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Bast Fibers and Their Composites

Processing, Properties and Applications

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ISSN 2364-1878 ISSN 2364-1886 (electronic)
Springer Series on Polymer and Composite Materials
ISBN 978-981-19-4865-7 ISBN 978-981-19-4866-4 (eBook)
https://doi.org/10.1007/978-981-19-4866-4

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Contents

Introduction to Bast Fibers

G. Rajeshkumar, T. Vikram Raj, A. Shake Ashik, R. L. Sooraj, and S. Aravindh

Abstract Natural fiber-based composites have made significant progress in recent decades due to their environmental friendliness, lightweight, and low cost. While there are numerous sources of natural fibers, this chapter focuses on bast fibers because they possess desirable characteristics for a variety of applications. These fibers are derived from the phloem that surrounds the stems of fibrous plants, primarily dicotyledonous. Bast fibers' qualities are regulated by environmental conditions, maturity, extraction method, and processing. This chapter discusses various aspects of different types of bast fibers, their physical, chemical, and mechanical properties, and their applications in a variety of fields, intending to promote their use in advanced technology sectors.

Keywords Bast fibers · Mechanical properties · Composite reinforcement · Cellulose

1 Introduction

In recent years, the significance of natural fibers has been appealing for the reinforcement of polymers. These natural fibers have excellent chemical, mechanical, and physical properties with more desirable characteristics. They are also environmentally friendly, renewable, biodegradable, and abundant in nature [1, 2]. These properties have created a great interest in the production of renewable polymers and as well in composite applications. However, there are some limitations to the use of natural fibers such as they are inferior to synthetic fibers in some way and natural fibers possess hydrophilic nature [3]. So, certain physical and chemical methods have been conducted to increase the mechanical strength and make the fiber hydrophobic. Each natural fiber demands a specific type of technique to make them strong and water-resistant [4].

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G. Rajeshkumar et al. (eds.), *Bast Fibers and Their Composites*, Springer Series on Polymer and Composite Materials, https://doi.org/10.1007/978-981-19-4866-4_1

Natural fibers are acquired from three sources: animals, plants, and minerals. Animal fiber includes animal hair and silk fibers. Mineral fibers predominantly involve asbestos and basalt on the other hand it causes health problems. In general, the most economic and befitting fibers for the production of biopolymers and other bioproducts are plant-based fibers. Plant fibers are generally obtained from different parts such as leaves, seeds, bast, roots, and grass [5, 6]. Among these, fibers obtained from the bast part of the plant have excellent characteristics. The major chemical elements of bast fibers are cellulose, hemicellulose, and lignin. The pectin and proteins are available in minor constituents. Fats, waxes, and other components occur in small numbers. Bast fibers obtained from the phloem contribute to most of the natural fiber production around the world. Some of the bast fibers are kenaf, jute, ramie, hemp, and so on. These fibers are cultivated in various parts of the world, each fiber requires unique climatic conditions for its growth and development. For instance, India is the largest producer of jute followed by Bangladesh, Ramie is another fiber that is cultivated mostly in China and hemp is grown mainly for fiber application in Europe, Canada, and the United States [7, 8].

Approximately, around 2000 plant species can be utilized as a source for natural fibers, but only a few of these are commercially accessible, prominent, and found to be applicable for making biopolymers and composites. In this chapter, basic facts and information about various types of bast fibers are discussed. Furthermore, at the end of this chapter, the mechanical, physical, and chemical constituents of the bast fibers are summarized.

2 Bast Fibers

2.1 Kenaf

Kenaf (botanical name: *Hibiscus cannabinus*, family name: Malvaceae) is an annual fiber crop of the warm season and it has a close relationship with cotton and jute. Kenaf is a natural fiber that is widely used as reinforcement for producing polymer matrix composites. Kenaf is well known for its economic and ecological merits. Its period of growth is 3 months and it can grow in a variety of weather conditions. It grows more than 3 m and its base diameter ranges from 3 to 5 cm. This plant has a fibrous stalk that creates resistance to insect damage, so it demands very less pesticides. Only minimal chemical, herbicide treatment, and some fertilizers are enough to grow kenaf effectively. This plant is adaptable to various soils and 1 kg of kenaf can produce by spending 15 MJ of energy. This fiber possesses better tensile strength and is the material of choice for a variety of extruded, molded, and non-woven products. Some of the applications of kenaf are paper commodities, building supplies, animal feeds, and absorbents [9, 10] (Fig. 1).

