FIBERS, VEGETABLE

1. Introduction

Fibers for commercial and domestic use are broadly classified as natural or synthetic. The natural fibers are vegetable, animal, or mineral in origin. Vegetable fibers, as the name implies, are derived from plants. The principal chemical component in plants is cellulose, and therefore they are also referred to as cellulosic fibers. The fibers are usually bound by a natural phenolic polymer, lignin, which also is frequently present in the cell wall of the fiber; thus vegetable fibers are also often referred to as lignocellulosic fibers, except for cotton, which does not contain lignin.

Vegetable fibers are classified according to their source in plants as follows: (*1*) the bast or stem fibers, which form the fibrous bundles in the inner bark (phloem or bast) of the plant stems, are often referred to as soft fibers for textile use; (*2*) the leaf fibers, which run lengthwise through the leaves of monocotyledonous plants, are also referred to as hard fibers; and (*3*) the seed-hair fibers, the source of cotton, which is the most important vegetable fiber and is discussed in this Encyclopedia (see COTTON). There are >250,000 species of higher plants; however, only a very limited number of species have been exploited for commercial uses (<0.1%). The commercially important fibers are given in Table 1 (1–3).

The fibers in bast and leaf fiber plants are integral with the plant structure, providing strength and support. In bast fiber plants, the fibers are next to the outer bark in the bast or phloem and serve to strengthen the stems of these reed-like plants. The fibers are in strands running the length of the stem or between joints (Fig. 1). To separate the strands, the natural gum binding them must be removed. This operation is called retting (controlled rotting). For most uses, particularly for textiles, this long composite-type strand fiber is used directly; however, when such fiber strands are pulped by chemical means the strand is broken down into much shorter and finer fibers, the ultimate fibers shown in Figure 1.

Table 1. **Vegetable Fibers of Commercial Interest**[a]

Commercial name	Source	Botanical name of plant	Growing area
		Bast or soft fibers	
China jute	Abutilon	*Abutilon theophrasti*	China
flax		*Linum usitatissimum*	north and south temperate zones
hemp		*Cannabis sativa*	all temperate zones
jute		*Corchorus capsularis; C. olitorius*	India
kenaf		*Hibiscus cannabinus*	India, Iran, CIS, South America
ramie		*Boehmeria nivea*	China, Japan, United States
roselle		*Hibiscus sabdariffa*	Brazil, Indonesia (Java)
sunn		*Crotalaria juncea*	India
urena	cadillo	*Urena lobata*	Zaire, Brazil
		Leaf or hard fibers	
abaca		*Musa textilis*	Borneo, Philippines, Sumatra
cantala	Manila maguey	*Agave cantala*	Philippines, Indonesia
caroa		*Neoglaziovia variegata*	Brazil
henequen		*Agave fourcroydes*	Australia, Cuba, Mexico
istle		*Agave* (various species)	Mexico
mauritius		*Furcraea gigantea*	Brazil, Mauritius, Venezuela, tropics
phormium		*Phormium tenax*	Argentina, Chile, New Zealand
pineapple	piña	*Ananas comasus*	Hawaii, Philippines, Indonesia, India, West Indies
sansevieria	bowstring hemp	*Sansevieria* (entire genus)	Africa, Asia, South America
sisal		*Agave sisalana*	Haiti, Java, Mexico, South Africa, Brazil
		Seed-hair fibers	
coir	coconut husk fiber	*Cocos nucifera*	tropics, India, Mexico
cotton		*Gossypium* sp.	United States, Asia, Africa
kapok		*Ceiba pentandra*	tropics
milkweed floss		*Chorisia* sp.	North America
		Other fibers	
broom root	roots	*Muhlenbergia macroura*	Mexico
broom corn	flower head	*Sorghum vulgare technicum*	United States
crin vegetal	palm leaf segments	*Chamaerops humilis*	North Africa
palmyra palm	palm leaf stem	*Brossus flabellifera*	India
pissava	palm leaf base fibers	*Attalea funifera*	Brazil
raffia	palm leaf segments	*Raphia raffia*	East Africa

[a]Refs. 1–3.

