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REVIEW

Plant-Based Natural Fibers For Food Packaging: A Green Approach To The Reinforcement of Biopolymers

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Abstract

Petro-based plastics are linked to various environmental issues throughout their lifecycle, including pollution, greenhouse gas emissions, persistence in marine and terrestrial habitats, etc. The utilization of biopolymers is a prominent substitute for petro-based materials. Further, the reinforcement of natural fibers (NFs) to biopolymers significantly improves the functionality of biopolymers. The functionality of NFs is crucial to promote the interfacial interaction with biopolymers and achieving high-performance materials which could compete with traditional petro-based materials. NFs have several benefits over synthetic fiber, including biodegradability, low density and cost, lighter weight, superior life cycle, and good mechanical properties. This review article focuses on the characterization and properties of plant-based NFs and their synergistic application. This thorough assessment of the state-of-the-art focuses on current research on how NFs can be used for their potential role as reinforcement in the packaging industry.

Keywords Fibers · Biopolymers · Reinforcement · Properties; packaging

Introduction

Environmental plastic pollution has become a priority of major global entities, including the United Nations (UN), the World Health Organization (WHO), the World Economic Forum (WEF), and the European Union (EU). In the context of circular economy and sustainable development, countries worldwide are looking for new materials that are more eco-friendly and cost-effective to replace traditional petrochemical-based plastics [1]. Interestingly, bioplastics are a fast-expanding class of polymeric materials frequently offered as substitutes for traditional petro-based plastics [2]. The sustainability performance of bio-based plastics concluded that bio-based plastics could save up to 315 million tons of CO_2 equivalents annually [3]. Plant-based natural fibers (NFs) are a promising and sustainable reinforcing material for packaging applications because they have several benefits over synthetic fiber, including reduced density, biodegradability, abundance, good damping qualities, less abrasive damage to equipment, and high health safety (Table 1). Several plant-based NFs have been isolated from various parts of the plant, including bast, leaves, seeds, fruits, and stalks [4], which includes jute, cotton, sisal, banana, oil palm, kenaf, pineapple, okra, coir, etc. are widely used in fabrication [5]. According to the Natural Fiber Composites Market Forecast research, the market for Natural fiber–reinforced composites will grow from $4.46 billion in 2016 to $10.89 billion in 2024 (NFC, 2018). In order to address sustainability challenges, including environmental pollution and the depletion of natural resources, NFs-reinforced biopolymer composites are the “green composites” of the future. The advantages of using NFs in composites fabrication are lower specific weight results in a higher specific

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Table 1 Comparison and benefits of using natural fibers (NFs) over synthetic fibers

Properties	Natural fibers	Synthetic fibers	Plastics
Biodegradability	NFs are environmentally friendly, being biodegradable. Examples: cotton, jute, bamboo, etc	Production and decomposition of synthetic fibers are difficult and not eco-friendly	Non-biodegradable
Renewable	Made from renewable resources	Made from petroleum	Made from petroleum
Sustainability	Yes, environmentally sustainable	No, environmentally harmful	No, environmentally harmful
Decomposition	Decomposes naturally without harm to the environment	Does not decompose, releasing toxic substances into the environment	Does not decompose, releasing toxic substances into the environment
Recyclability	Can be recycled multiple times	Limited recyclability	Limited recyclability
Safety	Generally safe for food contact	May release harmful chemicals that contaminate food	May release harmful chemicals that contaminate food
Cost	Can be expensive due to production methods and materials	Can be cheaper due to abundance and production methods	Can be cheaper due to abundance and production methods

Sources: Chadha et al. [80], Bangar et al. [6, 7]

stiffness than glass, low mechanical properties, especially impact resistance, renewable resource, moisture sensitivity, production with low investment, low thermal stability, low abrasion and hence less tool wear, low durability, widely available, poor fire resistance, biodegradable, etc. [5]. NFs are frequently employed as reinforcers/fillers in polymeric matrices where polymers are binding agents for holding fibers together and offering dimensional stability. Reinforcement of NFs improves functionality and broad applicability by improving various mechanical properties, including tensile strength, tensile modulus, bending strength, bending modulus, elongation at break, impact strength, compressive strength, toughness, etc. [5–7]. Further, adding NFs such as flax, sisal, hemp, kenaf, jute, etc., can also improve antimicrobial and thermal properties. Additionally, NFs contribute to the circular economy concept by reducing costs and improving eco-friendliness.

To the best of our knowledge, few studies have compiled this information based on recent research studies to provide the latest scientific support for plant-based natural fiber for biopolymer-based packaging. The current review focuses on collecting, comprehending, and synthesizing the fundamental functions of the characterization, properties, and application of NFs in food packaging. Also, the review examines several strategies to improve and enhance the properties of biopolymer-based materials.

Extraction and Characterization of Natural Fibers

Cellulosic fibers originating from trees and plants are termed natural fibers (NFs). Plant fibers come together to form a stem and ribbon. Fibers are extracted to improve their physical properties and remove cellulose, lignin, and other micro-level fibers. Extraction methods are suitably selected based on the parts of the plant from which the fiber is to be extracted. The choice of extraction methods governs the characteristics and properties of composites fabricated from it. The process of extracting fibers from the plants through separating, dissolving, and decomposing pectins, gums, and other muscle elements is called retting. This process is tedious and time-consuming, and the quality of extracted NFs depends on the skill of the laborer. Retting separated the fibers into smaller bundles and elementary fibers. This is a key process and an important criterion to determine the properties of extracted fibers. Dew and water retting are the traditional methods: other methods include chemical, mechanical, and enzymatic retting. A brief comparison between different retting processes is shown in Table 2.

The deliberation of NFs characteristics is a prerequisite to exploring its usefulness and effective application in composites to replace synthetic polymers. Different kinds of analysis are performed to characterize the plant fibers: physical, chemical, thermal, spectroscopic, and surface morphology. Figure 1. shows the structure characterization of plant fibers.

A physical analysis is fundamental to envision the density and fiber's geometrical parameters. The cell wall length, thickness, diameter, and density are the dominant factors in plant fibers to decide the peculiar physical attributes. The density is generally estimated by employing toluene and a real density analyzer, also known as a helium pycnometer, for pycnometer experimentation. A micrometer instrument or optical microscope predicts diameter, fiber length, and thickness. Comparatively, a more accurate method to determine density is based on standard procedures of ASTM (American Society for Testing and Materials) D8171-18 [8]. Otherwise, Archimedes' principle (using hexane) is also applied to determine fiber density [9].

Every natural plant fiber's chemical composition beholds in species or its variety; the source of fiber is obtained from different parts like stem, root, fruit, leaf,

Table 2 Comparison between different retting processes

Type of retting	Methods	Advantages	Disadvantages	Time-period
Dew retting	The plant material is spread on the ground and exposed to moisture from the atmosphere, which breaks down the pectin and lignin in the fibers	No chemicals are needed, and low cost	Dependent on weather conditions, slow process, and potential for uneven fiber quality	2–10 weeks
Water Retting	The plant material is submerged in water, encouraging microbial activity that breaks down the pectin and lignin in the fibers	Faster than dew retting, more consistent fiber quality	Requires large amounts of water, the potential for water pollution, can be energy intensive to dry the fibers	7–14 days
Chemical Retting	Chemicals such as acids, alkalis, or oxidizing agents are used dot break down the pectin and lignin	Faster than natural retting methods, consistent fiber quality	Requires chemicals that can be expensive and environmentally damaging, can be hazardous to workers	75 min–1 h
Mechanical retting	Plant material is crushed or beaten to break down the fibers Enzymes are used to break down the pectin and lignin in the fibers	Faster than natural retting methods, consistent fiber quality	Can damage the fiber quality and requires specialized equipment	2–3 days
Enzymatic retting	Enzymes are used to break down the pectin and lignin in the fibers	Can be more eco-friendly than chemical retting, and consistent fiber quality	Can be expensive, requires specialized equipment and expertise	8–24 h

Sources: Ramamoorthy et al. [65], Sisti et al. [123], Tavares et al. [124], Ntenga et al. [125]

and seed [10]. The evaluation of chemical composition is important to quantify the plant fiber constituents- (i) cellulose, (ii) lignin, (iii) hemicellulose, (iv) moisture, (v) ash, (vi) wax. This quantification aids in identifying the bonding ability and strength of the fibers [11, 12]. An ideal plant fiber with good mechanical properties must have a high percentage of cellulose. Still, low amounts of other constituents like lignin are required, and hemicellulose, moisture, ash, and wax contents should be small [13, 14]. The specific standard test procedures and specifications are used to evaluate each type of chemical component. The Kurchner-Hoffer procedure determines the composition of cellulose in plant fiber, lignin, and hemicellulose content by ASTM D 1104–56 method, wax by Contard method, and ash by ASTM D 1102–84 method [8].