Fig. 1 Kenaf: **a** plant, and **b** fiber (adopted from [11] with permission)

2.2 Ramie

Ramie (botanical name: *Boehmeria nivea*, family name: *Urticaceae*) is commonly known as China grass. It is a robust, perennial, and herbaceous plant. It is planted largely in China and other Asian countries such as the Philippines, India, South Korea, and Thailand [12]. This plant species was cultivated in the Mediterranean region in the early 1900s. Since Ramie is a bast fiber, some of the characteristics are great thermal conductivity and tensile strength. Also, it has fine coolness, ventilation function, and moisture absorption. Advantages of Ramie fiber: good antibacterial properties, provides resistance to mildew and insect attacks. Furthermore, this fiber establishes a silk luster appearance and can reduce shrinkage in various kinds of textile material. The ramie plant gets a very high amount of growth in warm and humid climatic conditions. They are commonly used in the fabric industry because of their softness, bleachability, and superior dyeability [13] (Fig. 2).

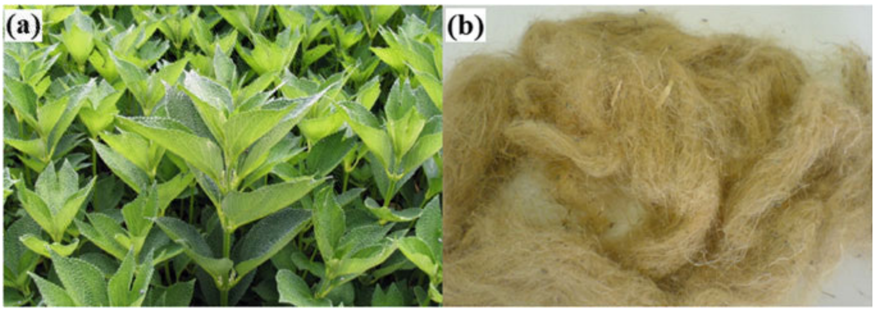

Fig. 2 Ramie: **a** plant and **b** fiber (adopted from [14] with permission)

Fig. 3 Jute: **a** plant and **b** fiber (adopted from [17] with permission)

2.3 Jute

The most commonly cultivated jute fibers are *Corchorus olitorius* (tossa jute) and *Corchorus capsularis* (white jute). Jute belongs to the *Tiliaceae* family. After cotton, jute is the most crucial natural fiber in terms of production, global utilization, availability, and usage. The major constituents that make jute are cellulose, hemicellulose, and lignin. It also comprises pectin, fats, and waxes in small volumes [7, 8]. Jute is a rainy season crop as it is seeded from March to May according to the rainfall and nature of the land. So, the harvest time differs from June to September. Jute cultivation is prominent in the Ganges delta which is shared between Bangladesh and parts of India (mainly West Bengal). Some other major sources of raw jute are China, Myanmar, Nepal, and Thailand. Key positive facts about jute are that they are agro-origin, annual renewability, soil friendly organic properties, and biodegradable in nature. Various applications of jute are in home textiles, agricultural textiles, automobile textiles and jute fibers are used in the manufacture of canvas, carpet, ropes, and sacks [15, 16] (Fig. 3).

2.4 Hemp

Hemp or industrial hemp is from the family *Cannabaceae* and its botanical name is *Cannabis sativa*. More than 30 countries cultivate hemp, among them, China is the largest hemp producing and exporting country. Hemp plants can grow in several types of soil and environmental conditions, making suitable surroundings available in many countries around the world. Temperatures around (semi-humid conditions) 7.8–27 °C are good for the growth of hemp plants. Harvesting of hemp occurs before the flowering, then it is cut down and rolled into large bails ready to be transported for

Fig. 4 Hemp: **a** plant and **b** fiber (adopted from [20, 21] with permission)

extraction and formation of fibers. This fiber shows an economically viable option to cotton, hemp fiber encourages cleaner production through material choice with a lower ecological footprint. Hemp is used in the production of apparel, fabrics, papers, biodegradable plastics, biofuels, and animal feed [18, 19] (Fig. 4).