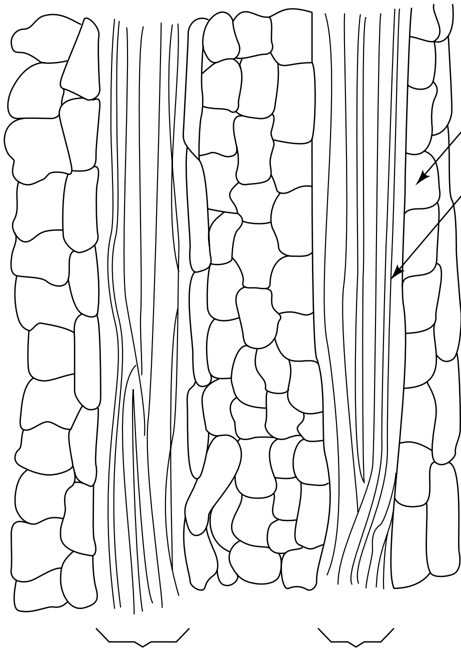

Fig. 1. Typical longitudinal section of bast fiber showing very long fiber strands composed of many ultimate fibers (see Table 3 for dimensions).

The long leaf-fibers contribute strength to the leaves of certain nonwoody, monocotyledonous plants. They extend longitudinally the full length of the leaf and are buried in tissues of a parenchymatous nature. The fibers found nearest the leaf surface are the strongest. The fibers are separated from the pulp tissue by scraping because there is little bonding between fiber and pulp; this operation is called decortication. Leaf fiber strands are also multicelled in structure.

Ancient humans used cordage in fishing, trapping, and transport, and in fabrics for clothing. Rope and cord making started in Paleolithic times, as seen in cave drawings. Rope, cords, and fabrics were made from reeds and grasses in ancient Egypt (400 BC). Ropes, boats, sails, and mats were made from palm leaf fibers and papyrus stalks and writing surfaces, known as papyrus, from the pith section. Jute, flax, ramie, sedges, rushes, and reeds have long been used for fabrics and baskets. Jute was cultivated in India in ancient times and used for spinning and weaving. The first true paper is believed to have been made in southeastern China in the second century AD from old rags (bast fibers) of hemp and ramie and later from the bast fiber of the mulberry tree.

Scientists at the U.S. Department of Agriculture (USDA) Northern Regional Research Center in Peoria, Illinois, carried out an extensive screening of over 500 species of plants as potential sources of papermaking fibers (4–7). The species were rated for agronomic potential, chemical composition, fiber properties, and physical characteristics. The species with the greatest potential were in

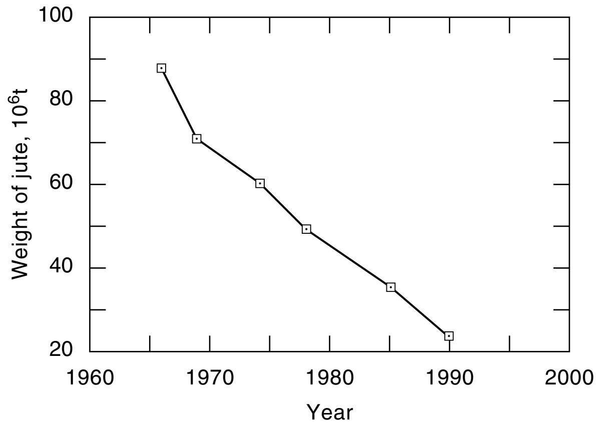

Fig. 2. Export of jute goods from India (1965–1990).

the genera *Hibiscus, Crotalaria, Sorghum, Cannabis, Gynerium, Lygerum, and Sinarundinaria*.

World markets for vegetable fibers have been steadily declining in recent years, mainly as a result of substitution with synthetic materials. Jute has traditionally been one of the principal bast fibers (tonnage basis) sold on the world market; however, the precipitous decline in jute exports by India (Fig. 2) indicate the decreasing market demand for this fiber that has been vitally important to the economies of India (West Bengal), Bangladesh, and Pakistan.

2. General Properties

2.1. Chemical Composition.

The chemical composition of the principal commercial vegetable fibers is given in Table 2 (8,9). These compositions are for

Table 2. **Chemical Composition of Vegetable Fibers, wt %**[a]

Fiber	Cellulose	Hemicellulose	Pectins	Lignin	Extractives
		Bast fibers			
flax	71.2	18.6	2.0	2.2	6.0
hemp	74.9	17.9	0.9	3.7	3.1
jute	71.5	13.4	0.2	13.1	1.8
kenaf	63.0	18.0		17.0	2.0
ramie	76.2	14.6	2.1	0.7	6.4
		Leaf fibers			
abaca	70.1	21.8	0.6	5.7	1.8
phormium	71.3				
sisal	73.1	13.3	0.9	11.0	1.6
		Seed-hair fibers			
coir	43.0	0.1		45.0	
cotton	92.9	2.6	2.6		1.9
kapok	64.0	23.0	23.0	13.0	