The surface morphological study of fiber includes the roughness of the fiber surface, structure of the cell wall, diameter, and so on. Scanning electron microscopy (SEM), atomic force microscopy (AFM), and others demonstrate such properties. SEM scans the fiber through a beam of electrons and focuses on the top of the vital facet of the fiber by deducing the secondary signals and backscattered electronic signals to finally provide a high-resolution meticulous image [15]. AFM is characterized by its very high-resolution microscopic property. AFM depicts the resolution up to a fragment of a single nanometer (nm), a thousand times improved resolution compared to the optical diffraction limit. AFM can determine the extraordinary surface parameter such as average roughness of the surface, maximum peak, root mean square (RMS) roughness, and others. Vertical scanning procedures have been adopted to determine fiber surface roughness, specifically using a confocal microscope, confocal chromatic aberration, and coherence scanning interferometer. While scanning, laser microscopy and structured light scanner can also be employed based on the principle of horizontal scanning. However, surface roughness is measured by methods other than scanning, including a digital holography microscope [14]. During the formation of a matrix and composite reinforcement, fiber wettability is considered crucial and drastically influenced by the diameter and roughness of the fiber surface. The wettability of natural fiber relies on the nature and portion of waxes present in the fiber, and it is calculated by contact angle measurement [16].

Fourier-transform infrared (FTIR) spectroscopy analyzes the organic and inorganic compounds qualitatively and quantitatively, providing essential information on chemical functional groups and molecular structures in the natural plant fibers to disclose the accurate chemical composition [17]. The two types of FTIR spectroscopy methods are prevalent, testing absorbance and transmittance. FTIR with transmittance is broadly accepted for NFs [14]. The spectrograms extended by the specific peaks emerge in a graph composed of wave number versus transmittance, which is embodied by

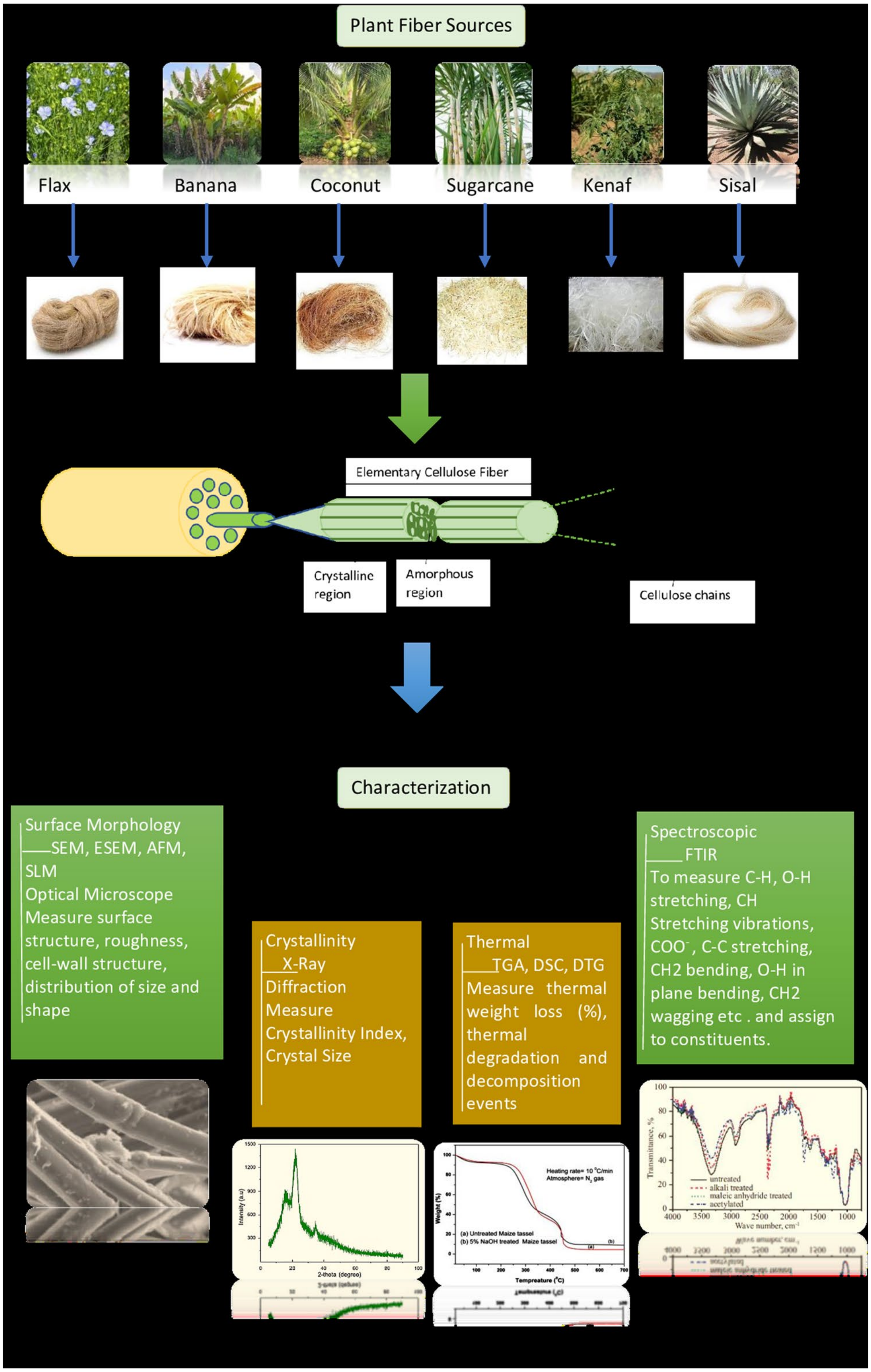


Fig. 1 Characterization of natural plant fibers

the bending, stretching, and vibration brought about by the varied functional groups owned by the fibers [11].

X-ray diffraction is routinely used to analyze the crystal type and crystallinity of plant cellulose [18]. Crystallinity analysis grabs great importance by offering information regarding the nature of amorphous cellulose [19]. Among several diffraction methods, the Segal peak height method is the most prevalent in analyzing cellulose crystallinity [20]. Another method is based on peak deconvolution, in which the area under diffraction peaks is to be divided by the total area Hermans and Weidinger [21]. One more approach given by Rietveld [22] is occasionally applied to determine cellulose crystallinity. Unlike the deconvolution method, this approach uses all the diffraction peaks lost or ignored as the amorphous scattering. But the accuracy of such methods has been doubted. For instance, Scherrer [23] depicted that sharp peaks are related to large crystals, and broad peaks are related to small crystals. When such peaks are enlarged to compare with the peaks that arose from model crystals, it demonstrated that much of the intensity previously attributed to “amorphous scatter” was only the overlapped intensity out of adjacent crystalline peaks [18]. The intensity among the peaks came out of peak overlap and was observed specifically in the region dedicated to only amorphous intensity by Segal. This raise doubt on crystallinity determination by Segal method [24]. same way, many other analysis methods bears the flaws and doubted for their accuracy. French [18] determined the powder diffraction patterns from cellulose Iα, Iβ, II, III_I, and III_{II} on the basis of published atomic coordinates and unit cell dimentions. Their calculation included peak widths at half maximum height of both 0.1 and 1.5° 2θ, offered highly convinced prospects of the each contributing contemplation to the detectable diffraction peaks and intensity profiles, appear more firmly simulate standard cellulose samples.

Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) are the primary analytical instruments to determine the thermal performance and chemical constitution of natural plant fibers. TGA evaluates thermal stability and weight loss percentage in the various constituents of NFs during thermal degradation. Plant fibers have excellent thermal insulation properties; products from such fibers can be used in different thermal applications [14]. Cellulose fiber generally decomposes at around 200 ℃, mainly occurring in the amorphous regions. Whereas crystalline a-cellulose of untreated jute fibers was decomposed at a temperature of 362.2 ℃, but after mercerization, decomposition was reduced to 348 ℃ [25].

Properties of NFs

Morphological Properties

Plant fibers have been widely used for diverse commercial applications for a long. Classification of plant fibers is generally based on botanical origin like (i) bast- kenaf, hemp, ramie, flax, jute, (ii) leaf- bananas, sisal, abaca, pineapple leaves, curaua, raphia, fique, (iii) seeds and fruits- coir, cotton, Java cotton, soybean husk, paddy-husk, (v) stalk- paddy, wheat, corn, barley, rye, oats, (vi) grass- bamboos, baggase, esparto, elephant-grass, canary-grass, switch-grass, (vii) wood fibers- phragmites, rosewood, teak, etc. [16].

