Green, Natural Fibre and Hybrid Composites

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Abstract The use of composite materials has seen a surge in many applications such as aerospace, automotive, marine, and medical and sports equipment. The increasing demand for more sustainable and renewable materials has increased natural fibres' interest as a reinforcement for composite materials. Natural fibres are environmentally friendly, but they also have high specific properties due to their lightweight. This chapter provides an overview of natural fibre and hybrid composites, the types of fibre used, their extraction methods, properties, and microstructure. Moreover, a special section is dedicated to the conversion techniques from fibres to preforms, and the manufacturing methods from preforms to final composites. At the end of the chapter, there is a comprehensive list of all commercial applications of natural fibre composites compiled from JEC Composites Market news from 2011 to 2019, with a discussion on the prospects of adopting natural fibre composites in the industry.

1 Introduction

The twentieth century's advent brought a new generation of composite materials marked by their high strength to weight ratio, high specific stiffness, and outstanding corrosion resistance compared to most common metallic materials, such as steel and aluminium. Composites can form directional mechanical properties, low thermal expansion properties and high dimensional stability. This unique combination of outstanding mechanical, thermal and physical properties makes composites eligible to take over traditional materials in many applications, especially when weight saving

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is needed. Composites are currently used in various applications such as aircraft, spacecraft, satellites, ships, wind turbine blades, automotive, chemical equipment, sporting goods and construction technology.

Most of the current commercial composites are made from petroleum-based synthetic polymers. This raises a sustainability concern, due to the reliance on the ever-depleting petroleum resource, concerns about environmental pollution, increased petroleum price, and disposal difficulty. Meanwhile, naturally based materials are abundant from agriculture, animal resources, and urban environments that accumulate to problematic levels. This raises a major challenge on maximizing the sustainable and profitable use of these natural resources as a raw material for high value-added products which require innovative and environmentally friendly solutions. Consequently, the utilization of natural-based materials (green resources), has gained considerable attention. Green composites are made up from natural fibres as reinforcements, such as wood pulp, kenaf, hemp, flax, jute, sisal, wool, silk…etc. and matrix. Matrix or resins could be synthetic or could be natural or green based. Using synthetic matrix with natural based materials as reinforcements or vice versa, this is called hybrid composites.

Natural fibres are fibres obtained from natural sources which could either be a protein or cellulosic fibres. Protein or animal fibres are mostly obtained from animals, while cellulosic fibres are obtained from plants. Cellulose natural fibres consist of three main organic constituents; cellulose, hemicellulose, and lignin.

Usually, cellulosic fibres are classified depending on the part of the plant from which they are extracted, for instance, fibres extracted from the stem are classified as bast fibres. In contrast, fibres extracted from the leaves are classified as leaf fibres, in addition to other parts of the plants, such as seed, fruit, stalk, or grass as shown in Fig. 1.

Natural fibres could be further classified into two types based on how they are found in nature. First, fibres that are present in fibre form. Second, fibres embedded in a natural matrix. The first type of fibres is used right away since the fibres are already found in fibre form, they don't need further extraction, they may only require washing, drying then cutting such as cotton and wool. However, the second type of fibres requires further processing through many extractions or separation processes. These processes could be chemical, biological, or mechanical. The extraction process is considered successful upon efficient extraction of the cellulose fibrils from the hemicellulose binding them and from within the lignin matrix in which they are embedded. Examples of these types of extracted fibres are flax, hemp, jute, sisal, etc.

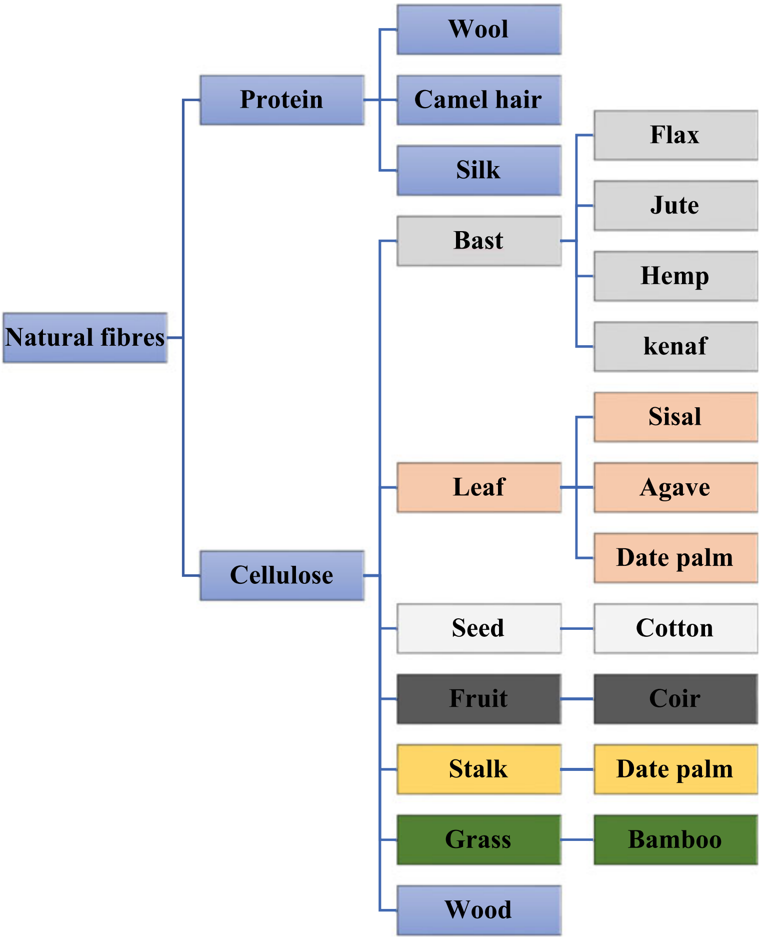

Fig. 1 Natural fibre classification [1]

2 Cellulosic Fibres

2.1 World Consumption of Cellulosic Fibres

Cellulosic fibres are the primary natural materials used in technical applications, especially composites, Table 1. shows the world consumption of natural cellulosic fibres by type in values and quantities. Cotton fibres are excluded as they mainly used for textile applications. As it can be noticed that Flax and Jute are the two most consumed natural fibres. Flax and Jute are used in many other applications rather than composites such as clothing, home textile and packaging materials.