[a]Refs. 1,2,8, and 9.

the commercial fibrous materials after processing and differ from the chemical composition of the whole plant material that is frequently cited in the literature (1,10). Chemically, cotton is the purest, containing >90% cellulose with little or no lignin. The other fibers contain 40–75% cellulose, depending on processing. Boiled and bleached flax and degummed ramie may contain >95% cellulose. Kenaf and jute contain higher contents of lignin, which contributes to their stiffness. Although the cellulose contents shown in Table 2 are fairly uniform, the other components, eg, hemicelluloses, pectins, extractives, and lignin vary widely without obvious pattern. These differences may characterize specific fibers.

2.2. Fiber Dimensions. Except for the seed-hair fibers, the vegetable fibers of bast or leaf origins are multicelled (Fig. 1) and are used as strands (see Table 3) (1,2,9,11). In contrast to the bast fibers, leaf fibers are not readily

Table 3. **Dimensions of Ultimate Fibers and Strands**[a]

	Ultimate fiber		Cell cross-section		Fiber strand	
Fiber	Length, mm	Diameter, μm	Shape	Diameter,[b] μm	Length, cm	Width, mm
			Bast fibers			
Chinese jute	2–6.5	7–33				
flax	4–69	8–31	polygonal	8.8–16.1	25–120	0.04–0.62
hemp	5–55	16	polygonal	13.1–23.6	100–400	0.5–5
jute	0.7–6	15–25	polygonal to oval	12.3–18.6	150–360	
kenaf	2–11	13–33	cylindrical		200–400	
ramie	60–250	16–120	hexagonal to oval	6.2–32.4	10–180	
sunn	2–11	13–64	irregular	13.6–24.6	108–216	
nettle	4–70	20–70		50–50		
			Leaf fibers			
abaca	2–12	6–40	oval to round	14–20	150–360	0.01–0.28
cantala				13.8–16.4		
caroa	2–10	3–13		3.2–8.2		
henequen	1.5–4	8.3–33.2		11.6–22.2		
istle		9.6–16		11.2–13.4	30–75	
mauritius	1.3–6	15–32	cylindrical		124–210	
phormium	2–11	5.25	round	10.3–12.1	150–240	
sansevieria	1–7	13–40				
sisal	0.8–7.5	8–48	cylindrical	11–16	60–120	0.1–0.5
			Seed-hair fibers			
coir	0.2–1	6.24				1
cotton	10–50	12–25	circular elliptical		1.5–5.6	0.012–0.025
kapok	15–30	10–30	round		1.5–3	0.03–0.036
			Others			
broom root					25–40	

[a]Refs. 1,2,8–11.
[b]Minor and major diameters, respectively.

Table 4. **Mechanical Properties of Vegetable Fibers**[a]

Fiber	Fineness km/kg	Tensile strength,[b] km	Elongation %	Modulus of elasticity,[c] N/tex[d]	Modulus of rupture mN/tex[d]
		Bast (soft) fibers			
flax		24–70	2–3	18–20	8–9
hemp	139	38–62	1–6	18–22	6–9
jute	489	25–53	1.5	17–18	2.7–3
kenaf	180	24	2.7		
ramie		32–67	4.0	14–16	11
urena	342	16	1.9		
		Leaf (hard) fibers			
abaca	32	32–69	2–4.5		6
cantala	58	30			
henequen	32	20–42	3.5–5		
istle	34	22–27	4.8		
phormium	38	26			
sansevieria	118	43	4.0		
sisal	40	36–45	2–3	25–26	7–8
		Seed-hair fibers			
coir		18	16	4.3	16
kapok		16–30	1.2	13	10

[a] Refs. 9–12.
[b] Based on breaking length, which measures strength per unit area.
[c] Young's modulus.
[d] To convert N/tex to gf/den, multiply by 11.33.

broken down into their ultimate cells. The ultimate cells are composites of microfibrils, which, in turn, are comprised of groups of parallel cellulose chains.

2.3. Physical Properties. Mechanical properties are given in Table 4 (1,11,12). Bast and leaf fibers are stronger (higher tensile strength and modulus of elasticity) but lower in elongation (extensibility) than cotton. Vegetable fibers are stiffer but less tough than synthetic fibers. Kapok and coir are relatively low in strength; kapok is known for its buoyancy.

