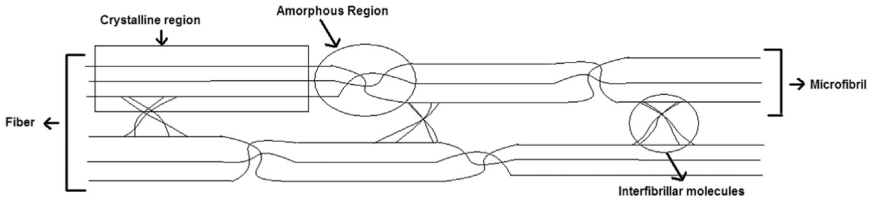

Fig. 2. Crystalline and amorphous regions of cellulose.

Table 2
Advantage and disadvantage of various nanocellulosic fiber isolation processes.

Methods	Advantages	Disadvantages	References
High pressure homogenization	High amount of clogging, need pretreatment to reduce fiber size and prevent from clogging. Quick, effective, continues process. Reproducibility of laboratory results in industrial scale and ease scale-up. Possibility of finding right degree of defibrillation by varying pressure.	High passing time though homogenization. Great energy consumption. Increasing of suspension temperature during procedure.	[64-66]
Microfluidization	Less clogging. Uniformity in reduction of sample size. Fewer cycle are need to optimize fiber processing.	Inappropriate for industrial scale.	[64,66,67]
Microgrinding	Low amount of energy consumption. Less cycle are required to prepare CNF. No need to refining pretreatment.	Difficulty in maintenance and replacement of disk. Reduction in crystallinity of CNF.	[66]
High intensity ultrasonication	High power output. High efficiency of defibrillation.	Generated heat by this method must be dissipated. High level of noise. Pretreatments are needed to release CNF. Only for laboratory scale is useful.	[64,68]

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 cellulose nanofibres.

Recently, considerable attention has been devoted to cellulose 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 II, 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 cellulose 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 cm^3/g of fibres, and a larger lumen size leads to lower

Table 3
Chronological event for the CNF isolation using various technologies.