Table 1 World consumption of vegetable fibres by fibre type in values and quantities

	$US million			10^3 tons		
	2010	2017	CAGR (%)	2010	2017	CAGR (%)
Flax	1641.00	1963.20	2.6	427.8	455	0.9
Jute and other bast	1056.90	1085.60	0.4	815.9	592.4	-4.5
Coconut	306.4	543.1	8.5	672.5	1080.10	7
Hemp	10.9	16.3	5.8	13.2	20	6.1
Sisal	5.8	8.2	5.1	5.7	4	-4.9
Other vegetables	77.9	93.6	2.7	31.6	0	–
Total	3100	3700	2.6	2000	2200	1.3

Table 2 Unit values of vegetable fibres in US$/Kg

	$US/ Kg*		
	2010	2017	CAGR (%)
Flax	3.8	4.3	1.7
Jute and other bast	1.3	1.8	5.1
Coconut	0.5	0.5	1.4
Hemp	0.8	0.8	−0.2
Sisal	1.0	2.0	10.4
Other vegetables	2.5	0.0	–

*Unit values (for each fibre) are average of fibre, yarn and fabric form

As it can be noticed from Table 2 that Flax prices are the highest among the other natural fibres. Jute comes after Flax from the price point of view. This can be attributed to using these fibres in other high added value applications such as clothing and home textiles, as mentioned earlier.

The Asia Pacific and Europe are the main regions consuming natural fibres, as indicated in Table 3. It is known that Asia Pacific countries are primary producers

Table 3 World consumption of vegetable fibres by region in values

	$US million		
	2010	2017	CAGR (%)
Asia Pacific	1244.4	1825.7	5.6
Europe	1110.6	1028.6	−1.1
Middle East	447.3	460.0	0.4
North America	228.0	299.3	4.0
Africa	162.3	168.3	0.5
South America	64.2	48.0	−4.1
World	**3270**	**3830**	**2.3**

for many natural cellulosic fibres such as Jute, Kenaf, Coir, Kapok…. etc. While in Europe are the primary producers of Flax fibres namely France, Belgium, Belarus and Ukraine.

2.2 The Microstrucsssture of Cellulosic Fibres

Cellulosic natural fibres, which are also called lignocellulosic fibres, consist of three major organic constituents, cellulose, hemicellulose, and lignin. Table 4 indicates the percentages of cellulose, Lignin and Hemicellulose of some standard natural cellulosic fibres. This structure is thought to be like a composite; where cellulose is surrounded by hemicellulose and embedded in lignin as a matrix, as shown in Fig. 2. Lignin is an amorphous organic polymer that consists of aromatic structures in addition to aliphatic chains. Lignin acts as a natural glue, and it binds the cellulose fibres together. Its weight fraction is 10–25% for non-woody plants and 20–30% for

Table 4 Cellulose, lignin and hemicellulose content of some standard natural cellulosic fibres (1, 2, 3, and 4)

Fibre	Cellulose (wt. %)	Hemicellulose (wt. %)	Lignin (wt. %)	Waxes (wt. %)
Cotton	82.7	5.7	0.7–1.6	0.6
Bagasse	55.2	16.8	25.3	–
Bamboo	26–43	30	21–31	–
Date palm fibre (midribs)	45.47	24.9	29.31	–
Flax	71	18.6–20.6	2.2	1.5
Kenaf	72	20.3	9	–
Jute	61–71	14–20	12–13	0.5
Hemp	68	15	10	0.8
Ramie	68.6–76.2	13–16	0.6–0.7	0.3
Sisal	67–78	10–14	8–11	2
Abaca	56–63	20–25	7–9	3
Coir	32–43	0.15–0.25	40–45	
Oil palm	65	—	29	–
Pineapple	81	—	12.7	–
Banana	64	20	5	–
Curaua	73.6	9.9	7.5	–
Wheat straw	38–45	15–31	12–20	–
Rice husk	35–45	19–25	20	–
Rice straw	41–57	33	8–19	8–38

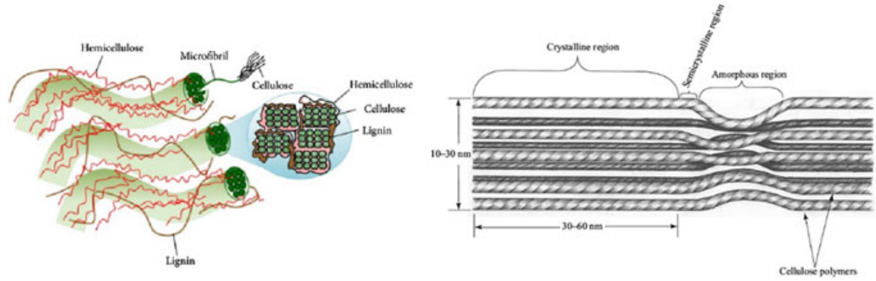

Fig. 2 The microstructure of natural cellulosic fibres and cellulose polymer chains showing cellulose crystalline and amorphous regions [1]

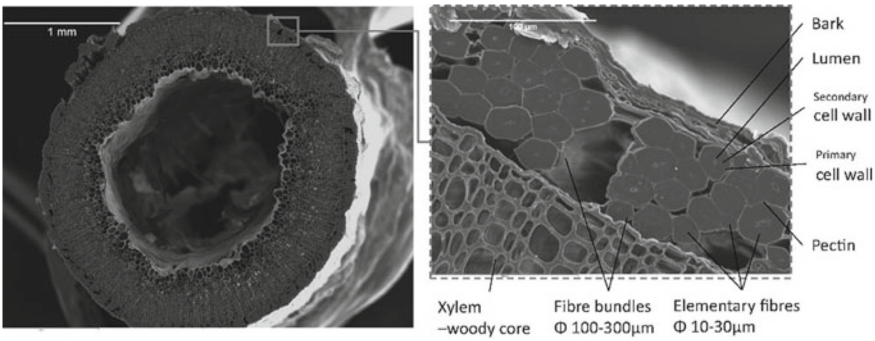

Fig. 3 SEM image of the cross-section of flax plant stem [3]

woody plants. The hemicellulose acts as the bridge between cellulose microfibrils and lignin.