Table 5. **Textile-Associated Properties of Bast Fibers Compared to Polyester**[a]

Property	Cotton	Flax	Hemp	Jute	Ramie	Polyester
density, g/cm^3	1.54–1.5	1.50	1.48	1.50	1.51	1.22–1.35
moisture regain, %	8–11	12	12	13.7	6	0.4–0.8
fiber tenacity, mN/tex[b]	260–440	230–240	510–600	260–510	450–653	180–790
elongation, dry, %	3–10	2.7–3.3	1.6	1.2–1.9	3.0–7.0	18–67
recovery from 2% elongation, %	75	65		74	52	85–97
length/width ratio	1400	1200			3000	

[a]Ref. 13.
[b]To convert N/tex to gf/den, multiply by 11.33.

Among the bast textile fibers, the density is close to 1.5 g/cm^3, or that of cellulose itself, and they are denser than polyester, as shown in Table 5. Moisture regain (absorbency) is highest in jute at 14%, whereas that of polyester is $<1\%$. The bast fibers are typically low in elongation and recovery from stretch. Ramie fiber has a particularly high fiber length/width ratio.

The microfibrils in vegetable fibers are spiral and parallel to one another in the cell wall. The spiral angles in flax, hemp, ramie, and other bast fibers are lower than cotton, which accounts for the low extensibility of bast fibers.

3. Processing and Fiber Characteristics

3.1. Bast Fibers. Bast fibers occur in the phloem or bark of certain plants. The bast fibers are in the form of bundles or strands that act as reinforcing elements and help the plant to remain erect (Fig. 1). The plants are harvested and the strands of bast fibers are released from the rest of the tissue by retting, common for isolation of most bast fibers. The retted material is then further processed by breaking, scutching, and hackling. A general description of the processing of bast fibers is given below with modifications for specific fibers described in the following sections.

Processing. Harvesting and Pretreatment. At optimum maturity, the plants are pulled or mowed by hand or machine and, if necessary, threshed to remove seeds. The plants are spread out in a field to dry.

Retting. The removal of the bast fibers from bark and woody stem parts is promoted by a biological treatment called retting (rotting). This treatment is an enzymatic or bacterial action on the pectinous matter of the stem. After retting, the bundles are dried in fields. Retting may be carried out in several ways.

Dew retting involves the action of dew, sun, and fungi on the plants spread thinly on the ground. Dew retting takes 4–6 weeks, but the action is not uniform and it tends to yield a dark-colored fiber. However, it is far less labor intensive and less expensive than water retting. It is commonly used in regions of low water supply and accounts for 85% of the western European crop, especially in France, and also in the former Soviet Union.

Water retting involves immersion of bundles of plants in stagnant pools, rivers, ditches (dam retting), or in specially designed tanks (tank retting). The biological effect is achieved through bacterial action and takes 2–4 weeks for dam retting. In tanks with warm water (tank retting), the time is reduced to a few days. Water retting gives a more uniform product. In stream retting the plants are immersed in slow moving streams for a longer time and the quality of the product is high.

Chemical retting involves immersion of the dried plants in a tank with a solution of chemicals, such as sodium hydroxide, sodium carbonate, soaps, or mineral acids. The fibers are loosened in a few hours, but close control is required to prevent deterioration. Chemical retting is more expensive and does not produce a superior fiber to that obtained from biological retting.

Breaking and Scutching. The dried retted stalks in bundles are passed through fluted rolls to break or reduce the woody portion into small particles, which are then separated by scutching. The scutching is done by beating with blunt wooden or metal blades by hand or mechanically.

Hackling. The bundles are hackled or combed to separate the short and long fibers. This is done by drawing the fibers through sets of pins, each set finer than the previous one. As a result the fibers are further cleaned and aligned parallel to one another.

Flax. The flax fiber from the annual plant *Linum usitatissimum* (flax family, Linaceae) has been used since ancient times as the fiber for linen. The plant grows in temperate, moderately moist climates, for example, in Belgium, France, Ireland, Italy, and Russia. The plant is also cultivated for its seed, from which linseed oil is produced. A by-product of the seed plant is the tow fiber used in papermaking.