Year	Progress	CNF isolation technology	Reference
1927	Production of board by wood CNF isolated using steam explosion	Steam explosion	[72]
1930	Formhal introduced electrospinning method	Electrospinning	[73]
1962	Defibrillation of wood pulp by ultrasonication	High intensity ultrasonication	[74]
1983	Defibrillation the wood fibers to CNF	HPH	[75]
2000	Isolation of CNF from potato tuber cells	HPH	[76]
2004	Silylation of CNF from sugar beet pulp and its rheological characterization	HPH	[77]
2005	Comparing the effect of grinding and high pressure homogenization on the properties of isolated CNF	Microgrinding	[78]
2006	Isolation of individualized CNF from never-dried cotton by TEMPO oxidization pretreatment	HPH	[51]
	Study the influence of LiCl, DMAc, NMMO, water solvent system, spinning conditions, cellulose degree of polymerization and post-electrospinning modifications on the structure of electrospun cotton CNF	Electrospinning	[79]
2007	Preparation and characterization of CNF and strong gel from softwood pulp by enzymatic pretreatment and high pressure homogenization	HPH	[80]
	Application of non-dried wood to prepare CNF using grinding process	High intensity ultrasonication	[81]
2008	Evaluation of pressure and hardwood/water slurry concentration to isolate CNF for polyurethane based nanocomposites application	HPH	[82]
	Isolation and characterization of CNF with different degree of polymerization using enzymatic pretreatment and microfluidization to prepare high toughness nanopaper	Microfluidization	[83]
	Electrospinning of cotton in LiCl/(DMAc) to prepare CNF for electro-active paper actuator	Electrospinning	[84]
2009	The effect of ultrasonic time on the properties of TEMPO oxidized wood CNF for nanocomposite applications	High intensity ultrasonication	[85]
	Electrospinning of cotton and wood fiber in TFA and application of the resultant drug loaded CNF for biomedical	Electrospinning	[86]
2010	Comparison between the thermal stability of CNF prepared by atomization, oven and freeze-drying methods	HPH	[87]
	The impact of moisture on the thermo-mechanical and morphological characteristics of electrospun rami CNW/poly (vinyl alcohol)(PVA) composite nanofibers	Electrospinning	[56]
	Isolation and characterization of pineapple leaf CNF prepared by steam explosion	Steam explosion	[71]
2011	Isolation of CNF from bleached birch kraft pulp by grinding and spray drying method and evaluation of environmental and health aspects	Microgrinding	[88]
	Preparation of superhydrophobic and superoleophobic aerogel membranes using CNF from bleached birch kraft pulp by grinding method	Microgrinding	[89]
	The impact of ultrasonication power on the properties of wood CNF	High intensity ultrasonication	[90]
	Nanostructural re-orientation of bacterial cellulose using ultrasonication	High intensity ultrasonication	[91]
	Influence of ultrasonication on the oxidization rate of TEMPO oxidized hardwood CNF	High intensity ultrasonication	[92]
	Electrospinning and characterization of CNF isolated by single or binary ionic liquid solvents system at room temperature	Electrospinning	[93]
	Isolation of banana CNF by steam explosion method	Steam explosion	[70]
	Preparation and properties analysis of wheat straw CNF obtained by steam explosion-high pressure homogenization	Steam explosion	[94]
2012	Preparation of sugarcane bagasse CNF by ionic liquid pretreatment and high pressure homogenization	HPH	[95]
	Preparation of CNF from by microfluidization process to produce nanopaper	Microfluidization	[96]
	Optimization of refining-microfluidization process to isolate CNF from bagasse and rice straw and nanopaper preparation	Microfluidization	[97]
	Measuring young modulus of softwood CNF produced by microfluidization in comparison to bacterial cellulose	Microfluidization	[98]
	Isolation and characterization of sludge CNF by grinding method	Microgrinding	[99]
	Preparation of CNW by ultrasonication from microcrystalline cellulose to reinforce polyvinyl alcohol (PVA) film	High intensity ultrasonication	[95]
	Influence of various bacterial CNW concentration on the properties of ethylene vinyl alcohol (EVOH)/CNW composite nanofibers	Electrospinning	[100]
	Isolation of jute CNF by steam explosion, biodegradation and XRD characterization of CNF/rubber nanocomposites	Steam explosion	[101]
	Dynamic rheological behavior of wood CNF produced by ultrasonication as a function of fiber/water slurry concentration	High intensity ultrasonication	[102]
2013	Comparison between CNF isolated from unbleached kenaf bast and scotch pine produced by microfluidization to improve physical and mechanical properties of hardwood handsheets	Microfluidization	[103]
	Comparison between nanocellulose produced from rice husk and rice straw by ultrasonication	High intensity ultrasonication	[103]
	Preparation of jute CNW/electrospun nanofibrous membrane using immersion-drying method for filtration applications	Electrospinning	[104]
	Isolation of CNF by steam explosion pretreated with ultrasonication	Steam explosion	[105]
2014	Controlling pressure and shear force in microenvironment to homogenous preparation of bagasse CNF by dynamic microfluidizer	Microfluidization	[106]
	Comparison between bleached and unbleached kenaf bast CNF isolated by grinding	Microgrinding	[107]
	Effect of grinding time on the characteristics of CNF	Microgrinding	[108]
	Isolation of softwood CNF by NaOH/urea/thiourea pretreatment and ultrasonication	High intensity ultrasonication	[109]
	Electrospinning of cellulose/cotton CNW with different CNW loading percentages for tissue engineering applications	Electrospinning	[110]
2015	Isolation of eucalyptus CNF by enzymatic pretreatment-microfluidization	Microfluidization	[111]
	Isolation of cotton linter CNW by acid hydrolysis and high pressure homogenization process in thermoplastic starch film	HPH	[112]
	Optimization the isolation process of kenaf nanocellusic fiber	HPH	[21]