Kenaf (*Hibiscus cannabinus L.*) is a native to Central Africa and belongs family *Malvaceae*; it is an annual herbaceous plant that requires a warm season to grow [26]. Kenaf plants are stiff, tough, and strong, with high resistance to insect attack [27]. Kenaf bast fiber is widely utilized for different injection molded or extruded polymer applications in the packaging [28]. One more bast fiber crop, flax (*Linum usitatissimum*), belongs to the same family *Malvaceae* and has been grown in temperate regions since ancient times and grows up to 1 m in height depending on the species [29]. Canada produces and exports flax at the largest level in the world [30]. Flax fiber is found as the most suitable replacement for glass fibers to embody the reinforcements in panel boards, lining, and packaging materials [28]. Hemp (*Cannabis sativa*) bast fiber is obtained from an annual herbaceous plant, belongs to the *Cannabaceae* family, and is largely cultivated in Europe but native to Asia [31]. It attains a height of 1.2–4.5 m when fully grown [32]. Raw Hemp fiber in raw form is generally thin, coarser, shinier, and light-colored hemp fibers are utilized in packaging paper applications [26]. Jute (*Corchorus capsularis*) is an annual plant from the family *Tiliaceae,* which grows in the monsoon season in Asian countries (Bangladesh, India, and China) and grows up to a height of 15–20 cm [33]. Bast fibers from jute are used to manufacture shopping bags and reinforcement materials for polymer manufacturing. Ramie (*Boehmeria nivea*) is a flowering plant belonging to *Urticaceae* family that requires normal soil conditions for growth and grows up to 1–2 m. China, Japan, and Malaysia are the native and the largest producer of ramie [34]. This bast fiber is the longest, finest, and strongest among all bast fibers. Ramie, flax, and hemp bast fibers highly resist insects and pests [28].

Leaf fiber is obtained from the sisal (*Agave sisalana*) plant from the *Asparagaceae* family and reaches up to 1.5–2 m [35]. Sisal is native to Mexico and produced abundantly in Brazil (Varghese et al., 2018). Nowadays, it also grows commercially in India, Brazil, Indonesia, and East Africa. It is comparatively easily cultivated in soil other than clay in hot weather and arid zones. In a life span of 6 to 7 years, the sisal plant produces approximately 200 to 250 leaves for commercial use [36]. Sisal fibers are employed in polymer composites for package trays [37]. Abaca is one of the strongest leaf fibers from the banana (*Musa textilis*) plant from the family *Musaceae*, grown abundantly in Ecuador and the Philippines. Pineapple leaf fiber containing high cellulose, drawn from the pineapple (*Ananas comosus)* plant, belongs to the large genus Ananas of the family *Bromeliaceae*, a tropics plant that originated from Brazil. Pineapple leaf fiber is mostly used in polymer reinforcement applications [29]. Another leaf fiber from the Curaua (*Ananas erectifolius*) plant originated from the Amazon forest and is similar to the pineapple.

Coconut fiber is also known as coir; this lignocellulosic fiber is found between the coconut shell and husk (*Cocus nucifera*). Coconut is a tropical palm belonging to the family *Arecaceae* [38]. The countries, including Indonesia, India, Sri Lanka, Philippines, and Malaysia, are the prime commercial producers of coconut and coir fiber [39]. In particular, coir fiber is light in weight and strong fiber. Coconut coir is getting wide acceptance to reinforce the material in polymers by virtue of its strength and durability [31].

The bamboo (*Bambusoideae*) plant is a kind of grass belonging to the family Poaceae, an evergreen perennial plant that gains a height of approximately 40 m in the monsoon season [29]. Many bamboo plant parts (leaves, hard trunk, and branches) are used to obtain fibers mainly via steam explosion and mechanical treatment [31]. One exquisite property of bamboo fiber is its considerable absorbance of ultraviolet (UV) light, which is utilized to produce handcrafted paper [28]. Bagasse is a stalk fiber, a by-product residue of sugarcane (*Saccharum officinarum*) juice milling. Bagasse fiber is getting acceptance as a reinforcement material for composite preparation [38].

Chemical Properties

The chemical constituents and internal structure of plant fiber provide the basis for the characteristic physical properties. Cellulose, hemicellulose, and lignin are primary units to comprise lignocellulosic structures of plant fibers, including other minor constituents like pectins, wax, ash, proteins, tannins, oils, and inorganic salts. The amorphous components like hemicelluloses, lignin, pectin, and others create a matrix to sustain cellulosic fibrils together, which works as a reinforcement. However, such composition varies in accordance with the plant source or species, plant growth conditions, life cycle phase, and fiber extraction procedure that ultimately influence the structural development and performance of the fiber [40]. These factors must be considered to overcome the quality variation of plant fiber. Further, higher cellulosic content and diminishing microfibrillar angle are responsible for the alluring mechanical attributes [41, 42]. This property is utilized foremost during composites' reinforcement [43]. NFs containing a relatively excellent amount of cellulose, primarily the crystalline parts including cotton, cotton linter, kapok, and ramie, and the low lignin content are subjected to high tensile strength (TS) due to the higher crystallinity [44]. Likewise, the cellulose content of natural fiber from ramie is 68.6–85 wt. %, and higher Young modulus (YM) and TS are produced at 24.5–128 MPa and 400–1000 MPa, respectively [43]. Although several other factors influence the TS, this correlation cannot always be linear [44]. In contrast, rising non-cellulosic constituents pare the TS and YM, thereby decrementing the properties of natural plant fiber-reinforced composites [45]. Pectin and lignin compose the middle lamella of fiber cells; these fiber cells assist in yielding plant fiber structure by compiling and binding fiber bundles. The presence of pectin with lignin in fibril bundles alters the mechanical attributes of plant fibers by plunging the interfacial characteristics among the fibers and composites matrix [46].

Cellulose is a glucan polymer with higher hydrophilic properties and is more thermally stable than hemicellulose. It has a higher thermal decomposition temperature from 315 °C to 400 °C. In natural plant fibers, cellulose unites with pectin and produces a stronger cell wall, helping retain cell structure in water [17]. The glucose units link together to form linear chains via β-(1–4) glycosidic linkages, confer strength, stability, and stiffness, subsequently forming the characteristic cellulose structure with a higher degree of polymerization [47]. Cellulosic plant fiber generally swells when water exposure, demonstrates high moisture absorption, and becomes dimensionally unstable [44]. The hydrophobic and hydrophilic properties of fibers, and when fiber interacts with the respective matrix, significantly affect the adhesion of the fibers with NFs in terms of reinforcement [28].

Lignin is an amorphous and cross-linked polymer, abundantly found in plant cells, that enhances the structural support comprised of non-uniform hydroxy- and methoxy-substituted phenylpropane units [28, 48]. The molecular structure of lignin is aromatic and links by forming an ester bond with hemicellulose. It consists of three functional groups in active form, coniferyl alcohol (G), p-coumaryl alcohol (H), and synapyl alcohol (S). Lignin predominantly forms aryl ether linkage (β-O-4) and is easily cleaved during conversion and depolymerization [49]. Another interesting fact about lignin is that it accounts for destroying UV and forming char in plant fibers [50]. Lignins are comparatively thermally stable and decompose at 165 to 900 °C [17].

Hemicellulose is also one of the primary components of the cell wall of lignocellulosic plants, possessing branched structures and a reduced degree of polymerization. As a result, pre-treatment processing of lignocellulose leads to easy degradation in the liquid fraction. Further, a large amount of pentose (principle hemicellulose) in non-wood plants impacts the evolution of fibrils from fibers by multiplied bond formation, and ultimately flexibility of fiber increases in pulp sheets [51]. Hemicellulose content inversely influences the crystallinity of cellulose, and stunted content incurs beneficial effects on amorphous cellulose [52]. In addition, the existence of hemicellulose downturns the biological and thermal solidity, including moisture absorption in NFs [50].

Pectin is a structurally complex heteropolysaccharide (acidic) largely consisting of esterified d- glucuronic acid and rhamnose residues, which lies in an α-(1–4) chain. Pectin chains enhance the structural solidarity of plant fibers

Table 3 Chemical composition of different plant fibers

Plant Fiber	Cellulose (%)	Lignin (%)	Hemicellulose (%)	Ash (%)	Wax (%)	Pectin (%)	References
Bast							
Flax	71	2.2	18.6–20.6	0.68	1.5	2.3	[43, 48, 126, 127]
Kenaf	31–57	9–21.2	20.3–33.9	2–5	–	–	[127–129]
Jute	45–71.6 -	21–26	13.6–21	0.5–2	0.5	0.2	[55, 127, 129]
Hemp	57–77	3.7–13	14–22.4	0.8	0.8	0.9	[127, 129, 130, 131]
Ramie	68.6–91	0.6–0.7	5–16.7	–	0.3	1.9	[127–129]
Leaf							
Banana	60–65	5–10	19	–	–	–	[130]
Abaca	56–63	7–9	15–25	3	3	1	[10, 16, 30, 33, 38, 52, 132]
Sisal	47–78	7–11	10–24	0.6–1	2	10	[55, 69, 71, 132]
Pineapple	81	12.7	18.80	–	–	1.10	[32, 132]
Fruit							
Coir	32–43	40–45	0.15–0.25	–	–	3.4	[130, 132]
Kapok	64	13	23	–	2.3	4	[132]
Husk							
Rice Husk	35–45	0.5–20	19–25	–	14–17	–	[43, 52, 132]
Wheat Husk	36	16	18	7	–	–	[40]

by means of cross-linking with ions of calcium. The unified role of lignin, hemicellulose, and pectin in the form of a matrix collectively holds the structure of the cellulosic biomass in fiber composites. Plant fiber comprises cellulose (60%–80%), lignin (5%–20%), and an average moisture content of about 20% [28]. The chemical attributes of various NFs are demonstrated in Table 3**.**