The bast fibers are dew or water retted with dew retting generally yielding a gray fiber. High quality flax fiber is produced by water (stream) retting in the river Lys in Belgium. A cross-sectional view of the flax fiber is shown in Figure 3**a**; the fibers are round to polygonal with a small lumen. The boiled, bleached fiber contains almost 100% cellulose. The flax fiber is the strongest of the vegetable fibers, even stronger than cotton. The fiber is highly absorbent, an important property for clothing, but is particularly inextensible. The most important application is in linen for clothing, fabrics, lace, and sheeting. Flax fiber is also used in canvas, threads and twines, and certain industrial applications such as fire hoses. Chemical pulping of flax provides the raw material for production of high quality currency and writing paper. Flax fiber is also commonly used in cigarette papers. Flax fibers are graded for fineness, softness, stretch, density, color, uniformity, luster, length, handle, and cleanliness.

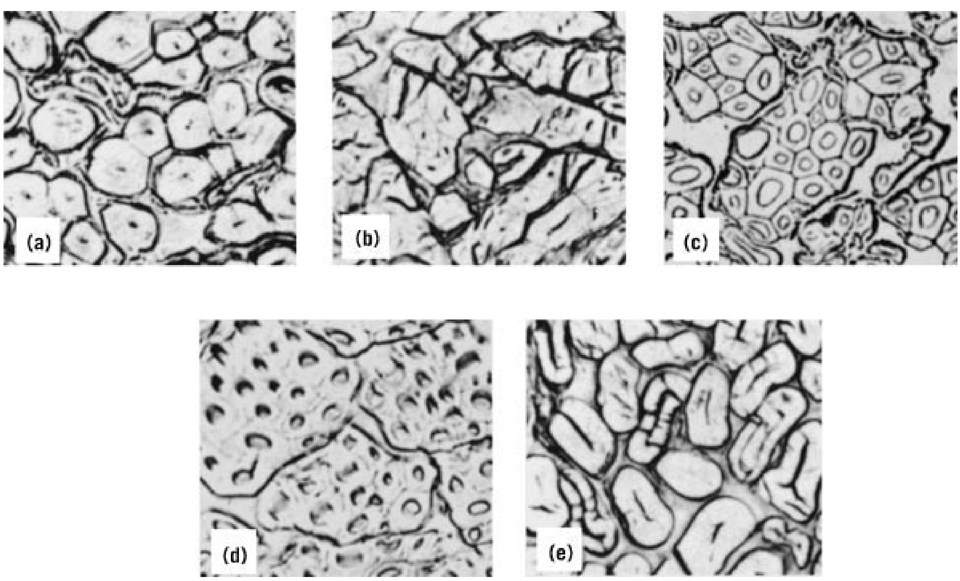

Fig. 3. Cross-sections (500×) of bast fibers: (**a**), flax; (**b**), hemp; (**c**), jute; (**d**), kenaf; and (**e**), ramie. (Courtesy of the American Association of Textile Chemists and Colorists (14).)

Hemp. The source of hemp fiber is the plant *Cannabis sativa* (mulberry family, Moraceae) originating in central China. It is grown in central Asia and eastern Europe. The stem is used for fiber, the seeds for oil, and leaves and flowers for drugs, among them marijuana. The stalks grow 5–7 m tall and 6–16 mm thick. The hollow stems, smooth until the rough foliage at the top, are hand cut and spread on the ground for dew retting for the highest quality product. Water retting is used on sun-dried bundles from which the seeds and leaves have been removed. Strands of hemp fiber can be 2 m in length. The fibers are graded for color, luster, spinning quality, density, cleanliness, and strength.

A cross-sectional view of hemp fiber is shown in Figure 3**b**. It has a Z twist in contrast to the S twist of flax. Hemp is regarded as a substitute for flax in yarn and twine. Its earlier use in ropes has been replaced by leaf and synthetic fibers. Hemp fiber is used in Japan, China, Hungry, and Italy to make specialty papers, including cigarette paper, but bleaching is difficult. The fiber is coarser and has less flexibility than flax. There is currently interest in reintroducing hemp into the United States and Canada as an alternate fiber crop for farmers. However, this is wrought with political and legal problems due to the inability to distinguish industrial hemp from hemp plants with high narcotic content.

Jute. Jute fiber is obtained from two herbaceous annual plants, *Corchorus capsularis* (linden family, Tiliaceae) originating from Asia, and *C. olitorius* originating from Africa. The former has a round seed pod, and the latter a long pod. Jute is grown mainly in India, Bangladesh, Thailand, and Nepal.