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 S_1, S_2 and S_3 (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 S_2) [69]. Essentially, rigid cellulose microfibrils

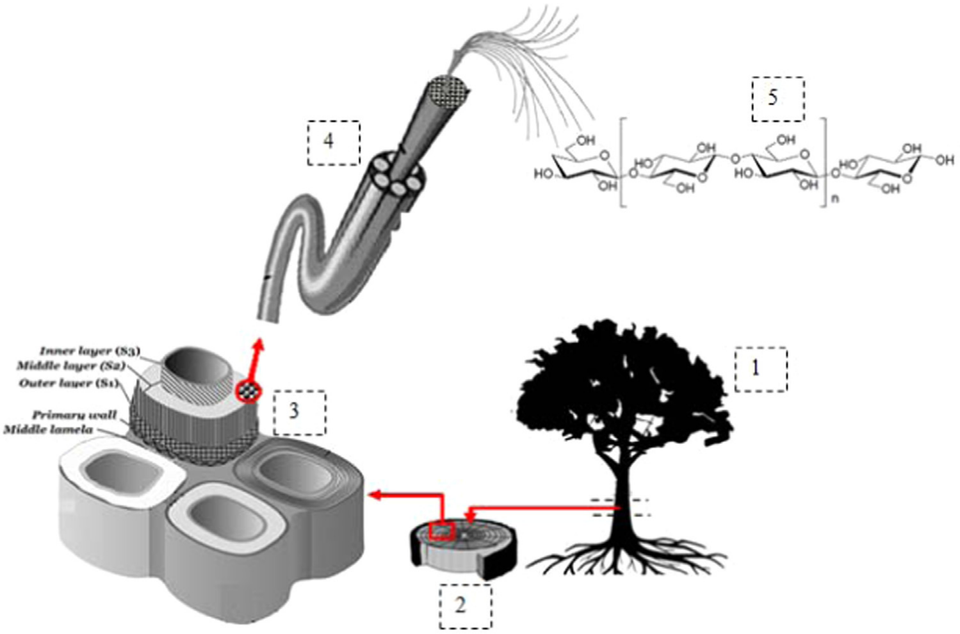

Fig. 3. Schematic drawing of cellulosic fiber hierarchical structure. (1) Bark Cambium pith, (2) Cambium (3) mature cell wall, (4) cellulose fiber, and (5) chemical structure of cellulose.

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 cellulosic 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.