2.5 Sunn Hemp

Sunn hemp fibers are one of the oldest yielding crops used in textiles. Its botanical name is *Crotalaria juncea* from the family *Fabaceae*. The majority of sunn hemp production is in India, Bangladesh, and Brazil. Due to the presence of high cellulose and low microfibril angle, this fiber has high tensile strength. This fiber is easily recognized by its white color appearance. Sunn hemp ensures good strength-to-weight ratio, corrosion resistance, high toughness, and resistance to fatigue [22]. Also, this fiber is broadly famous for its high aspect ratio, cost-effectiveness, and as a reinforcing material for composites. Various techniques and treatments are performed to improve the tensile strength of the fiber. It is mainly utilized in the manufacturing of pulp and paper [23] (Fig. 5).

2.6 Roselle

Roselle is from the *Malvaceae* family and its botanical name is *Hibiscus sabdariffa*. It is mostly grown in tropical Africa and parts of India. Roselle plants need direct sunlight and sufficient water supply for their growth and are mostly grown in tropical countries. Roselle fiber has a smooth surface, excellent tensile strength, and modulus [26]. To develop fiber from the plant, it is suitable to have a long neat stem free of

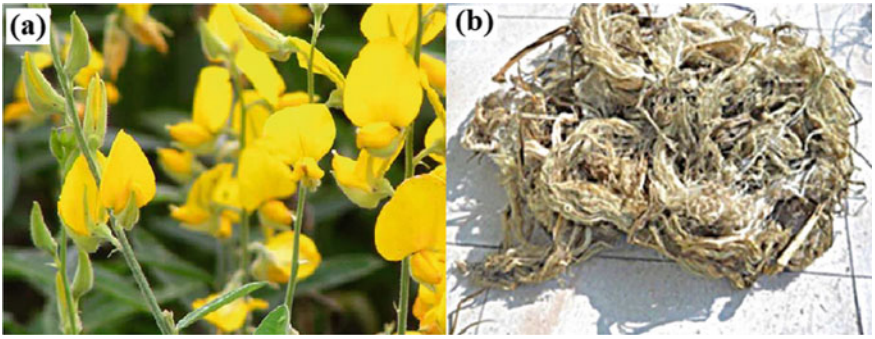

Fig. 5 Sunn hemp: **a** plant and **b** fiber (adopted from [24, 25] with permission)

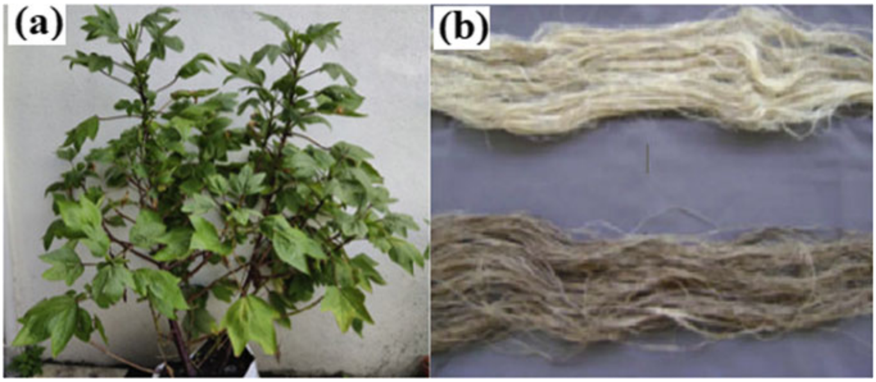

Fig. 6 Roselle: **a** plant and **b** fiber (adopted from [29] with permission)

branches or fruiting stalks. 18–20 inches of rainfall is necessary for roselle plants to grow, it normally takes 3–4 months to fully grow [27]. The primary constituents are cellulose, lignin, and hemicellulose. Polymer composites can be reinforced with the help of roselle fibers. It is further applied in automobile, aerospace, building, and construction fields [28] (Fig. 6).