The plants are harvested by hand, dried in the field for defoliation, and water (pool) retted for periods up to a month. The depth of the retting pools is dependent on the volume of rainfall during the monsoon season in Southeast Asia. Thus a year with less rainfall results in low water levels in the retting pools and a lower grade jute product due to contamination with sand and silt. The fibers for export are graded for color, length, fineness, strength, cleanliness, luster, softness, and uniformity. The color ranges from cream white to reddish brown, but usually the fiber has a golden luster. A cross-sectional view of the fiber is shown in Figure 3**c**. The fibers are polygonal in cross-section with a wide lumen. Jute has traditionally been an important textile fiber, second only to cotton; however, jute has been steadily replaced by synthetics in the traditional high volume uses such as carpet backings and burlap (hessian) fabrics and sacks (Fig. 2). The strands are also used for twine, while kraft pulping of jute gives ultimate fibers for cigarette papers. The Indian government in cooperation with the United Nations Development Program has been involved in a significant jute diversification program to find new uses for jute in finer yarns and textiles, composites and boards, and paper products. A particularly promising outlet for jute is in molded composites with thermoplastic materials for interior automobile head, door and trunk liners (1).

Kenaf and Roselle. These closely related bast fibers are derived from *Hibiscus cannabinus* and *H. sabdariffa* (mallow family, Malvaceae), respectively. The fibers have other local names. Kenaf is grown for production in China, Egypt, and regions of the former Soviet Union; roselle is produced in India and Thailand. Plantation-grown kenaf is capable of growing from seedlings to 5 m at maturity in five months. It is reported to yield ~6–10 tons of dry matter per acre, nine times the yield of wood (15,16).

The plants are hand-cut, mowed, or pulled in developing countries while mechanized harvesting methods are under investigation in the United States. Ribboning machines are sometimes used to separate the fiber-containing bark before retting for recovery of the kenaf strands. For pulping, the kenaf is shredded or hammermilled to 5-cm pieces, washed, and screened.

A cross-sectional view of kenaf is shown in Figure 3**d**. The ultimate cells are nearly cylindrical with thick cell walls. Kenaf fibers are shorter and coarser than those of jute. Both chemical (kraft) and mechanical pulps have been produced from kenaf, and successful demonstration runs of newsprint have been made for the Dallas Morning News, the St. Petersburg Times, and the Bakersfield Californian with a furnish of 82% kenaf chemithermomechanical pulp and 18% softwood kraft pulp. Kenaf fiber is also considered a substitute for jute and used in sacking, rope, twine, bags, and as papermaking pulp in India, Thailand, and the Balkan countries. Roselle bleached pulp is marketed in Thailand.

Ramie. The ramie fiber is located in the bark of *Boehmeria nivea*, a member of the nettle family (Urticaceae). The plant is a native of China (hence, its name China grass), where it has been used for fabrics and fishing nets for hundreds of years. It is also grown in the Philippines, Japan, Brazil, and Europe. The ramie plant grows 1–2.5 m high with stems 8–16 mm thick. The roots send up shoots on harvesting, and two to four cuttings are possible annually, depending on soil and climate.

The plant is harvested by hand sickle and, after defoliation, is stripped and scraped by hand or machine decorticated. Because of the high gum (xylan and araban) content of up to 35%, retting is not possible. The fibers are separated chemically by boiling in an alkaline solution in open vats or under pressure, then washed, bleached with hypochlorite, neutralized, oiled to facilitate spinning, and dried.

The degummed, bleached fiber contains 96–98% cellulose. A cross-sectional view is shown in Figure 3**e**. The ramie fibers are oval-like in cross-section with thick cell walls and a fine lumen. The cell wall constituents in the ramie fiber, like other bast fibers except flax, have a counterclockwise twist. Ramie is the longest of the vegetable fibers and has excellent luster and exceptional strength; however, it tends to be stiff and brittle. Wet strength is high and the fiber dries rapidly, an advantage in fish nets.

Traditional uses for ramie have been for heavy industrial-type fabrics such as canvas, packaging material, and upholstery. Increased production of the fiber in Asia, particularly China, has promoted the use in blended fabrics with silk, linen, and cotton which can now be found on the market.

Sunn Hemp. The stems of the herbaceous plant *Crotalaria juncea* (legume family, Fabaceae), called sunn or sunn hemp, provide a bast fiber. The plant is native to India, the chief fiber producer, and it is also grown in Bangladesh, Brazil, and Pakistan. It has a long tap root and grows to a height of up to 5 m. Harvesting is done manually by pulling or cutting. The plant is defoliated in the field, water retted, and processed similarly to jute. The white fiber is graded by color, firmness, length, strength, uniformity, and extraneous matter content. Sunn is used for canvas, paper, fishing nets, twine, and other cordage.