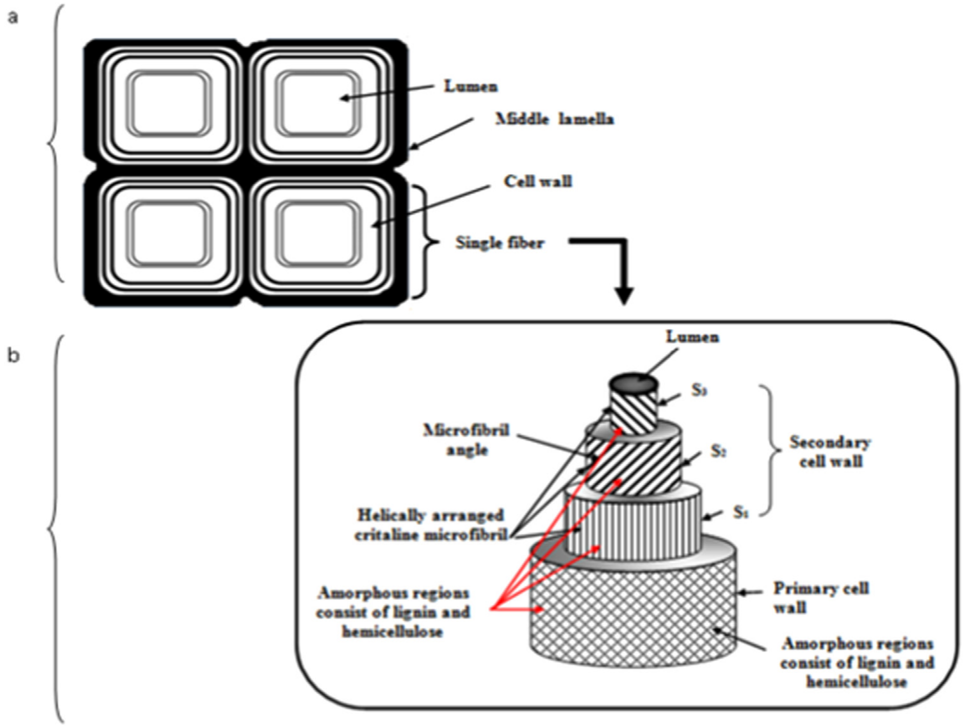

Fig. 4. Schematic drawing of (a) cellulosic fibers; (b) cell wall of cellulosic fiber (Source: [119].

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

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

[123] reported that cellulose based materials offer various advantages, such as edibility, biodegradability, barrier properties, non-toxicity and low cost [123]. Industrial progression would exploit the ecological advantages of converting these valuable biomaterials into value added products for various applications, including packaging. Table 4 highlights the utilization of lignocellulose fibres in packaging for food and non-food products.

4.1. Foods and beverages

Cellulosic 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 Films, released NatureFlex™ a cellulose film that offers an extremely wide heat seal range, printability, long shelf life and good gas barrier properties. These improved properties have allowed NatureFlex™ to find applications in various markets, such as dried foods, confectionary, fresh produce, home personal products, dairy, meat, pouches and tea packaging. This bio based film is certified according to the European (EN13432), American (ASTM D6400) and Australian (AS4736) norms for compostable packaging [142]. Fibre Form® was introduced in 2009 by Billerud Korsnäs, a leading provider of renewable packaging materials originating from Sweden. FibreForm® packaging is consists of 100% primary fibre which offers high elasticity and strength, and its high purity are approved for direct contact with food, furthermore, it can be coated with a wide range of coatings to protect foods from light, moisture, bacteria and other hazard [142].

Elopak is one of the world's leading liquid food packaging suppliers, and this company produces Pure-Pak® cartons that consist of paperboard coated with a polyethylene (PE) layer which 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 cellulosic 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 multilayered 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 integrating functional ingredients in the structure of the packaging with the packed 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 cellulosic 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 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, Bilck 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 5
Some examples of antimicrobial immobilization into cellulose nanofibers [155].

Antimicrobial agent	Function
ZnO incorporated into the cellulose acetate nanofiber.	Exhibited strong antibacterial activity against the S. aureus, E. Coli and Citrobacter.
Silver nitrate (particle size ranging from 10–20 nm) incorporated into the cellulose acetate nanofiber.	Very strong antimicrobial activity against S. aureus, K. pneumoniae, E. coli and P. aeruginosa.
Silver nanoparticles (average size of 21 nm) incorporated into the cellulose acetate nanofiber.	Excellent antibacterial action against Gram-positive S. aureus and Gram-negative E. coli, K. pneumonia and P. aeruginosa.
Silver nanoparticles incorporated into bacterial cellulose nanofibers.	Strong antimicrobial potential against E. coli and S. saureus bacteria.
T4 bacteriophage incorporated into core/shell electrospun fibers of poly(ethylene oxide) (PEO), cellulose diacetate (CDA), and their blends.	Prevent bacterial growth on contaminated food surfaces.

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 packing 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].