Physical Characteristics

Physical attributes of plant fiber are merely related to their chemical composition, but several other factors are also responsible, like plant species, maturity, size, geographical conditions, and methods for fiber extraction [46]. Cell wall length, thickness, diameter, aspect ratio (ratio of length and diameter), and density are generally measured to estimate the physical properties of natural plant fibers. But a reliable density value in natural plant fibers is hard to achieve, considering their porous nature. While the density and lumen size of fiber increase with the increase in porosity and vice versa. Sisal leaf and ramie bast fibers possess low densities of 0.76 g/cm3 and 1.38 g/cm3, respectively [53]. The general range of densities of NFs is 1.2 to 1.6 g/cm3, which is lesser than glass fibers (2.4 g/cm3), thereby producing lightweight composites by incorporating plant fibers [54]. The curtailing density of NFs produces an advantageous effect on particular mechanical properties, so NFs' performance looks right compared to artificial fibers. Correspondingly, ramie fiber showed a low density of 1.0–1.55 g/cm3, illustrating higher strength and YM [43]. Different plant fibers have disparity in diameter measures, which is significant in determining the mechanical performance. Yet, it was seen that mechanical characteristics improve with decreasing diameter of plant fiber [55]. For example, ramie has a small diameter of its fiber, i.e., 20–80 mm, but demonstrates very high YM and TS [43]. The physical characteristics of various NFs are enlisted in Table 4.

Mechanical Properties

The mechanical strength of the plant fiber has been the leading factor to consider when choosing natural plant fibers for precise applications [29]. Mechanical attributes of a plant fiber particularly count on the proportion of cellulose content, degree of polymerization, and microfibril angles.

Table 4 Physical properties of plant fibers [43]

Properties	Flax	Kenaf	Jute	Hemp	Ramie	Banana	Abaca	Sisal	Pineapple	Coir
Density (g/cm3)	1.40–1.50	1.4	1.30–1.49	1.40–1.50	1–1.55	1.35	1.5	1.33–1.50	0.80–1.60	1.15–1.46
Length (mm)	5–900	–	1.50–120	5–900	900–1200	300–900	–	900	900–1500	20–150
Diameter (mm)	12–600	–	20–200	12–500	20–80	12–30	–	8–200	20–80	10–460

Table 5 Mechanical properties of plant fibers [43]

Properties	Flax	Kenaf	Jute	Hemp	Ramie	Banana	Abaca	Sisal	Pineapple	Coir
Tensile strength (MPa)	343–2000	223–930	320–800	270–900	400–1000	500	400–980	363–700	180–1627	95–230
Young's modulus (GPa)	27.60–103	14.50–53	8–78	23.50–90	24.50–128	12	6.20–20	9–38	1.44–2.50	2.80–6
Specific modulus (GPa[g/cm^3])	45	24	30	40	60	9	9	17	35	4
Elongation (%)	1.20–3.30	1.50–2.70	1–1.80	1–3.50	1.20–4	1.50–9	1–10	2–7	1.60–14.50	15–51.40

Table 5 depicts the salient mechanical properties of NFs. The hydrogen bonding and structural linkages of cellulose are the prime determinants of TS and the stiffness of plant fibers [56]. With the increase in the amount of cellulose, TS and YM also rise while decreasing by multiplying the portion of non-cellulosic chemical constituents, like lignin, hemicellulose, pectin, and wax [57]. The fiber strength is evaluated by testing only one fiber or a bundle of fibers. A single unit fiber test offers accuracy in results during practical application, but in reality, the testing with a bundle of fiber is comparatively preferred, considering the ease of performance and faster outcomes.

The cross-section area of the fiber is a key component to impact the strength of the fiber [58], whereas the microstructure and chemical composition govern the mechanical attributes of fibers [59]. During extraction and chemical treatments, the TS of cellulose, hemicellulose, and lignin of gets affected. Besides, soaking carrot grass (*Parthenium hysterophorus*) in alkali increased the TS values [60]. The mechanical attributes of NFs stand nowhere in front of synthetic fibers, but surface modification techniques can improve the mechanical performance of natural plant fibers to a great extent, even with the varied and comparatively lower mechanical properties, in particular, density, TS, microfibrillar angle, specific modulus, modulus of elasticity, in addition to elongation at break. The natural origins of plant fibers attract different fabrication companies to incorporate plant fibers into engineered polymer composite manufacturing [13]. Since plant fibers provide greater advantages over synthetic fiber (Table 4). The administration of plant fibers in reinforcing materials in composites is established by its characteristic TS and stiffness. Generally, plant fibers are rigid (fructurability) and withstand during processing, which makes their specific strength as well as stiffness comparable with glass fibers [48]. Most plant fibers possess diminishing density with competing for YM or elasticity [61]. As per Elanchezhian et al. [62], NFs are easily available, inexpensive, renewable, light in weight, low density, and toughness, and could be a potential replacement for glass and carbon fibers. These biodegradable fibers contain the potency to be applied as a substitute for conventional reinforcement materials during composite manufacturing, where high strength/weight ratio and reduction are prerequisites in various applications.

Microfibrillar angle is a characteristic that deviates amid the different fiber axis and even among the plant species. Microfibrillar angle significantly affects the mechanical features of NFs. The values of the microfibrillar angle are inversely related to TS along with the YM of fiber [63]. For instance, the microfibrillar angle of natural fiber ramie was observed at 7.5, exhibiting a higher TS, i.e., 400–1000 MPa, with 24.5–128 GPa YM [43]. NFs from flax and hemp also have higher TS. The TS of bamboo fiber is somewhat greater than the maximum of the plant fibers, including sisal and jowar [64]. The observation from stress–strain of plant fibers stipulates the low-strain and high-stress properties of ramie, kenaf, pineapple, sansevieria, and sisal, although coconut husk fiber exemplifies high strain and low stress [58]. Further, pineapple and jute fiber followed a similar representation of the stress–strain curve [65]. Karimah et al. [66],Yamanaka et al. [67] also mentioned that the ramie fiber's tremendous mechanical performance was governed by its high molecular weight and amount of cellulose (69%–97%) with limiting microfibrillar angle (7%–12%). It was also reported that sisal fiber has good physicomechanical properties with regard to porosity, bulk, absorbency, TS, and folding strength [68]. Nevertheless, such plant fibers possess stunned stiffness properties balanced with high elastic recovery and elongation [69]. Interestingly, banana stem fiber confers a comparable or even higher mechanical strength than synthetic fibers. These natural plant fibers with great mechanical properties offer substantial scopes to produce brawny composites with synthetic or glass fibers. For instance, enforcing sisal in glass fibers biocomposites multiplied the tensile and bend strength [70]. Hariprasad et al. [71] also exhibited the upsurge in TS of composite, composed of polypropylene by reinforcing fibers from hay, milkweed, kusha grass and sisal fiber.

Applications

Petro-based plastics are the most often used packaging material in the food sector. However, the extensive use of these traditional plastics has had significant adverse environmental consequences and is damaging the environment daily [72]. Due to the increased need for sustainability, the

Fig. 2 Potential applications of plant-based natural fibers for food packaging applications

innovation of bio-derived plastics derived from renewable sources has received a lot of attention [73, 74]. To address this issue, food packaging materials should be replaced with "green" or biodegradable materials, typically NFs reinforced with biopolymer composites. Numerous research has been conducted over the years to find an eco-friendly substitute for these packaging plastics to address the ongoing plastic waste disposal problems [75–77]. Using a sustainable bio-polymer combined with NFs filler produces a biocomposite that provides a technical and potential long-term alternative to plastics in the food packaging market [78]. In this section, the review application of different plant-based fibers for food packaging has been discussed. Figure 2 demonstrates the potential applications of plant-based fibers for food packaging applications.

Sugar Palm Starch (SPS)

The major purpose of food packaging is to protect the quality and food safety throughout transit and storage and to extend the shelf-life of food goods by avoiding adverse circumstances. Packaging materials are employed as a packaging bag and a defensive barrier with a specific function. Sanyang et al. [79] presented sugar palm starch (SPS) as a green biopolymer for developing bio-based packaging materials to tackle the challenges involved with food packaging. One of the substitutes for petroleum-based plastic in the packaging industry is a starch-based packaging material. SPS is advantageous in producing packaging films because it is a compostable, environmentally sustainable polymer derived from renewable sources. According to this study, SPS is often collected from the trunk of sugar palm trees, particularly those that are unproductive and unable to generate sap. Although SPS is a great alternative to petroleum-based food packaging materials, there are some drawbacks that must be addressed before SPS can be considered a high-performing thermoplastic starch for packaging applications. Due to its high hydrophilicity, multiple modification methods were used to resolve the drawbacks in the properties of starch-based films. Using nanotechnology and nanomaterials to improve the functional characteristics of SPS-based films was discovered to be an effective option for food packaging films. Because of their physical and chemical properties, nanomaterials make them broadly accessible in numerous areas [80].