2.7 Urena Lobata

Its full name is *Urena lobata* from the family *Malvaceae*. Urena plant is commonly known as Caesar weed or Congo jute. The fiber is fine, soft, flexible, and bright [30]. It is easily available and can be broadly grown under various conditions. For the extraction of urena, the stems were cut down and then the retting process takes place in a flowing stream usually for 14–16 days. After which the retted fibers were washed and dried out. It is traditionally used for making coarse textiles, industrially

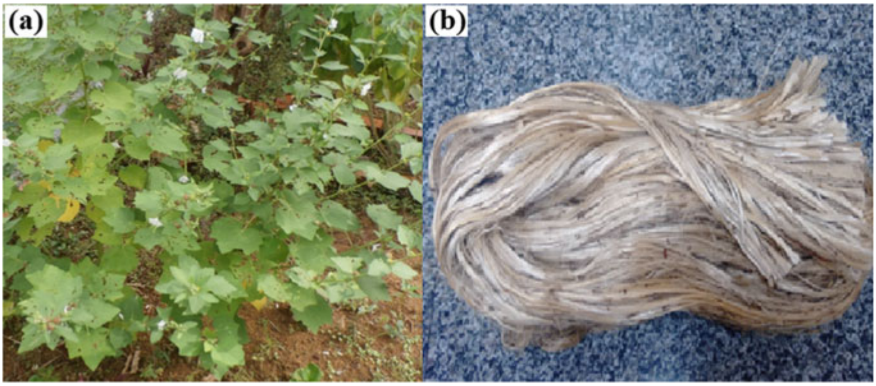

Fig. 7 Urena lobata: **a** plant and **b** fiber (adopted from [33] with permission)

as a substitute for jute, and sometimes mixed with jute. Whole urena plants can be pulped and also made into strong, bank-note quality paper [31, 32] (Fig. 7).

2.8 Flax

This fiber is acquired from the skin or bast surface of the flax plant which is present on its stem surface. The botanical name of the flax plant is *Linum usitatissimum.* These plants are cultivated in subtropical countries and are also available in temperate regions. This is one of the oldest fibers and is stronger than cotton. The length of flax fibers varies from 10 to 100 cm. The diameter of these fibers lies between 40 and 80 μm. Growing worldwide demand for linen makes flax a cash crop. Today flax is a high-end fiber because of its less production and high cost. Since 1994, Canada is playing as the largest producer of flax fiber. During 2005 and 2006, Canada has produced 1.035 million tons of flax fiber and currently supplying 60% to EU and 30% to the US. Fabrics made from flax are called linen. These linens are used as a high-quality textile for household purposes such as bed coverings, furnishing, and household interior decorations. Flax fibers produce thick yarns suitable for tents, kitchen towels, canvas, and sails. Reinforced flax fibers are used in automobile interiors [34, 35] (Fig. 8).

2.9 Nettle

The botanical name for nettle is *Urtica dioica*, which comes under the family Urticaceae. This plant is mostly grown in temperate and tropical areas of the earth, it can height range from 0.6 m to over 2 m [37]. The level of fiber that can be obtained

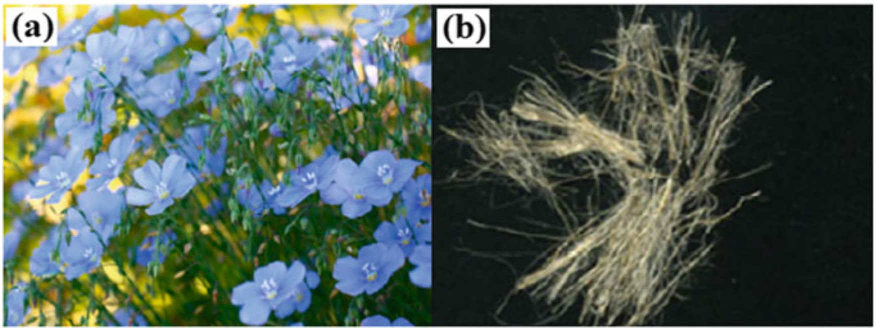

Fig. 8 Flax: **a** plant and **b** fiber (adopted from [34, 36] with permission)

in the stem of the plant differs. Stinging nettle is also a type of fibrous nettle plant with a great quantity of fiber where ever this plant is grown, where the local people procure this fiber and make use of it in textiles or for cordage. This fiber is present around the outside of the plant stem. The nettle fiber is used mostly for its medicinal aspects. The overall plant might be used for uncontrolled menstrual bleeding, diarrhea, diabetes, urinary problems, and respiratory issues. It can also be found in a wide range of pain relief medications for the diseases such as muscular dystrophy, eczema, ulcers, and rheumatism [38, 39]. Another type of nettle called *Girardinia diversifolia* (Himalayan Nettle) is quite similar to flax or hemp, it is used widely in textile industries [40] (Fig. 9).