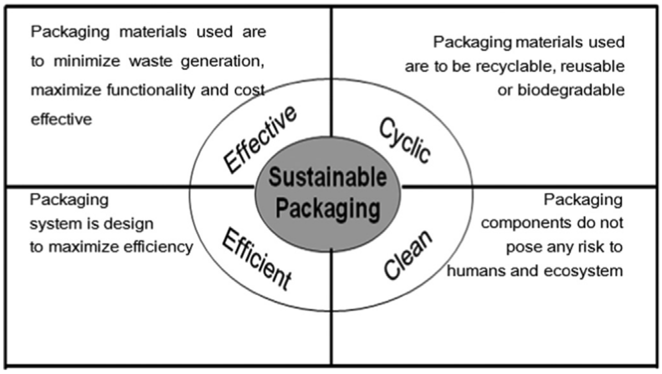

Fig. 5. Sustainable Packaging Alliance (SPA) first definition of sustainable packaging (Source [165]).

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 cellulosic 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 interrelationship. 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

Table 6
Sustainability impact of nanocellulosic fiber in packaging applications.

Principle	Strategies of Sustainable Packaging[a]	Key features of nanocellulosic fiber in sustainable packaging application
1. Effective	Minimize waste generation	Nanocellulosic fiber is biodegradable, recyclable and abundance available; therefore the utilization of nanocellulosic fiber in packaging will lead the packaging materials recycle and reuse [2,63]
	Maximize functionality	The unique properties nanocellulosic fiber including low weight, high strength, stiffness and durability would enhance mechanical and barrier properties of a packaging [115].
	cost effective	Since CNF is available in abundance, recyclable and reusable, thus the application of CNF in packaging would be cost effective [17,22].
2. Efficient	Maximize products to packaging ratio	Nanocellulosic fiber in packaging application has the high potential to maximize the products to packaging ratio due durable and flexible nature of nanocellulosic materials [2,37].
	Maximize materials efficiency	The nanocellulosic fiber in packaging application can be recycled continuously with minimal degradation [2,65].
3. Cyclic	Recyclable Reusable Biodegradable	Since nanocellulosic fiber derived from the natural resource, thus the nanocellulosic materials in packaging application will recyclable, reusable and biodegradable [115].
4. Clean/safe	Minimize airborne and waterborne emissions to environment. Minimize greenhouse gas emissions Reduce toxicity and litter impacts	Ecological impact will minimize with the application of nanocellulosic fiber in packaging. Owning the biodegradable nature, the nanocellulosic fiber will be dispose off after certain use. Thus, the use of nanocellulosic materials in packaging application will minimize the greenhouse gas emissions [65].

[a] Source: [165].

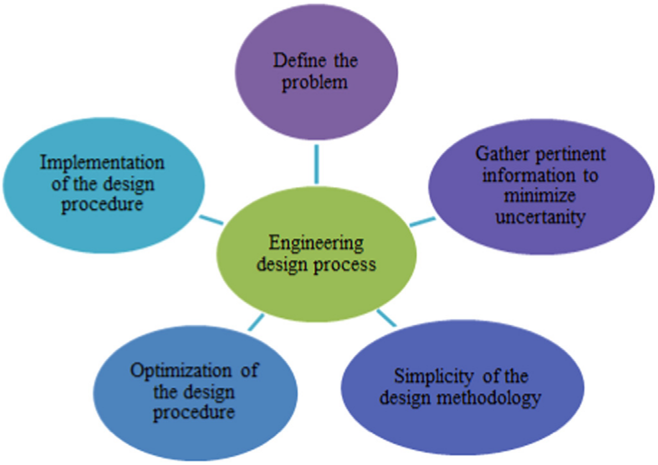

Fig. 6. Engineering design process of nanocellulosics fibres for packaging applications.

stage planning of a project based on key thinking and important decision making. As reported by Bieniawski [169], a design processes is "a sequence of events within which the design develops logically, and a process that provides a work plan in the planning of a design programme". The design methodology for cellulose nanofibres in sustainable packaging applications can be expressed as shown in Fig. 6.

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 nanocellulose 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 cellulosic 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 cellulosic 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 cellulosic 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 nanofibre materials 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.

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