However, it has been found that using a starch polymer as a film has low water barrier capabilities. Due to their high hydrophilicity, multiple modification methods were used to resolve the drawbacks in the properties of starch-based films. Using nanosized NFs during starch biopolymer film preparation is a viable method for improving food packaging films ([81, 82]. The use of nanotechnology to improve the functional characteristics of SPS-based films has been discussed later in this section.

Poly(Hydroxy-3-Butyrate-co-3-Valerate) (PHBV)

Mechanical and gas transfer qualities of food packaging material must be changed as a function of the food product needs to provide optimal preservation. Biodegradable materials are an appealing food storage option for items with a limited shelf life. Poly(hydroxy-3-butyrate-co-3-valerate) (PHBV) is bio-based and potentially manufactured from food industry by-products ([83–85]. However, PHBV is quite costly, and its barrier qualities are too high to meet the demands of respiratory products. As a result, one technique for modulating PHBV while retaining complete biodegradability and lowering final material costs is to blend it with cheap lignocellulosic fibers, including wood fibers, powdered olive stone, spruce fibers, and so on. On the other hand, Berthet et al. [86] obtained lignocellulosic fibers from the olive pomace, wheat straw, and spent grains by dry grinding these agro-wastes to assess their suitability as fillers in PHBV for food packaging. The major purpose of this research was to understand the impact of fiber origin on grinding behavior, interfacial properties, and melt extrusion processability. This research also looked at the correlations between several composite's key structural traits and their ingredients, as well as the composite's attributes. According to the findings, brewing spent grains contained more cellulose, whereas olive mills contained more lignin. The grinding capability and energy usage of various fibers differed due to differences in composition [81, 82]. Meanwhile, the inclusion of fibers harmed the mechanical characteristics of PHBV-based materials, resulting in a significant reduction in both PHBV stress and strain at break, as shown in Fig. 3a. The effect of fibers on water vapor permeability (WVP) isn't the same since adding wheat straw fibers to PHBV enhanced the water vapor transmission rate while adding olive mills lowered the water vapor transmission rate. Therefore, PHBV/wheat straw fiber composites are suitable for respiring food goods, whereas PHBV/olive mills composites are better equipped for water-sensitive products [86].

Biodegradable Composites

Biodegradable composites, including consumable components such as starch and fiber-rich lentil flour, show great promise for application as biodegradable and edible food coatings [87, 88]. Ochoa-Yepes et al. [89] examined the structure, physicochemical properties, and biodegradability of thermoplastic starch films containing rich fiber lentil flour. Starch-lentil flour films with various concentrations of rich fiber lentil flour were prepared by the casting method. It was discovered that adding lentil flour to the composites increased their YM, strength at break, and durability, demonstrating that it is a fantastic enhancer to use as reinforcement for starch-glycerol films, making them more resistant and capable of protecting food products from damage. Moreover, the addition of lentil flour also improved the permeability of water vapor, and all the films were proved to be thermally stable. These films are also completely biodegraded in vegetal compost.

Lignocellulosic Wastes

On the other hand, Sánchez-Safont et al. [78] investigated the eligibility of seagrass (SG), rice husk (RH), and almond shell (AS), which are other kinds of lignocellulosic wastes, as fillers in PHB/fiber composites implementations. Melt blending was used in this work to prepare the PHB/Fiber. While PHB is a great alternative for environmentally friendly packaging, it has significant disadvantages that restrict its usage in food packaging. Using excellent, sustainable fillers to overcome these deficiencies is an appealing and long-term option. The fiber type and content had little influence on the crystallinity of PHB, however, variances in size and shape generated variations in the composite characteristics.

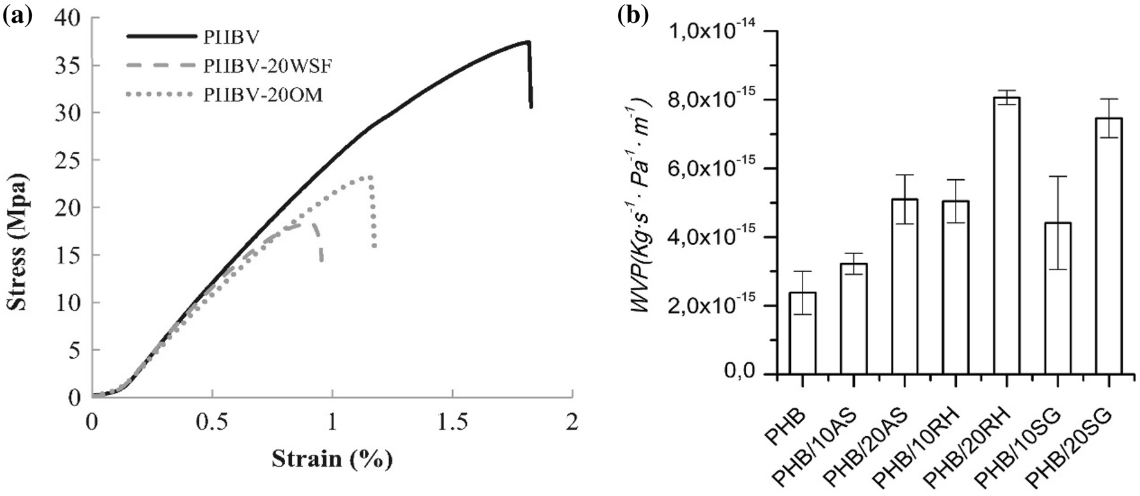
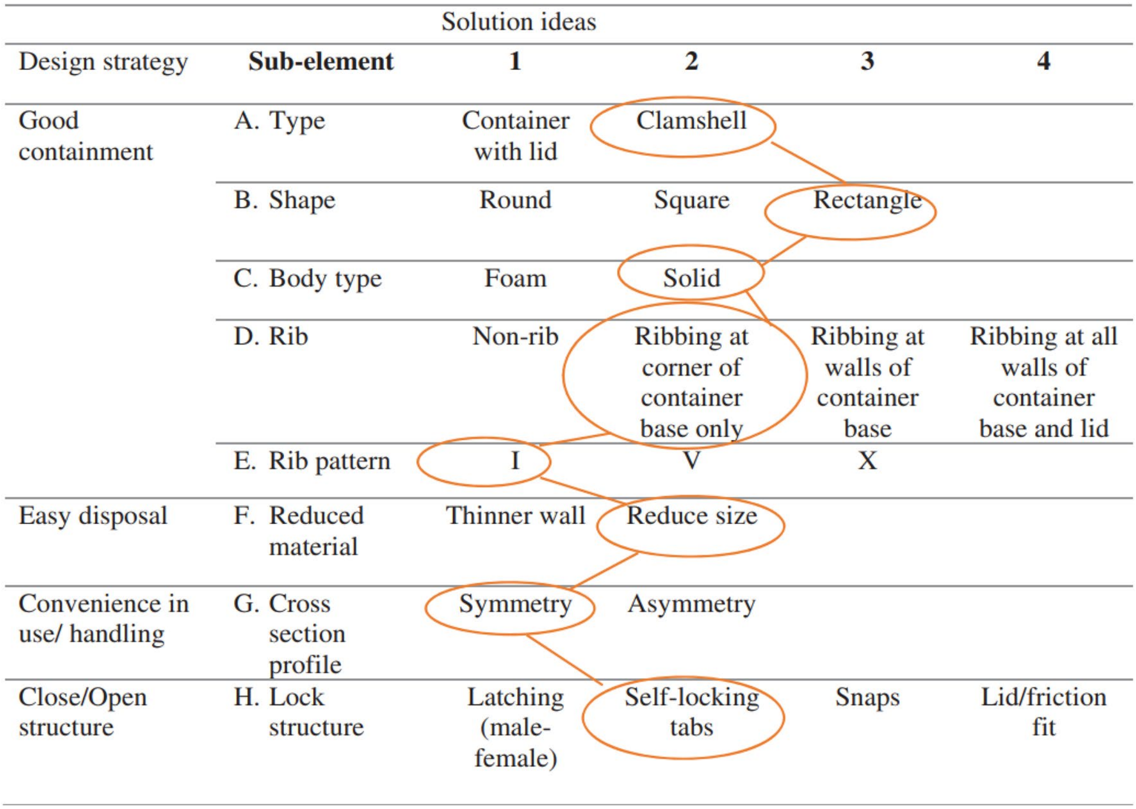


Fig. 3 **a** Stress vs. strain curves of PHBV and PHBV-based composites. **b** WVP of neat PHB and PHB/fiber composites [78]

The addition of fibers was observed to diminish thermal stability and barrier characteristics. When compared to clean PHB, the reduction in barrier performance resulted in an increase in WVP for all of the composites, as shown in Fig. 3b. Meanwhile, the fibers have demonstrated mechanical reinforcement through increased elastic modulus. The addition of AS resulted in the smallest rise in permeability and improved the thermoformability of PHB.