Cellulosic fibres have both crystalline and amorphous regions. Crystalline regions are highly oriented and packed, unlike the amorphous regions, as shown in Fig. 2. Native cellulose initially found in plants is cellulose I, while after alkaline treatment it is converted to regenerated cellulose or cellulose II. Cellulose I is a crystalline material formed of parallel chains oriented in the same direction with amorphous regions between the crystalline regions as shown in Fig. 2. Native cellulosic or cellulose I fibres such as cotton, flax, jute, ramie…etc., have a high degree of crystallinity ranged from 65 to 70%. On the contrary, regenerated cellulose fibres or cellulose II have crystallinity ranged from 35 to 40% [2]. Figures 3 and 4 are showing the morphological structure and the cross-section of different cellulosic fibres.

2.3 Cellulosic Fibres Classification

As mentioned earlier in this chapter, cellulosic fibres are classified depend on the part of the plant from which they are extracted; for instance, fibres extracted from

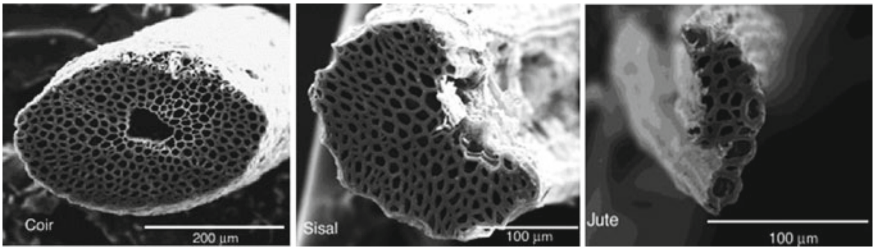

Fig. 4 SEM image Cross-section of different cellulosic fibres [4]

the stem are classified as bast fibres. In contrast, fibres extracted from the leaves are classified as leaf fibres.

1. ***Bast fibres***

Bast fibres are those obtained from the stems of different plants. Flax, Jute, Hemp, Ramie and Kenaf are the main plants used to supply bast fibres. Bast fibres, especially Flax, are long, fine and soft, so they are usually used for textile, sacks and cordage products. Bast fibre has a high cellulose content which can reach up to 70% as shown in Table 4. Bast sfibres crystallinity can be 80 to 90%, which lead to better mechanical properties [3, 4].

2. ***Leaf fibres***

Leaf fibres are extracted from leaves of flowering plants (monocotyledonous) that usually have parallel-veined leaves. The main plants supply the leaf fibres: sisal, abaca, pineapple, banana and Date palm leaves. Leaf fibre can have cellulose contents as high as 70% [3]. Longleaf fibre can be obtained in sisal and abaca plants, where the fibre can reach 1 to 4 m long [5]. These fibres are usually used for cordage as it is long and stiff.

3. ***Seed fibres***

Seed fibres are obtained from the seed of plants. Cotton is one of the most known and used fibres, which is obtained from seeds. Cotton fibre has a high cellulose content reach 85–91% with a crystallinity around 65%.

4. ***Fruit fibres***

Fruit fibres are usually obtained from the fruit of the plant. Coir fibre is the most widespread fruit fibres. It is obtained from the outer shell, or husk, of the coconut.

5. ***Stalk fibres***

Stalk fibres are extracted from the straw or stalk of different crops such as rice, wheat and barley. These fibres usually have a length of 0.5–2.5 mm and have low lignin, while the cellulose level is broadly similar to wood [4].

6. ***Grass fibres***

sAlso known as grass, canes or reeds fibres. Sugar cane (bagasse) and bamboo are examples of canes fibres. At the same time, Esparto Spanish grass or Halfa are examples of grasses fibres and reeds that are a common fibre source. These fibres are usually used to make different technical products such as ropes, sandals, baskets, mats and paper [4].

7. ***Wood fibres***

Wood fibre is mostly obtained from the wood tree. Wood fibre usually has a high lignin content and short length in millimetres to not be spun or woven. The main applications of wood fibres in wood composites are particle boards and MDF and paper making.

2.4 Cellulosic Fibres Extraction

The cellulosic part of the lignocellulosic material can be obtained by removing the non-cellulosic parts, lignin and hemicellulose. This process is called fibre extraction in which one has to get rid of the non-cellulosic materials and get the high crystalline part which is the cellulosic fibres. The reason is that the non-cellulose components, such as lignin and hemicellulose, do not contribute to the tensile loads, limiting the fibre's load-bearing capacity. Besides, noncellulosic materials accelerate biological, ultraviolet and thermal degradation [6].

Fibre extraction methods include different techniques. It could be biological, chemical and physical. The extraction techniques can be listed as shown in Fig. 5. Each method has its advantages and disadvantages in terms of the yield and quality of the extracted fibres. One technique could be chosen, or it could be a combination of more than one technique to achieve the maximum cellulose content.

2.5 Cellulosic Fibres Properties

Interest in natural fibre-based products is growing for many reasons such as low cost, lightweight, biodegradability and sustainability. The type of fibre selected for a certain application depends on its properties. Consequently, natural fibres characteristics such as mechanical, physical and chemical properties will be of great importance when the material is selected for any engineering or technical applications.

Although all-natural cellulosic fibres have the same three main constituents which are cellulose, hemicellulose and lignin, yet, they differ in the content percentages as it can be seen above in Table 4 which directly lead to a significant difference in the physical and mechanical properties such as density, fibre length, tensile strength and modulus.

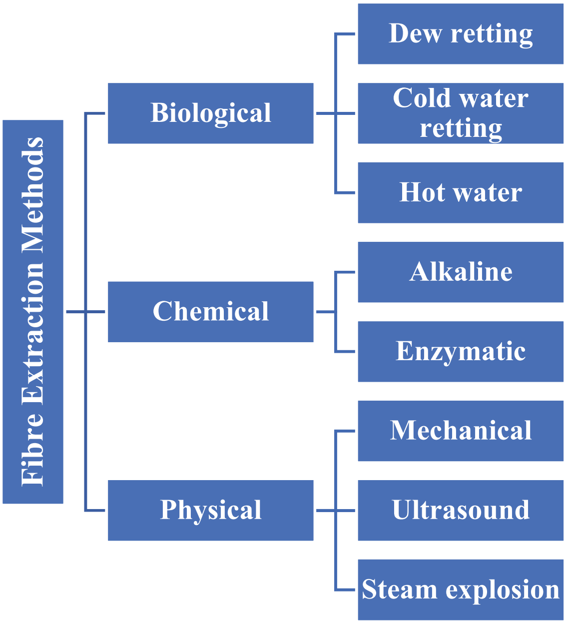

Fig. 5 Cellulosic fibre extraction methods [7]

It can be clearly noticed from Table 5 that flax, hemp, ramie and jute fibres have the highest mechanical properties (tensile strength and young modulus). Specific tensile strengths of flax, hemp, jute and ramie are very close to E-glass values, while the specific young modulus is equal to or greater sometimes than E-glass.