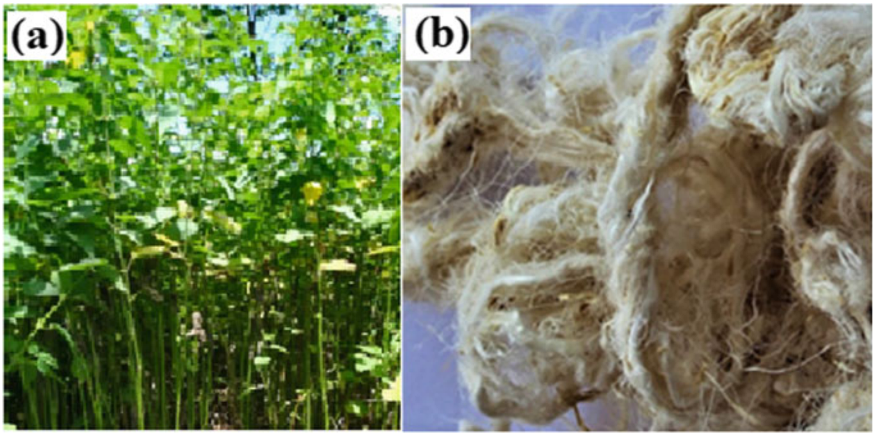

Fig. 9 Nettle: **a** plant and **b** fiber (adopted from [41, 46] with permission)

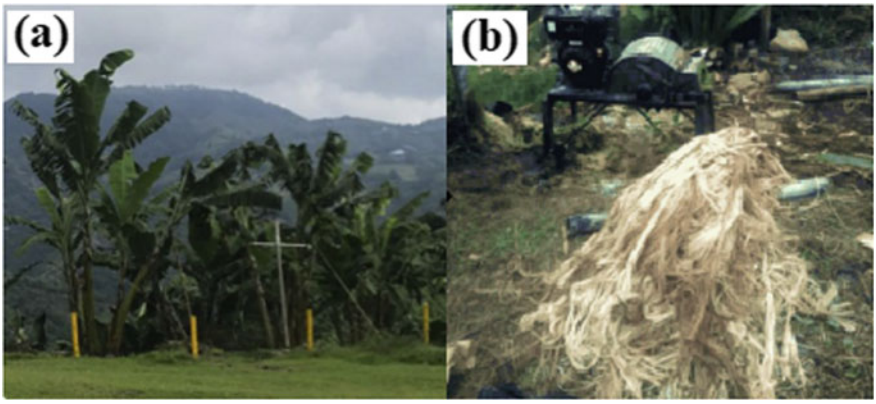

Fig. 10 Banana: **a** plant and **b** fiber (adopted from [44] with permission)

2.10 Banana

The botanical name for banana is *Musa acuminate*. Rather than delicious fruits, banana also provides fibers for textile purposes. India is one of the largest producers of banana fiber. Merely 10% of pseudostem can be utilized to make the fiber and the remaining is waste or applied as fertilizers [42]. They also have low density, high tensile strength, and modulus. This fiber has numerous applications due to the presence of properties like moisture absorption, anti-oxidant, UV protection, and weather resistance. Banana fibers have the potential to be used as reinforcement for composites in non-structural applications [43]. Ropes and yarns are made using banana fibers. Due to its resistance to seawater and natural buoyancy, it is used to make shipping cables (Fig. 10).

3 Properties of Bast Fibers

The various properties of bast fibers are evaluated in order to determine their suitability for use as reinforcement in the manufacture of polymer matrix composites. One significant disadvantage of bast fibers is that the properties of each fiber vary. Additionally, the properties are influenced by the environment in which the plants are grown. The properties of different bast fibers are given in Table 1.