According to Salwa et al. [90], most bio composite materials contain only the matrix or the fiber/filler from natural renewable resources. As a result, green biocomposites, made of full compostable NFs and a biopolymer matrix, would be an excellent choice since they can be decomposed naturally and returned to the environment safely after being used [90]. Biocomposites are advantageous due to their significant mechanical properties and several processing benefits. Furthermore, biocomposites are less expensive, more widely available, lighter in weight, and more environmentally sustainable due to their renewability and degradability. Salwa et al. [91] studied the conceptual design and selection of NFs-reinforced biopolymers. The authors used the Kano Model, Quality Function Deployment for Environment (QFDE), morphological map, and Analytic Hierarchy Method (AHP) framework to describe the conceptual design of biopolymer reinforced with NFs for takeout food containers. The morphological chart (MC) is employed to organize all potential ideas into one place, and the conceptual design is produced by sequentially combining the solution ideas for the design aspects proposed for the food container [92, 93]. The MC created in this design generation activity is shown in Fig. 4. Nineteen generated conceptual designs are detailed. The conceptual designs were created by combining each MC solution. The Autodesk Inventor Professional 2020 design modeling process yielded all the design attributes displayed. In Fig. 5a–f, six idea designs are displayed.

Biocomposite material has gained wide attention from scientists due to the ordered structure of cellulose that produces micro-sized or nanosized dimensions chemically, mechanically, or by combining both means. Nanocellulose can be used to enhance the effectiveness of biocomposites. Nanocellulose can be classified into three types that are a) cellulose nanocrystals; b) nano-fibrillated cellulose; and c) bacterial nanocellulose [94, 95]. Nanocrystalline cellulose is captivating due to its versatility and strength. Nanocrystalline cellulose can be used as a filler while also improving the properties of composites, which makes it a promising biomaterial for food packaging applications [45, 46, 96–98]. The awe-inspiring characteristics of nanocrystalline cellulose were proven in another research work where Hachaichi



		Solution ideas			
Design strategy	**Sub-element**	1	2	3	4
Good containment	A. Type	Container with lid	Clamshell		
	B. Shape	Round	Square	Rectangle	
	C. Body type	Foam	Solid		
	D. Rib	Non-rib	Ribbing at corner of container base only	Ribbing at walls of container base	Ribbing at all walls of container base and lid
	E. Rib pattern	I	V	X	
Easy disposal	F. Reduced material	Thinner wall	Reduce size		
Convenience in use/ handling	G. Cross section profile	Symmetry	Asymmetry		
Close/Open structure	H. Lock structure	Latching (male-female)	Self-locking tabs	Snaps	Lid/friction fit

Fig. 4 A chart with the ideas of new conceptual designs for the new biocomposite takeout food containers [91]

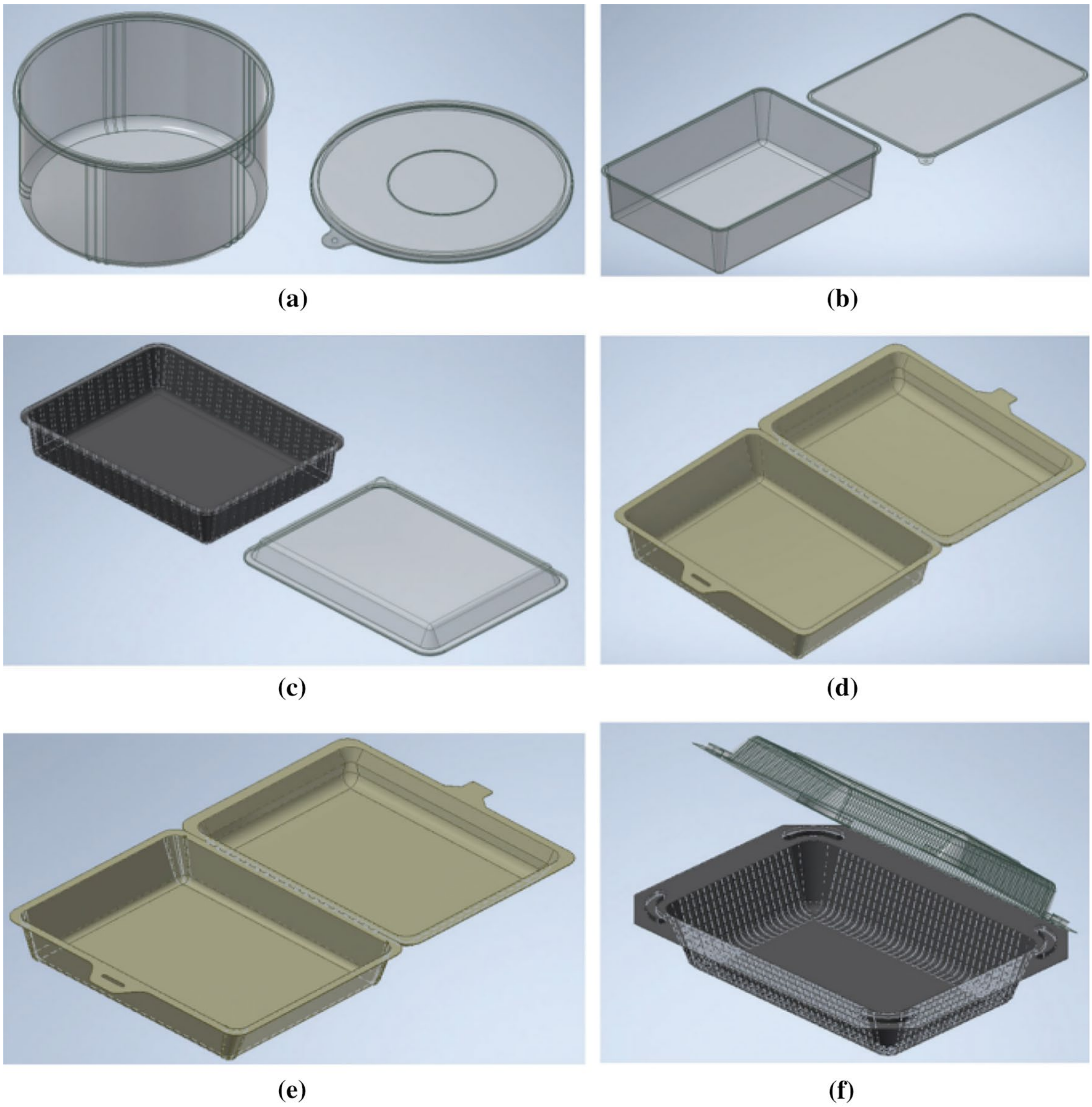


Fig. 5 **a** CP-2; **b** CP-6; **c** CP -10; **d** CP-13; **e** CP-14; **f** CP-18 [91], where CP = Conceptual design

et al. [99] successfully managed to isolate nanocrystalline cellulose (NCC) from date palm microcrystalline cellulose (MCC-DP) by sulfuric acid hydrolysis. NCC is gaining popularity owing to its remarkable properties, which include a wide surface area, a high aspect ratio, and greater mechanical and barrier properties. NCC was characterized to investigate its properties. As illustrated in Fig. 6, the morphological investigation using FESEM and TEM demonstrated the effective extraction of NCC from MCC-DP when the samples displayed noticeable needles. The findings of the XRD spectra suggest that NCC is acceptable for usage in excellent tensile applications, and the thermal analysis suggests that it has strong thermostability, implying that it might be employed in high-temperature synthesis processes [100]. Hence, the isolated NCC could be a potential bio filler for food packaging applications [6, 7].