It is proven that achieving high mechanical properties in natural cellulosic fibres is related mainly to three critical factors: cellulose content, crystallinity, and microfibrils in fibre axes direction. These factors tend to be achieved in bast fibres such as flax, jute, hemp, kenaf and ramie. It should be noted that the properties of natural fibres suffer from high levels of variability, which is common in all-natural products.

Natural fibre properties can differ significantly depending on chemical composition and structure, which are related directly to the following factors:

- Fibre type
- Growing conditions
- Harvesting time
- Extraction technique
- Treatment
- Storage conditions.

Examples of such effects of factors mentioned above are the tensile strength reduction that has been noticed for flax fibres due to changing the extraction method from manually to mechanically. The drop was around 20% [8]. Tensile strength was reduced by 15% over 5 days after optimum harvest time in hemp fibres grown in New Zealand [9]. The tensile strength of hemp fibres grown in windy and dry conditions

Table 5 Natural sfibre properties compared to E-glass [17]

Fibre	Density (g/cm^3)	Length (mm)	Failure strain (%)	Tensile strength (MPa)	Young's Modulus (GPa)	Specific tensile strength (MPa/g cm^3)	Specific Young's modulus (GPa/g cm^3)
Ramie	1.5	900–1200	2.0–3.8	400–938	44–128	270–620	29–85
Flax	1.5	5–900	1.2–3.2	345–1830	27–80	230–1220	18–53
Hemp	1.5	5–55	1.6	550–1110	58–70	370–740	39–47
Jute	1.3–1.5	1.5–120	1.5–1.8	393–800	10–55	300–610	7.1–39
Harakeke	1.3	4–5	4.2–5.8	440–990	14–33	338–761	11–25
Sisal	1.3–1.5	900	2.0–2.5	507–855	9.4–28	362–610	6.7–20
Alfa	1.4	350	1.5–2.4	188–308	18–25	134–220	13–18
Cotton	1.5–1.6	10–60	3.0–10	287–800	5.5–13	190–530	3.7–8.4
Coir	1.2	20–150	15–30	131–220	4–6	110–180	3.3–5
Silk-	1.3	Continuous	15–60	100–1500	5–25	100–1500	4–20
Feather	0.9	10–30	6.9	100–203	3–10	112–226	3.3–11
Wool	1.3	38–152	13.2–35	50–315	2.3–5	38–242	1.8–3.8
E-glass	2.5	Continuous	2.5	2000–3000	70	800–1400	29

was lower than those grown under wind-free conditions [10]. The effect of fibre treatment showed significant influences on cellulosic fibres' physical and mechanical properties such as tensile strength, stiffness, crystallinity index, crystals size, degree of polymerization, and fibre surface properties [11–13]. Alkaline treatment or mercerization is one of the standard methods to treat natural fibre. During the mercerization process, lignin and hemicellulose are removed, which leads to:

- More fibrillation
- Less fibre diameter
- More surface roughness
- Increase surface area
- More reactive sites on the surface of fibre which leads to better fibre wetting.

Exceeding the optimum mercerization parameters, NaOH concentration, treatment duration, and treatment temperature will harm mechanical and physical properties. In many studies, it was proved that a transition from cellulose I (crystalline) to cellulose II (amorphous) would occur at severe alkaline treatment conditions. This transition will lead to a significant deterioration in mechanical properties [14–16].

3 Manufacturing Techniques of Natural Fibre and Hybrid Composites

Having known the fibres composition, types and characteristics, this part of the current chapter is devoted to illustrating the different manufacturing processes and techniques used to manufacture natural fibres and hybrid composites. Before we go forward to manufacturing techniques, it is necessary to go through a crucial issue: fibre architecture because many composites are firmly dependent on the arrangement and distribution of fibres inside the matrix. The fibre architecture definition encompasses many fibre parameters such as fibre diameter and length and the fibres' structural configuration [18].

3.1 Preform Manufacturing

Yarns used to prepare the composite preforms could be spun yarn or continues filaments, as shown in Fig. 6. Continuous filaments (CF) are mostly synthetic materials such as polypropylene, polyester and polyamide also CF could be regenerated cellulose such as rayon, modal, bamboo…etc. Continuous filaments are produced by melt spinning in case of thermoplastic polymers. On the other hand, wet or dry spinning is used to produce CF in thermoset polymers.

Spun yarns are produced by gathering together a bundle of staple fibres and then twist it to increase cohesion force between the staple fibres, consequently, form a

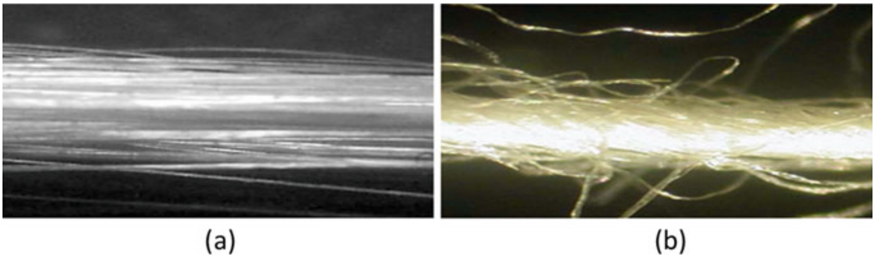

Fig. 6 Yarn types, **a** continuous filament yarn, and **b** spun yarn

yarn with enough mechanical properties for further processing. Ring spinning, open-end spinning, and air-jet spinning are the most used techniques to produce spun yarn from different staple fibres such as cotton, flax, jute, wool…etc.

Yarns either continuous filament or spun, can be assembled in different architectural forms as illustrated in Fig. 7. It could be stacks of unidirectional plies or produced using existing textile technologies such as weaving, knitting or braiding.