Table 1 Properties of various types of bast fibers

Fibers	Density (g/cm^3)	Diameter (μm)	Cellulose (%)	Hemicellulose (%)	Pectin (%)	Lignin (%)	Wax (%)	Ash (%)	Moisture (%)	Tensile strength (MPa)	Young's modulus (GPa)	% of elongation	References
Flax	1.4–1.5	12–600	62–72	18.6–20.6	2.3	2–5	1.5–1.7	–	5–10	343–2000	27.6–103	1.2–3.3	[45]
Nettle	1.5	20–80	53–82.6	–	0.9–4.8	0.5	–	–	–	650	38	1.7	[46]
Banana	1.35	12–30	63–67.6	10–19	–	5	–	–	8.7–12	500	12	1.5–9	[45]
Kenaf	1.31	65–71	45–57	21.5	3–5	8–13	0.8	2–5	6.2–12	930	53	1.6	[47, 48]
Jute	1.3–1.49	20–200	61–71	13.6–20.4	0.2	12–13	0.5	0.5–2	12.6	320–800	8–78	1–1.8	[16, 45]
Hemp	1.47	25–500	70–74	17.9–22.4	0.9	3.7–5.7	0.8	–	6.2–12	690	70	1.6	[47]
Roselle	1.332	40–100	64.50	20.23	–	6.21	–	1.25	5.8	147–184	2.76	5–8	[26, 28]
Urena	0.94	170	56.42	13.61	–	25.01	–	0.55	–	309.3	16.5	3.07	[32, 49, 50]
Ramie	1.50	20–80	68.6–76.2	13.1–16.2	1.9	0.6–0.7	0.3	–	8	400–100	24.5–128	1.2–4.0	[13, 45]
Sunn	1.53	20–70	70–88	12.2	–	4.3	0.58	0.3	–	272–529	2.686	5.50	[51, 52]

4 Applications of Bast Fibers

The applications of various bast fibers are given in Table 2.

Table 2 Applications of various types of bast fibers

Fibers	Application	References
Kenaf	• Paper commodities, building supplies, and absorbents • Kenaf core fibers are used in animal breeding, summer forage, and potting media	[53]
Ramie	• Composites reinforced with ramie fibers are used in armours and vests because of their better ballistic performance than Kevlar • Ramie with glass fibers is widely applied in the automobile industry to produce hybrid polymer composites	[54]
Jute	• It is primarily utilized in manufacturing ropes, jute sacks, and twines • Jute fibers also find their use in making automobile interior door panels and seat backs	[55, 56]
Hemp	• It is used in the production of apparel, biodegradable plastics, animal feeds, and biofuels • They also find applications in beverage industries and nutraceutical products	[18]
Roselle	• It is widely used in beverage industry • Roselle is commercially viable to be utilized in food, pharmaceuticals, paper, and textile industries	[57]
Urena	• Urena plant can be pulped and used for making paper • This fiber is used for producing coarse textiles and also as a substitute for jute	[50]
Flax	• Flax fibers have the potential to be used as livestock feed, linen in the textile industry, and in the manufacture of decorative fabrics/yarns • Flax composites are employed in wooden fittings, fixtures, and furniture	[58]
Nettle	• Nettle plant is used for its medicinal aspects such as be used for uncontrolled menstrual bleeding, diarrhea, diabetes, urinary and respiratory issues • It is used for making ropes, threads, and other related items	[59]
Banana	• This fiber is a very good raw material for the textile and packaging industry. Also, the remaining waste of pseudo stem is used as fertilizer • It is extensively used in making power transmission ropes, cordage, cables, and fishing nets	[42]
Sunn	• These fibers are utilized to make pulp and papers • It is also used in the manufacturing of twines, nets, canvas, and fancy articles like bags	[60]

5 Conclusions

The chapter describes a few bast fibers, despite the fact that they demonstrate the breadth of their application possibilities, most notably as composite reinforcement. Bast fibers can also be used in a variety of different applications, including nonwovens, filters, geotextiles, and technical textiles. All the bast fibers discussed in this chapter have a high amount of cellulose content and higher mechanical properties. It is possible to modify the qualities of bast fibers by altering their surface through surface modification techniques. Finally, bast fibers demonstrate significant promise as a substitute for inorganic fillers and reinforcements, and their use in the composites industry should be expanded.