Starch Polymer

Another study focused on using a starch polymer as a film. Even though starch is a viable solution for non-biodegradable plastic, the starch polymer has been demonstrated to have poor water barrier qualities when used as a film. Based on the research that various researchers have done, it can be concluded that adding nanosized NFs like nanocrystalline celluloses (NCCs) while preparing the starch biopolymer film is an impactful technique for enhancing the characteristics of packaging films [96, 97, 101–104]. It was also

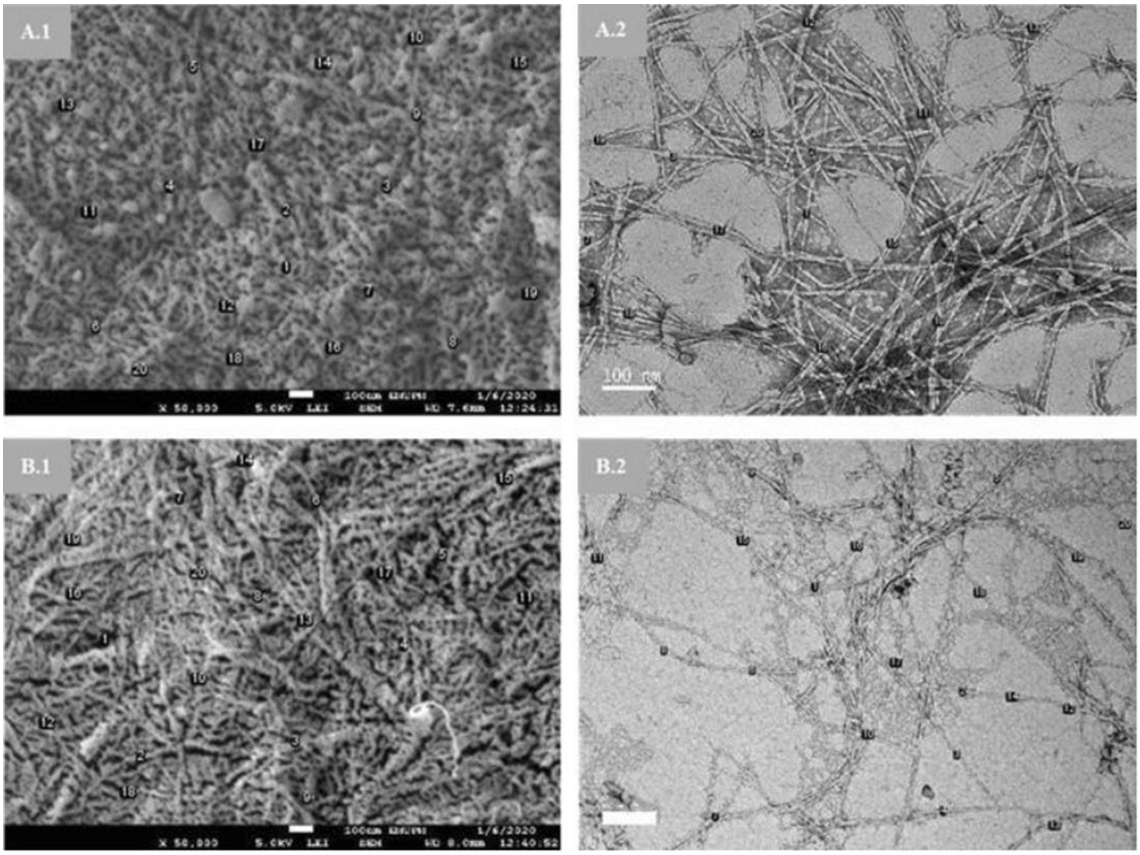


Fig. 6 FESEM (A.1, B.1) and TEM (A.2, B.2) images of NCC **A** and NCC **B** [99]

discovered that the nanocellulose and the starch matrix have high compatibility, which is important for improved barrier properties of the film. Consequently, Ilyas et al. [94, 95] synthesized sugar palm cellulose nanocrystals (SPCNCs) nanocomposites and used them as a biodegradable reinforcing material to boost the barrier properties of an SPS-based film. SPCNCs of varied sizes based on hydrolysis time were inserted into SPS plasticized with glycerol and sorbitol. The biodegradation analysis revealed that SPS degraded faster than SPS/SPCNCs by reducing 61.93% of its weight at the end of 7 days. Furthermore, when the size of the SPCNCs reinforced bio matrix was reduced, the WVP effect on the SPS and SPS/SPCNCs bio nanocomposites improved significantly. Hence, SPS/SPNCCs bionanocomposite showed good biodegradable and WVP properties for food packaging applications. The main objective is to minimize the production and material costs of these nanocomposites so that they can compete with synthetic polymers. To address these obstacles, researchers continue to develop innovative methods for making food packaging materials without neglecting food packaging safety.

Corn Starch Film

In another research work, by introducing immobilized bacteria, Bagde et al. [101] created an antibacterial corn starch film with increased. A flexible film was created using corn starch and glycerol. A bio-mechanical technique was used to produce nanocellulose crystals from cotton liners. After then, CNC was added to the corn starch film to increase its mechanical and barrier qualities. Then, as an antibacterial agent, a bacteriocin produced from LAB was put into the starch film to make antibacterial packaging. Incorporating bacteriocin-immobilized nanocellulose crystals into antibacterial films increased TS, antibacterial potential, and biodegradability. The addition of CNC increased the WVP of starch films by 36%, and the addition of BIN increased it by 41%–46%. When bacteriocins were introduced, however, the decrease was 19%–23%. Meanwhile, after including CNC, bacteriocins, and BIN in the films, a drop in WVP was seen, with the least reduction when CNC was introduced and the greatest reduction when bacteriocins were added. Also, the films incorporated with BIN were not spoiled for 28 days. Based on the findings of this study, corn starch film mixed with BIN might be a suitable antibacterial packaging film with better mechanical qualities. Other biopolymers, including chitosan and gelatin, have developed as viable options for petro-based packaging materials that provide the required packaging performance while being biodegradable. Unfortunately, when gelatin and chitosan are used independently for food packaging, they do not meet the food packaging standards due to various deficiencies. To solve this issue, Kumar et al. [105] employed solution casting to effectively produce a hybrid nanocomposite film composed of chitosan (CS), gelatin (GL), polyethylene glycol, and silver nanoparticles (AgNPs). The use of AgNPs as a filler in CS-GL biocomposite improved the antibacterial activities, thermal, mechanical, and barrier potential of the film. Several films with varying levels of chitosan and AgNPs were created in this work. The addition of silver nanoparticles improved mechanical properties and decreased transparency in the visible light region. The analysis shows that the TS decreases, whereas the percentage elongation at break increases when AgNPs concentration in the films increases. TheTS and extensibility of film are essential in determining its capacity to preserve integrity in the face of external stress factors involved with packaging applications. The storage time of red grapes covered in the developed CS-GL-AgNPs hybrid film was investigated with plastic wrap as a control to assess its potential food packaging applicability. Figure 7 shows red grapes covered in films for 14 days of storage at 37 ℃. The red grapes coated with the CS-GL-AgNPs hybrid film stayed fresh and free of odours, while the surface remained smooth and free of juice leakage. The findings suggest that the CS-GL-AgNPs hybrid films produced might be a suitable food packaging material capable of protecting food from microbial contamination and extending its shelf life.

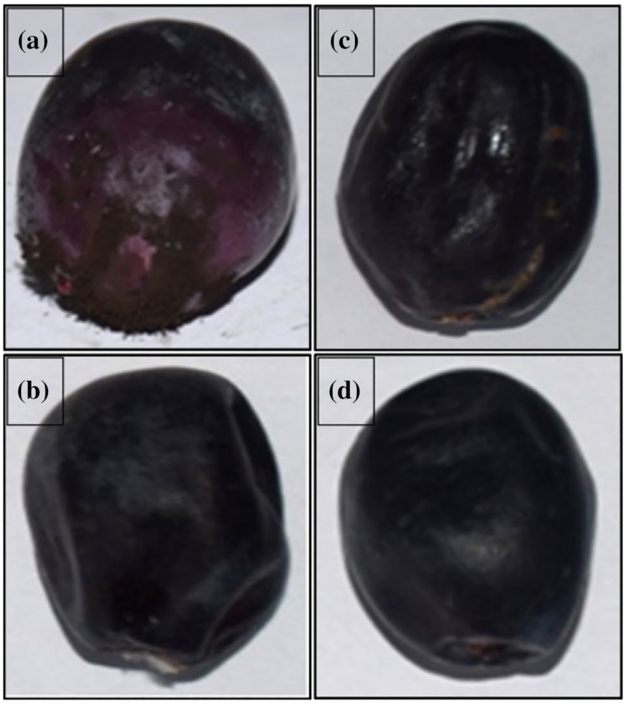


Fig. 7 Pictorial representation of red grapes packed with **a** Plastic, **b** CS-GL film, **c** CS-GL-AgNPs (0.05%) film & **d** CS-GL-AgNPs (0.1%) film after 14-days storage at 37 °C [105]

Compatibility Issue Between Biopolymers and NFs Materials

Biopolymers and natural fibers (NFs) have been widely used in composite materials due to their biodegradable nature and excellent mechanical properties. However, biocompatibility is major drawback fibers face due to improper wetting and improper bonding to the composite, leading to poor performance [14]. The choice of biopolymer and NF material depends on their compatibility, which plays a crucial role in determining the final properties of the composite product. Compatibility issues between biopolymers and NF materials:

The main compatibility issue between biopolymers and NF materials is their lack of intermolecular interactions [106]. Biopolymers are typically hydrophilic and have a high affinity for water molecules, while NF materials are typically hydrophobic and have a low affinity for water. This leads to poor wetting of the NF material by the biopolymer, resulting in weak adhesion and poor dispersion of the NF material in the biopolymer matrix. This, in turn, leads to poor mechanical properties of the composite product [106]. Another common compatibility issue is the difference in polarity between the biopolymer and NF material. Biopolymers are typically polar, while NF materials are nonpolar. This leads to a difference in surface energy between the two materials, leading to poor wetting and adhesion [107].