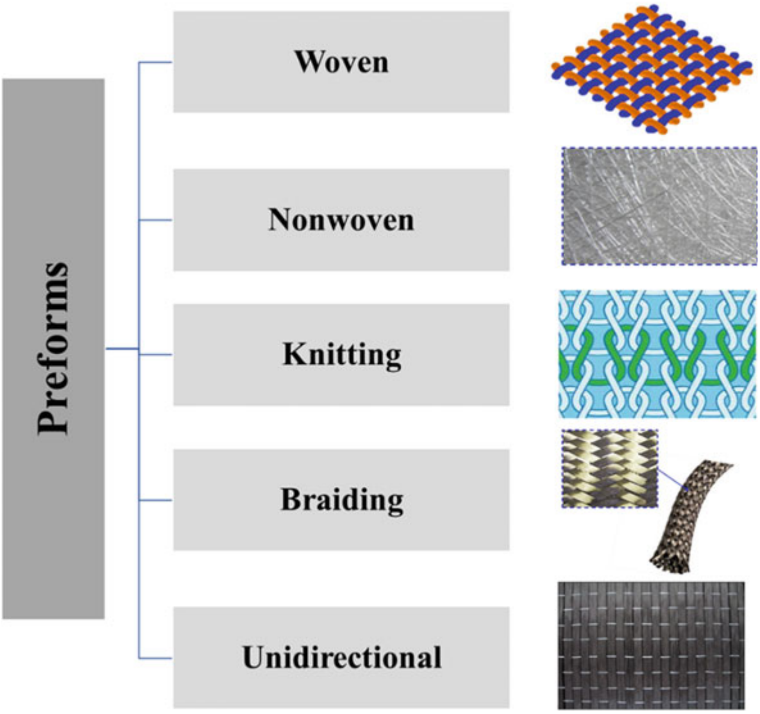

Fig. 7 Types of preforms

Woven fabric is composed of two constituents, warp yarns and weft yarns, usually the angle between the warp and weft direction is 90o. The most critical parameters of woven fabrics are related to fabric constructions.

Woven fabric construction parameters are:

- Dimeter of warp yarn or warp yarn count
- The diameter of weft yarn or weft yarn count
- Number of warp yarns per cm (warp density)
- Number of weft yarns per cm (weft density)
- The areal density of fabric gm/m^2
- Fabric structure.

In addition to the above parameter, fibre types of both warp and weft are of great importance. According to the above construction parameters and fibre material types, one can figure out the characteristics of woven fabric, which will be the preform for the composite structure.

Knitted fabrics are composed of interlaced loops. The horizontal row of loops is known as course, while the vertical row of loops is known as a wale. Knitted fabrics are formed with fewer stages than woven fabrics stages, making it much quicker, easier, and less costly. Knitting technology is classified into warp knitting, and weft knitting, usually weft knitted fabrics are not used in composites.

Knitted fabric construction parameters are:

- The diameter of yarn or yarn count
- Number of courses per cm
- Number of wales per cm
- Stitch length
- The areal density of fabric gm/m^2
- Fabric structure.

The braided fabric looks similar to woven fabric, but yarns are not orthogonal. Usually, the angle between yarns is between 20° and 160°. A braid is made by intertwining three or more yarns or strands with same or different materials. Braided fabric can be classified according to the shape, and it could be:

- Flat
- Tubular
- Solid.

Nonwoven fabric is neither woven nor knitted. These fabrics are made directly from fibre either short or continues filaments, that are consolidated with different methods. Consolidation method may be mechanical, or chemical or thermal. Properties and characterization of nonwoven fabric are firmly dependents on the fibre type and technology formation [19]. Unlike woven and knitted fabrics, nonwoven fabrics are engineered fabrics, and they are designed to perform a specific function. Moreover, the nonwoven fabrics are made through a one-step process from fibre to fabric, eliminating many steps, hence lowering the production cost to the extent that can make those fabrics cost-effective for even disposable applications.

3.2 Manufacturing Techniques

After constructing the preform that any technique from the ones mentioned above could be manufactured, the preform will go through the final stage or component production stage. The final properties of composite structure depend not only on the material type but also on how the composites are manufactured. Manufacturing green or natural fibre and hybrid composites can be manufactured using the conventional composite manufacturing processes such as hand layup, resin transfer moulding RTM, filaments winding and compression moulding. In this chapter, some selected techniques used in natural and hybrid composites will be reviewed.

Hand Layup

Resins or matrix materials are impregnated by hand into preforms that could be woven, knitted and nonwoven. This is usually carried out by rollers or brushes, using nip-roller type impregnators for pressing resin into the fabrics. Laminates are left to cure under standard atmospheric conditions or could be cured inside ovens or autoclaves. The main advantages of this method are simplicity and low tooling cost.

Pultrusion

Pultrusion is a composite manufacturing technique where continuous yarns are firstly entirely impregnated with the thermoset polymeric matrix then pulled through a heated die to form composites. The pultrusion process is accomplished by pull rather than push as in case of extrusion. The main advantage of the pultrusion process is the ability to form complex shapes such as I beam, C section, tubes and rods. The pultrusion process is a continuous production process.

Filament Winding

This process is mainly used for creating tubular components that are hollow and have a circular or oval cross-section, such as pipes and tanks. Yarns are passed through a resin bath then the impregnated yarns are wound onto a mandrel. Yarns orientations can be controlled by the traverse feeding mechanism, in conjunction with the mandrel's speed of rotation. Filament winding is mostly used for producing pipes especially for the petroleum industry and pressure vessels.

Resin Transfer Moulding (RTM)

In this process RTM, preforms are laid up in the form of single or multi stacks. These stacks of preforms are sometimes pre-pressed to the mould shape and held together using a binder. Then these preforms are stacked into the mould tool. The second mould tool is then clamped over the first mould. Resin is injected into the cavity mainly by pressure, and sometimes vacuum can also be applied to assist resin in being drawn into the fabrics. Once all the stack of preforms is wet out, the resin inlets are closed, and the laminate can be cured. This process can take place at either room temperature or elevated temperature. Generally, all thermoset resins such as unsaturated polyester, vinyl ester and epoxy can be used in this method.