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Effect of Extraction Methods on the Properties of Bast Fibres

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Abstract The advantages of using lignocellulosic natural fibres from the plant bast, as compared with synthetic ones, namely in terms of environmental impact and availability for a number of industrial sectors, from textile to wood replacement and even to automotive or aerospace one, are counterbalanced by the need to extract them from the plant. In principle, the number of plants that are suitable to obtain bast fibres is considerable: some of the most popular are, among others, jute, hemp, flax, ramie, kenaf, nettle, etc., although this work aims also at giving a hint on the wider picture of the possible expansion of the market to other species. However, the quality of the fibre obtained depends on the extraction method employed, namely mechanical extraction, decortication or retting in different environments (water, dew, chemical) for the single species. Information on this aspect is not always consistent and very precise, although this chapter would like to underline the importance to consider and thoroughly describe the extraction method for every batch of bast fibre obtained to try to improve the general quality of the products and generally expand further the market for natural fibres.

Keywords Extraction methods · Decortication · Chemical retting · Water retting · Dew retting

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G. Rajeshkumar et al. (eds.), *Bast Fibers and Their Composites*, Springer Series on Polymer and Composite Materials, https://doi.org/10.1007/978-981-19-4866-4_2

1 Introduction

Natural fibres play an essential role in the emerging "green" economy, which is concerned with the conditions of the environment: their use in materials, such as composites, does represent an important completion of their role in textile industry and, conversely, lignocellulose waste obtained from agro-forestry sector can often have a fibrous form. The use of natural fibres enables coming closer to carbon neutrality, which means absorbing as much as possible the same amount of carbon dioxide (CO_2) that is produced during the manufacturing of products. Another application that is promising is the use of natural fibres to produce environment-friendly building materials, also they are completely biodegradable at the end of their life cycle.

The International Year of Natural Fibres was celebrated in 2009 to raise worldwide awareness regarding the natural fibre's significance; this applied not only to natural fibre producers, consumers and industry but also to businesses relying on natural fibres for efficiency and long-term sustainability. The vast majority of natural fibres are harvested throughout developing countries, coming to a total of 30 million tonnes per year worldwide. The sale and proceeds outsourcing of natural fibres significantly donate to poor farmers' income and food security in many developing countries, giving, therefore, a significant economic importance to them: the diffusion of possible products can span also to highly technological industrial sectors, such as automotive [1]. Numerous parts of the plants are able to produce natural cellulosic fibres, which are then used to make products. Seed fibres (from kapok and cotton, for example), bast or stem fibres (from jute, flax, kenaf, sugarcane and hemp), leaf fibres (from a variety of plants, including several palms, pineapple, and banana) and fruit fibres (from coir or Borassus, for example) are the most commonly encountered types. The main difficulties in using natural fibres are the extraction, which is sometimes problematic, the not always very high repeatability of performance, and the usual local character of most of these [2].

Bast fibres are extracted, with various processes defined collectively as *retting,* from different plants and cultivars of these [3]. These include among others hemp, flax, jute, kenaf and ramie: to be a bast fibre indicates that the fibre is essentially found under the bark stalk plant, also recognized as phloem [4]. The fibres must be extracted and processed differently because of their inherent structure in the first place. A common characteristic of bast fibres is that, as with any natural material, a wide variability of quality is possible depending on the crops. After extraction, even only concentrating on their mechanical properties, they are affected by the variety of plant cultivated conditions for growth and the environment, harvest date, ripeness of harvest, decortication and cleaning processes [5].

2 The Possible Use of Bast Fibres

It is common for bast fibres to be both of sufficient length for use, e.g. in textiles, as well as reasonably strong. As a result, bast fibre, "soft" and derived from the stems of plants, is widely considered the most significant fraction of any plant [6]. In general, the stem of a fibre-producing plant is composed of three layers: the bark layer, the bast and the core stem. The external thin skin is the bark layer, or cuticle, covering the outside of the stem and holding the bast fibres in place while also protecting the entire structure. Between the stem core and the bark layer resides like a fibrous plant layer. The core of the stem consists of two parts: the pith and the tissue of wood (xylem) (Fig. 1). In the main and secondary fibre layers, fibrous layers are invented, paralleling dicotyledonous plants between nodes. Bast, phloem and soft fibres are the terms used to describe these fibre layers, which vary from stem to stem in various stem parts. Bast and phloem are the terms used to describe these fibre layers. There could be as few as 15 bundles or as many as 35 or more bundles. Each fibre bundle comprises 10–40 individual fibre cells, each of which is pointed at the extremities. The number of bundle cells is determined by their very location in the stem, with the most significant number of cells found in the centre of the stem (see figure). The ultimate fibre cell dimensions vary depending on where they are located in the stem, with cells at the stem base approximately three times as thick and long as cells on the upper end of the trunk. Bast fibres have a molecular structure composed of cellulose molecular chains in an amorphous matrix formed by pectin, lignin and hemicellulose [7]. When compared to the total number of plants grown and processed on a commercial basis, the bast fibre group contains a vast number of plants, many of which are possibly used also in textile products. Some of these are reported in Table 1.