Urena and Abutilon. These are less important vegetable fibers of a jutelike nature. *Urena lobata* (Cadillo) of the mallow family (Malvaceae) is a perennial that grows in Zaire and Brazil to a height of 4–5 m with stems 10–18 mm in diameter. Because of a lignified base, the stems are cut 20 cm above the ground. The plants are defoliated in the field and retted similarly to jute and kenaf. The retted material is stripped and washed and, in some cases, rubbed by hand. The soft, near-white fiber is graded for luster, color, uniformity, strength, and cleanliness. It is used for sacking, cordage, and coarse textiles.

Abutilon theophrasti is a herbaceous annual plant producing a jute-like fiber. The plant is native to China and is commercially grown in China and the former Soviet Union. Because of its association with jute in mixtures and export, it is also called China jute. The plant grows to a height of 3–6 in with a stem diameter of 6–16 mm. After harvesting by hand and defoliation, bundles of the stems are water retted and the fiber is extracted by methods similar to those for jute. The fiber is used for twine and ropes.

3.2. Leaf (Hard) Fibers. Hard or cordage fibers are found in the fibrovascular systems of the leaves of perennial, monocotyledonous plants growing in Central America, East Africa, Indonesia, Mexico, and the Philippines. They are generally of the Agave and Musa genera. The leaf elements are harvested by cutting at the base with a sickle-like tool, and bundled for processing by hand or by machine decortication. In the latter case, the leaves are crushed, scraped, and washed. The fibers are generally coarser than the bast fibers and are graded for export according to national rules for fineness, luster, cleanliness, color, and strength.

Abaca. The abaca fiber is obtained from the leaves of the banana-like plant (same genus) *Musa textilis* (banana family, Musaceae). The fiber is also called Manila hemp from the port of its first shipment, although it has no relationship with hemp, a bast fiber. The mature plant has 12–20 stalks growing from its rhizome root system; the stalks are 2.6–6.7 m tall and 10–20 cm thick at the base. The stalk has leaf sheaths that expand into leaves 1–2.5 m long, 10–20 cm wide, and 10 mm thick at the center, the fibers are in the outermost layer. The plant produces a crop after 5 years, and 2–4 stalks can be harvested about every 6 months.

In the Philippines, the principal supplier of abaca fiber, the fibrous layer in the sheath is separated with a knife between the layers, and the strips of fiber containing layers, called tuxies, are pulled off and cleaned by hand to remove the pulp. In Indonesia and Central America these operations are performed mechanically. Hand- and spindle-stripped fiber is graded for braids, fine textiles, and cordage; decorticated fiber is another class. A cross-sectional view is shown in Figure 4**a**. The abaca fiber has a large lumen and the presence of silicified plates is not unusual.

Abaca fiber is unique in its resistance to water, especially salt water, and it is used for marine ropes and cables, although it has been largely replaced by synthetic fibers. Abaca fiber is the strongest of the leaf fibers (Table 4), followed by sisal, phormium, and henequen; it is also the strongest among the papermaking fibers. It is used for sausage casings and it is the preferred fiber for tea bags because of its high wet strength, cleanliness, and structure that permits rapid diffusion of the tea extract.

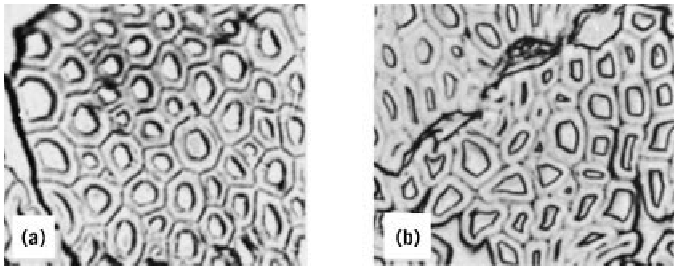

Fig. 4. Cross-sections (500×) of leaf fibers: (**a**), abaca and (**b**), sisal. (Courtesy of the American Association of Textile Chemists and Colorists (14).)

Cantala, Manila Maguey. *Agave cantala* is a member of the agave family (Agavaceae) that includes sisal. It originated in Mexico and was transported to Indonesia and the Philippines, where it is now produced commercially. The plant grows in a moist, humid soil. The fiber is extracted in Indonesia mechanically by a decorticator (raspador) and in the Philippines by retting in seawater and cleaning by hand or with a decorticator. The cantala fiber is lighter in color than other agaves, and its strength depends on its preparation.