Resin Infusion

Resin infusion or Vacuum Assisted Resin Transfer Moulding (VARTM) is a complicated manufacturing composite technique. Usually, it creates void-free or very low voids composites even in large or complicated moulds. In this process, the preform is laid into the mould in a dry form without any resin and then confined by a specific stack of bagging materials (such as peel ply, infusion mesh and bagging film) before being subjected to vacuum pressure using a vacuum pump. Once all the air has been removed or vacuumed from the bag, and the preform has been fully compressed, the resin is introduced to the preform through a pipe known as the spiral tube, then resin infuses through the preform under the vacuum pressure. After the resin has completely infused through the preform, the resin supply is closed, and the composite is left to cure under vacuum pressure.

Compression Moulding

There are two types of compression moulding, cold compression moulding and hot compression moulding. In this process, two matched metal moulds could be flat or shaped and used to fabricate composite products. In compression moulding, one plate is stationary while the other plate is movable. Preform and matrix are placed in between the two moulds then heat and pressure are applied as required for composite for a specific period. In the thermoplastic matrix, heat will be necessary to melt the matrix and flow through the preform. For thermoset matrix curing of the composite may take place either at room temperature or at some elevated temperature.

Many attempts have been tried to utilize the natural materials in the composite application using the techniques mentioned above and others. Sometimes just one technique has been used in the manufacturing process, and at other times a combination of more than one technique was used.

Mohareb et al. used VARTM to develop sandwich structure using lightweight and relatively thick core materials in particleboard panels from lignocellulosic resources attached to skin materials made of woven fabric to construct a high-performance structure for various technical applications [20]. In a similar work, Hassanin et al. used VARTM technique to develop high-performance particleboard from a mixture of wood particles and short glass fibres as hybrid core materials. In contrast, two layers of woven jute fabric were used as skin layers [21]. In the work of Hamouda et al. sandwich composites based on coir fibre nonwoven mats as core material and glass fibre is woven roving as the skin was manufactured by Vacuum Assisted Resin Transfer Moulding technique as well [22]. Sharkawi et al. have developed rebars for reinforcing light concrete to replace steel rebars. The RTM technique was implemented to produce natural yarns reinforced polyester bars with different fibre volume fractions [23].

4 Applications of Natural Fibre and Hybrid Composites

Applications of natural fibre composites (NFC) can be dated back to Ancient Egyptians who used to make bricks out of clay mud and straws, and this has been depicted on the tomb walls of Thebes showing Egyptian slaves mixing clay mud with straws and then drying the bricks in the sun [24]. Recently, the use of natural fibres as a reinforcement for polymer composites has gained a lot of attention, especially in the research community. There are numerous review articles published on the applications of NFC [25–28]. However, to date, the commercial use of NFC is limited to wood-plastic composites and automotive inner door panels [29]. Moreover, no single report or article has a statistic on the current NFC market, and most reports discuss the envisioned potential markets.

4.1 Barriers to the Diffusion of NFC

The world consumption of natural fibres that can be used as a reinforcement for composites is US$ 3.8 billion in 2017 with a CAGR of 2.3% from 2010 to 2017, as shown in Table 3. This is a strong indicator that the market is not growing as anticipated. This raises a valid concern; what's holding them back, what are the barriers to the adoption of NFC in the numerous applications of composite materials? To answer this question, one should refer to the diffusion of innovation theory developed by E. M. Rogers which explains how new ideas, technologies and products spread among participant in a certain social system [30].

i. Factors affecting the diffusion of innovation

Five main factors affect innovation diffusion: relative advantage, compatibility, complexity, trialability, and communicability.

In terms of comparative advantage, natural fibre reinforcements have many advantages over its inorganic counter-part glass fibres. They have low density, high specific properties, biodegradable, renewable resources, low carbon footprint, good thermal and acoustic insulation. Those relative advantages have to be emphasized when developing new products from NFC. This explains why the automotive industry is at the forefront of NFC adoption. These are all requirements for modern-day vehicles, especially with electric vehicles' growth and strict environmental regulation.

In terms of compatibility natural fibre reinforcements fall short, their hydrophilic nature makes them incompatible with the existing hydrophobic resin systems used in the industry. Moreover, their low thermal resistance limits their compatibility with thermoplastic matrices with high melting temperature. Furthermore, the high variability in their mechanical, chemical and physical properties and lack of standardization limit their compatibility with the quality standards set forth by specific industries such as the automotive and the aerospace. In addition, their coarse and hard nature makes them challenging to spin using existing spinning lines, and challenging to convert into woven preforms, this explains why most natural fibre reinforcements are used in the nonwoven form. Moreover, their surface functional groups' incompatibility with the functional groups in existing resin systems results in poor fibre-matrix interfacial adhesion and very low load transfer efficiency. Finally, their low annual availability and seasonality make them incompatible with the large and consistent consumption of specific supply chains, such as the wind energy and construction industries. Such a low level of compatibility is the main reason preventing the diffusion of NFC and limiting their adoption.

In terms of complexity, the majority of the industry has the very low experience and knowledge on how to deal with natural fibre reinforcements, and there is a big gap between different value chain actors; upstream processors of fibres are low-tech, while downstream composite manufacturers are very high-tech. Hence, there is a compelling need to bridge this gap between the different value-chain actors and educate the farmers, fibre processors, and fabric makers on this new end-use of natural fibres, and meanwhile educate the composite manufacturers on this new type of reinforcement and how it has unique nature which is different from their synthetic counterparts.

In terms of trialability, natural fibre reinforcements are mostly grown in developing countries such as Bangladesh, India, Sri Lanka and Kenya. At the same time, composite manufacturers are primarily located in developed countries such as the United States, Western Europe, and Japan. This geographic barrier makes it difficult for composite manufacturers to try and experiment with natural fibre reinforcements easily. Moreover, the wide ban on planting hemp significantly limits its trialability. Flax is an exception in this context since it's mostly grown in France and Belgium, and the fact that there are many composite manufacturers located in those regions with easy and quick access to flax has significantly increased its trialability and made it the leading natural fibre reinforcements and the most widely used.