To improve their compatibility and dispersion and distribution into an organic medium, two different strategies are usually practiced, specifically: (i) introduction of compatibilizing agents; for example, modified polymers containing polar groups [108], and (ii) chemical modification including,alkaline treatment/mercerization [109], acetylation treatment/esterification [110], silane treatment [111], benzoylation treatment [112], permanganate treatment [113], peroxide treatment [114] and maleated coupling agents [115]. When fiber surfaces are chemically treated, the chemicals enhance the intermolecular hydrogen bonding between the fibers, inhibiting fiber dispersion within the polymer matrix. Many researchers stated chemical treatments to improve fiber strength, fiber stiffness, and adhesion between fiber and matrix of natural fiber-reinforced composites [109–115] (Table 6).

Table 6 Chemical modifications of natural fibers and their effects on biocomposites

Biocomposites (Polymers + natural fibers +)	Modifications	Results	References
PLA + kenaf fiber	Peroxide treatment	↑ crystallinity index and surface roughness of fibers due to the removal of lignin and hemicellulose after the bleaching treatment ↑ surface roughness of the fiber improved the mechanical interlocking between the fiber and the PLA matrix	Razak et al. [114]
Polyester epoxy + jute fibers	Benzoylation treatment	↑ hydrophobic nature of the fiber and improves fiber-matrix adhesion, ↑ increases the strength and thermal stability	Singhal and Tiwari [112]
MAH-g-PLA + wood fiber	Maleated coupling agents	Better "coupling effect" in composites	Zhang et al. [115]
Polyester epoxy resin + sugarcane Bagasse Fiber	Permanganate treatment	↑ tensile strength, with an increase of as much as 26.37% modulus	Vidyashri et al. [113]
PLA + Bagasse fiber	Silane treatment	↑ interfacial compatibility of composites improved by silane coupling agents, ↓ mobility of PLA chains which hinder the crystallization of composites	Hong et al. [111]
Polyester resin + sisal & cattail fibers	Alkaline treatment/mercerization	↑ mechanical properties of fiber-reinforced polyester composites	Mbeche et al. [109]
PLA + Kenaf fiber	Acetylation treatment/esterification	As acetylation time was increased by 2 h, the composites were stronger and had strength than non-acetylated fibers	Chung et al. [110]

Industrial and Commercialization of Natural Fiber

Plant-based NFs are becoming increasingly popular as a sustainable alternative to synthetic materials for food packaging [116]. The industrial importance of plant-based natural fibers for food packaging lies in their environmental sustainability, biodegradability, and renewability [117]. Unlike synthetic materials, plant-based NFs are not derived from non-renewable resources and do not create as much environmental waste. In addition, they are biodegradable and can be composted, reducing the impact on landfills and the environment [118].

Plant-based natural fibers can be commercialized by using them to create a range of food packaging products such as bags, pouches, and containers. These products can be marketed to businesses in the food industry, such as grocery stores, restaurants, and food manufacturers. Additionally, consumers are becoming more conscious about the environmental impact of their purchases and are willing to pay a premium for eco-friendly products. Besides that, according to Martins [119], many customers are willing to pay more for sustainable products with high-quality, environmentally friendly packaging. Furthermore, sustainable products can be profitable. In the UK, the market for such goods was valued at £41 billion (approximately $56 billion) in 2019, indicating significant potential for financial gain. Similarly, in India, sales of organic and sustainable products have grown by 13% since 2018. As environmental concerns continue to rise on a worldwide level, an increasing number of companies are becoming more mindful of how the purchasing decisions of consumers can impact the environment. As such, they are placing more emphasis on promoting eco-friendly products and taking note of consumer behavior in this regard.

Sun and Yoon [120] conducted a study on a new theory-driven approach to understanding what makes consumers purchase eco-friendly products at a premium price. It draws on the Theory of Planned Behavior (TPB). It employs variables such as attitude toward eco-friendly companies, subjective norm, perceived behavioral control, ethical consumption consciousness, etc., to validate the factors affecting consumer behavior towards eco-friendly products. The results indicate that attitudes towards environmentally friendly products and ethical consumption consciousness positively impact the intention to buy them at higher prices. Therefore, marketing plant-based natural fiber food packaging to consumers can also be a lucrative strategy [121]. Motivating the industrial sector towards biopolymer food packaging can involve several strategies, including:

1. Raising awareness: Educate the industry about the benefits of biopolymer food packaging, such as reduced environmental impact, cost-effectiveness, and improved consumer perception. This can be done through workshops, seminars, and other forms of outreach.
2. Providing incentives: Offer incentives to companies that switch to biopolymer food packagings, such as tax breaks or grants. This can encourage companies to make the change by offsetting the costs associated with transitioning to new packaging material.
3. Collaboration: Foster collaboration between stakeholders, including suppliers, manufacturers, and distributors, to develop and implement sustainable biopolymer food packaging solutions that meet the needs of the industry.
4. Regulatory support: Provide regulatory support by creating policies that mandate the use of biopolymer food packaging or incentivize its use. This can provide a framework that encourages companies to switch to biopolymer packaging.
5. Highlighting successful case studies: Highlight successful case studies where companies have switched to biopolymer food packaging and seen positive results, such as increased sales or reduced environmental impact. This can help demonstrate the benefits of biopolymer food packaging and encourage others to change.

To successfully commercialize plant-based natural fiber food packaging, it is important to consider cost, durability, and performance factors. The cost of production and the durability of the packaging are important considerations for businesses looking to switch to more sustainable options. Additionally, the packaging should be able to perform its intended function, such as preserving the freshness of the food and preventing contamination [122]. Overall, motivating the industrial sector towards biopolymer food packaging will require a multi-faceted approach that addresses the economic, environmental, and social benefits of such a shift.

Challenges and Future Perspective

Despite the advantages of using NFs in packaging systems, there are also some challenges.

1. NFs are hydrophilic that cause moisture absorption and, consequently, swelling of the fibers, although, in the context of the materials for respiring food packaging, this property is considered an advantage. The polymers have hydrophobic properties, so their fiber affinity is weak. The good interfacial adhesion between the matrix and the filler is a key factor associated with the processing and production of composites. So, there is always a challenge of affinity of fibers to polymer matrices.
2. Compared to synthetic materials, natural fibers may not be as strong and durable, which can affect the overall performance of the packaging. Additional processing and treatment may be required to improve their strength and durability, which can increase costs.
3. Natural fibers can be more prone to contamination by bacteria, fungi, or other microorganisms, which can affect the hygiene and safety of the packaged products. Special precautions may be required to prevent contamination during processing and storage.
4. Further, there is a research gap regarding the safety, durability, and especially recyclability of NFs-reinforced polymer composites. The major technical challenges for recycling and application of NFs-reinforced polymer composites that need to be addressed include polymer and fiber degradation, high moisture content, flammability, variation in the natural fiber composition, and poor bonding between hydrophilic fibers and hydrophobic polymers.
5. A major challenge for external recycling of NFs-reinforced polymer composites is the contamination and immiscibility of polymers during recycling.

There is a future need to modify the NFs by chemical or physical means to impact the production of composites positively. Interesting materials that can be used in the food packaging industry are hybrid materials, such as nano clay/natural fibers filled composites with the polymeric matrix. This kind of composite is usually characterized by combining the advantages of components with eliminating their disadvantages. Future work must be performed to investigate more effective additives to improve composite properties. Fundamental research on the fiber-matrix interface for improving interfacial adhesion is necessary.

Conclusion

The present food packaging situation relies mostly on synthetic plastics derived from petroleum. As a result, excessive pressure is placed on using non-renewable fossil resources, and the non-biodegradable nature of these polymers makes municipal trash disposal extremely problematic. All these difficulties need the search for biodegradable alternatives that can handle them all simultaneously. NFs have shown great potential to replace synthetic fibers in packaging applications. They offer several advantages, such as renewability, biodegradability, and low cost, making them a sustainable and eco-friendly option. Various NFs such as jute, kenaf, sisal, and hemp have been used in combination with biopolymers to produce composites with excellent mechanical properties. However, the compatibility issue between biopolymers and NFs can lead to poor dispersion and weak adhesion resulting in decreased mechanical properties. Modifications of NFs have been used to improve the compatibility between biopolymers and NFs, leading to improved functionality of composite material. With ongoing research and development, NFs are expected to become even more prevalent in the packaging industry leading to a more sustainable future.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Human and Animal Rights This research contains no experiments with human participants or animals.

Consent to Participations All authors have approved the manuscript and agree with submission to Cellulose.

Consent to Publications This work is original and has not been published elsewhere, nor is it under consideration by another journal.

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