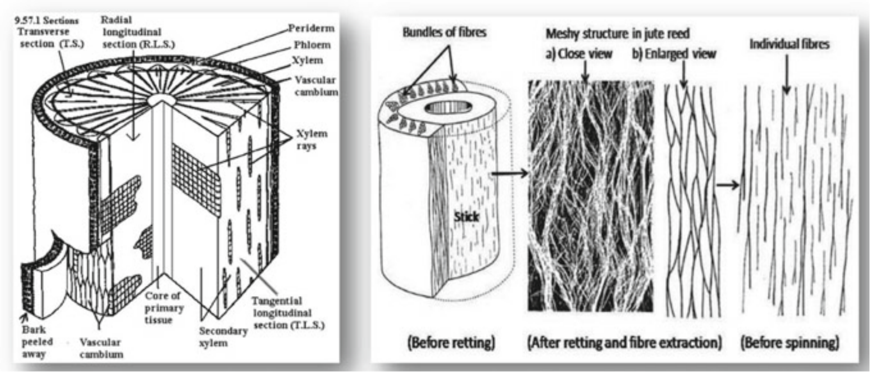

Fig. 1 Microscopical view of bast fibres (cross section and longitudinal) [8]

Table 1 List of potential fibres from bast plant sources

Order	Family	Botanical name (genus and species)
Sapindales	Anacardiaceae	*Rhus typhina*
Myrtales	Onagraceae	*Epilobium angustifolium and E. hirsutum*
	Lecythidaceae	*Couratari tauari*
Geraniales	Euphorbiaceae	*Euphorbia gregaria and E. gummifera*
Poales	Poaceae	*Saccharum officinarum*
Asterales	Compositae	*Eupatorium cannabinum*
Loasales	Datiscaceae	*Datisca cannabina*
Geraniales	Euphorbiaceae	*Euphorbia gregaria and E. gummifera*
	Linaceae	*Linum angustifolium and L. usitatissimum*
Gentianales	Apocynaceae	*Apocynum cannabinum, A. venetum, Chonemorpha macrophylla*
Polygalales	Polygalaceae	*Securidaca longipedunculata*
Laminales	Labiatae	*Phlomis lychnitis*
Malvales	Malvaceae	*Hibiscus cannabinus, Corchorus capsularis*
Rosales	Cannabacae Urticaceae	*Cannabis sativa* *Boehmeria nivea, Urtica dioica*

3 Bast Fibres Structure

Bast fibres can also be intended as a hierarchized material, therefore, including as the core part, giving strength to them, cellulose microfibrils arranged into different layers (S1–S3) internal to the phloem. The differentiation between S1, S2 and S3 is also offered by the different angles for winding of the microfibrils, which is referred to as the microfibrillar angle. The dimension of the microfibrillar angle of the different layers is also depending on their respective dimensions and of course on the species. At the very core of the fibre, an empty space is present, referred to as lumen, which may take different geometries from circular to more elliptical or even bow-shaped, although for ease of representation, as from Fig. 2, the first one is usually reported [9, 10].

Some of the above-mentioned bast fibres are more than a promising possibility, yet they are annually harvested for production purposes. In particular, Table 2 provides information about the five major bast fibre contributors.

The bast fibre is extracted from the plant's trunk, which is the outermost part of the plant. There are primary and secondary layers on each fibre and a hollow lumen within each fibre. The primary walls form an initial network of glycoproteins, lignin and hemicellulose microfibrils. The epidermis (bark) helps avoid wetness evaporating from the plant; also, it allows moderating the mechanical injuries to the plant structure. In particular, two types of transport tissue can be distinguished in the plant: xylem helps in transferring water and nutrients from the root to the whole extension of the plant [11]. The second transport tissue is phloem: phloem fibres