In terms of communicability, which means how easy is it for the user to see the benefits of using NFC? We will find that the most important benefits of using natural fibre reinforcements are intangible. They address a particular perceptual dimension related to protecting the environment, for instance, reduced carbon footprint, biodegradability, and renewability. Hence, their benefits cannot be easily and directly seen by the user. Other direct benefits can be easily perceived, such as their lightweight, high specific properties, good thermal insulation and vibration damping. The fact that their most important benefits cannot be easily seen by the user significantly limits their spread and adoption.

ii. The adopter groups

Another view of the diffusion of innovation theory is the adopter groups. The adopters of any new product or technology can be divided into two broad groups: the visionaries and the pragmatists [31]. The visionaries are those innovators and early adopters who are always excited about trying new things. Simultaneously, the pragmatists are the late adopters who are more resistant to changes and think hundred times before buying or trying a new product or technology. In this case, a value proposition that might attract the visionaries might never get acceptance by the pragmatists who

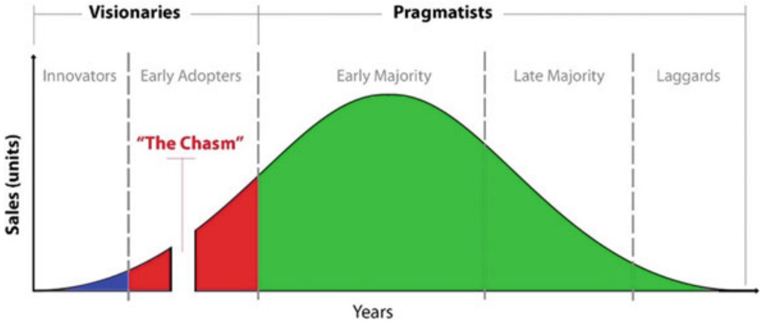

Fig. 8 Innovation adoption lifecycle

represent the mass market, and this is known as the chasm, as shown in Fig. 8. This clearly explains where the NFC is currently standing, and it's widely investigated and though after by researchers, hobbyists, entrepreneurs, and technology enthusiasts who represent the visionary group. Unfortunately, it's not getting that much acceptance by the industry and the end-markets who represent the pragmatist group. This is why most of the work done on NFC is part of a research program or coming out of a hobbyist garage. Their applications are mostly concentrated in sporting goods, musical instruments and small consumer products. NFC products should be developed from their early conception stages with the pragmatists in mind to cross this chasm and get a higher acceptance by the industry and the mass market. This is a big challenge because pragmatists look for fibres with competitive price, wide availability, and consistent properties. Unfortunately, this is not the case since most natural fibre reinforcements are expensive, and their annual availability is limited, and their properties suffer from high variability. The automotive industry is an exception in this context since the value proposition of the NFC, in this case, is fulfilling the strict environmental regulation imposed on such industry. Moreover, they can work closely with the tier 1 and 2 suppliers and control the entire chain from the farm to the final composite panels to ensure consistent quality, price and supply.

4.2 Commercial Applications of NFC

The commercial applications and indicators of industrial adoption of NFC have been compiled from JEC Composites International Market News (the world's leading composite industry magazine and exhibition) from 2011 to 2019, excluding wood-plastic composites [32]. Table 6 lists the commercial applications, indicating the product name, developer, announcement date, fibre type, and industry.

It's evident from Table 6 that NFC is widely used in sporting goods, including, surfboards, paddleboards and blades, skis, snowboards, bicycles, and skateboards. Figure 9 illustrates an example of NFC applications in sporting goods [33–37].

Table 6 Commercial applications of NFC compiled from JEC composites international market news 2011–2019 [32]

Application	Company/Institution	Date	Fibre	Industry
Domes for morris columns in Paris	JCDecaux and the city of Paris	Apr 2019	Flax	Outdoor advertising
Roof top tents	NaïtUp and Dehondt	Apr 2019	Flax	Sporting goods
Porsche 718 Cayman GT4 Clubsport body parts (driver and co-driver doors and the rear wing)	Porsche	Jan 2019	Flax and Hemp	Automotive
Mould tooling system	KS composites and composites evolution	Nov 2018	Carbon-flax hybrid	Industrial
Aerospace cabin interiors, cover panels and fuselage cladding panels, and onboard meals galleys	Assystem Technologies, Arkema, Cobratex, Specific Polymers, Cirimat, Compositadour, Lisa Aeronautics and Mécano ID	Nov 2018	Long bamboo strips	Aerospace
Volvo XC60 semi-structural automotive interior parts	Volvo Cars and Bcomp	Jun 2018	Flax (powerRibs)	Automotive
Longboard deck	ITA RWTH Aachen University and TU Clausthal	May 2018	Highly oriented natural fibre	Sporting goods
Savoy guitar	Blackbird and Ekoa linen	Dec 2017	Flax	Musical instruments
En V. fly-fishing rods	Edge rods and Lingrove	Dec 2017	Flax prepreg	Sporting goods
Electric GT racing car	Bcomp	Nov 2017	Flax (powerRibs)	Automotive
SeaBubble water taxi prototype	Décision and Carboman group	Jun 2017	Natural fibres	Marine
LINA car chassis	TU/Ecomotive	May 2017	Flax	Automotive
Pedestrian bridge	TU/e, TU Delft, NPSP composite, Avans Hogeschool and HZ University	Nov 2016	Hemp and Flax	Construction
Car parts (cup holder and fuse box)	Ford and Jose Cuervo	Jul 2016	Agave	Automotive
3D printed table	Oak Ridge National Laboratory	Jul 2016	Bamboo	Construction

(continued)

Table 6 (continued)

Application	Company/Institution	Date	Fibre	Industry
E-class of Mercedes-Benz roof frame	BASF and Mercedes-Benz	Apr 2016	Natural fibres	Automotive
CARBIO Hybrid automotive roof	Composites Evolution, SHD Composite Materials, KS Composites, Delta Motorsport, Jaguar Land Rover and Cranfield University	Oct 2015	Carbon-Flax hybrid	Automotive
AmpliTex SURF	Bcomp	Aug 2015	Flax	Sporting goods
Paddle board	BIC sports and Composites Evolution	Mar 2015	Flax	Sporting goods
Urban One Bamboo bicycle	Guapa Cycles and Composites Evolution	Feb 2015	Flax and bamboo	Sporting goods
Formula Student Electric car entire body	e-gnition team of the Technical University of Hamburg (TUHH)	Jan 2015	Flax	Automotive
Alpaca travel guitar	Alpaca Guitars	May 2014	Carbon-Flax hybrids	Musical Instruments
Volkswagen Golf seating, door panels, and front-end modules	FAURECIA and VW	Apr 2014	Flax	Automotive
Jaguar F-Type floor panel	EcoTechnilin and Jaguar	Dec 2013	Natural fibres	Automotive
Kayak paddle blade	VE Paddles and Bcomp	Dec 2013	Flax	Sporting goods
Speaker cone	Focal	Sept 2013	Flax	Musical instruments
Be.e electric scooter body	Van.Eko and Waarmakers	Aug 2013	Flax and Hemp	Automotive
BioMobile body, chassis and most structural parts	Haute Ecole du Paysage, d'Ingénièrie et d'Architecture de Genève	May 2013	Natural fibres	Automotive
ski Otwo	Stöckli and Bcomp	Jun 2013	Flax	Sporting goods
eco-kiteboard	FFC and Bcomp	Apr 2013	Flax	Sporting goods

(continued)

Table 6 (continued)

Application	Company/Institution	Date	Fibre	Industry
Wind turbine blade	University of Nottingham	Feb 2013	Flax	Energy
Packaging	VTT Technical Research Centre of Finland	Jan 2013	Peat	Industrial
Snowboard	Magine and Composites Evolution	Aug 2012	Flax	Sporting goods
Surfboard	Samsara and Composites Evolution	Jun 2012	Flax	Sporting goods
Monobloc chair	Werner Aisslinger and BASF	Jun 2011	Hemp and Kenaf	Construction

Moreover, the use of NFC in automotive is growing, especially in electric vehicles, racing and sports cars. Figure 10 illustrates examples of NFC applications in automotive [38–43].

Similarly, there is a growing interest in using NFC in interiors, building and construction, especially with the increasing trend for eco- and green buildings. Figure 11 illustrates examples of utilizing NFC in making chairs and pedestrian bridge [44, 45].

Finally, several attempts to develop musical instruments from NFC due to their special resonance and vibration damping. Figure 12 illustrates the applications of NFC in making guitars and speaker cones [46, 47].

5 Review Questions

(1) What are the main classes of natural fibres?
(2) Describe the microstructure of cellulosic fibres.
(3) What is the classification of cellulosic fibres?
(4) Discuss in details, the cellulosic fibre extraction methods.
(5) What are the main factors that affect natural fibre properties?
(6) What are the primary forms of composites preforming?
(7) Explain the available manufacturing methods to produce natural and hybrid fibre composites.
(8) What are the applications of natural fibre and hybrid composites?
(9) What are the reasons behind the fast-growing of natural fibres-based composites?
(10) Discuss in details the barriers to the diffusion if natural fibre composites.

Fig. 9 NFC applications in sporting goods, **a** Samsara surfboard, **b** Cobratex skateboard, **c** Magine snowboard, **d** Urban One bicycle and **e** ski Otwo (photos courtesy of JEC Composites) [33–37]

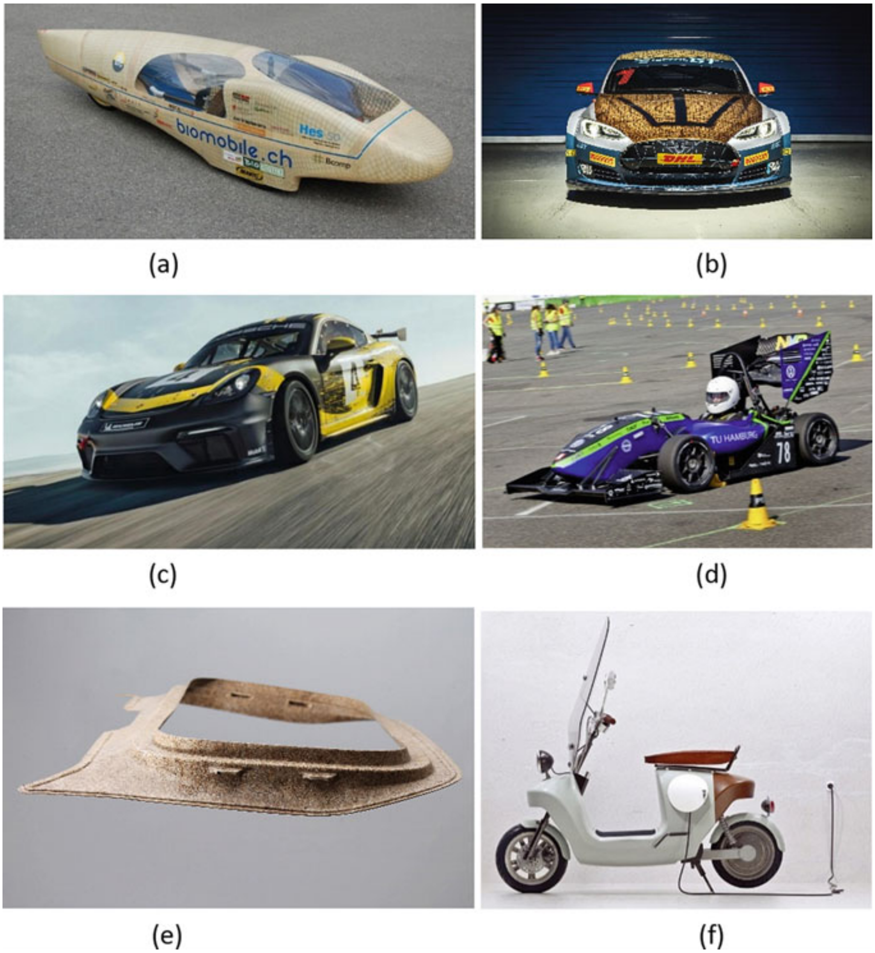

Fig. 10 NFC applications in automotive, **a** biomobile, **b** electric GT racing car, **c** Porsche 718 Cayman GT4 Clubsport **d** e-gnition Formula Student Electric car, **e** E-class of Mercedes-Benz roof frame, and **f** Be.e electric scooter (photos courtesy of JEC Composites) [38–43]

Fig. 11 NFC applications in building and construction, **a** Werner Aisslinger monobloc chair, and **b** AE + T pedestrian bridge (photos courtesy of JEC Composites) [44, 45]

Fig. 12 NFC applications in musical instruments, **a** Savoy guitar, and **b** Focal speaker cone (photos courtesy of JEC Composites) [46, 47]

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