Caroa. Caroa is a hard leaf fiber, resembling sisal, obtained from *Neoglaziovia variegata*, a plant of the pineapple family (Bromeliaceae) growing wild in eastern and northern Brazil. The sword-shaped leaves are 1–3 m long and 2.5–5 cm. wide. The fiber is extracted by hand scraping after beating or retting. The fiber is used for cordage and acoustic material.

Henequen. *Agave fourcroydes* grows in Mexico where it was first cultivated by the Mayans in the Yucatan (Yucatan Sisal). The plant produces for 20–30 years. The lower bottom leaves, which are up to 2 m long and 10–15 cm wide, are cut, machine decorticated, and cleaned. Henequen fibers are white to yellowish red and are inferior to sisal in strength, cleanliness, texture, and length, the other grading criteria. Henequen is grown for local use in Cuba (Cuban Sisal) and El Salvador. Twine, small ropes, coarse rugs, and sacks are made commercially from henequen.

Istle. Istle is the general name for several agave species and related plants producing short, coarse, hard fibers. The commercial name is tampico. The plants from which the fibers are harvested include tula istle (*A. lophantha*), jaumave istle (*A. funkiana*), and palma istle (*Samuela carnerosana*). They are grown in central and northern Mexico. The fibers are recovered by hand scraping and drying; the palma istle is gummy and requires presteaming. The jaumave istle fibers closely resemble animal bristles in brushes.

Mauritius Hemp. Mauritius hemp, also called piteira, is obtained from *Furcraea gigantea,* also a member of the Agavaceae. The plant is mostly grown on the island of Mauritius, but is also harvested in Brazil and other tropical countries. The leaves are longer and heavier than those of the agaves. The fiber is extracted by mechanical decortication. It is whiter, longer, and weaker than sisal fiber. Because of its color it is used in blends.

Phormium. The *Phormium tenax* plant yields a long, light-colored, hard fiber also known as New Zealand hemp or flax, although it has none of the bast fiber characteristics. The plant is a perennial of the Agavaceae with leaves up to 4 m long and 10 cm wide. The fibers are recovered by mechanical decortication.

Sansevieria. This genus of the Agavaceae is a perennial also known as bowstring hemp from its use in bow strings. The plant is native to tropical Africa and Asia but is widely grown, mainly as an ornamental plant. It is of minor importance as a fiber plant, even though the fiber is of high quality. The highest grade of *S. cylindrica* fiber is greenish yellow, very soft and fine, and compares with sisal in strength.

Sisal. The true sisal fiber from *Agave sisalana* is the most important of the leaf fibers in terms of quality and commercial use. Originating in the tropical western hemisphere, sisal has been transplanted to East Africa, Indonesia, and the Philippines. It is named after the port in the Yucatan from which it was first exported. The sisal plant leaves grow from a central bud and are 0.6–2 m long, ending in a thorn-like tip. The fibers are embedded longitudinally in the leaves, which are crushed, scraped, washed, and dried. The highest grades are further cleaned with a revolving drum. The growth of the sisal plant depends on water availability; it stores water during the wet season and consumes it during periods of drought.

A cross-section of the sisal ultimate fiber is shown in Figure 4**b**. The sisal fiber is coarse and strong, but compared with the abaca fiber it is inflexible, although with a relatively high elongation under stress. It is also resistant to salt water. The principal applications are in binder and baling twine and as a raw material for pulp for products requiring high strength. A large pulp mill is operating in Brazil based on sisal.

3.3. Seed- and Fruit-Hair Fibers. The seeds and fruits of plants are often attached to hairs or fibers or encased in a husk that may be fibrous. These fibers are cellulosic based and of commercial importance, especially cotton, the most important natural textile fiber.

Coir. This fiber, obtained from husks of the fruit of the coconut palm, *Cocos nucifera* (palm family, Arecaceae), is mainly produced in India and Sri Lanka. The fruits are broken by hand or machine, and the fiber extracted from the broken husks from which the coconut has been removed for the copra. The husks are retted in rivers, and the fiber separated by hand beating with sticks or by a decortication machine. The fibers are washed, dried, and hackled, and used in upholstery, cordage, fabrics, mats, and brushes.

Kapok. Kapok fiber is obtained from the seed pods of the kapok tree, *Ceiba pentandra*, of the Kapok tree family (Bombacaceae) which is indigenous to Africa and southeast Asia; the fiber is produced mainly in Java. The tree grows to a height of 35 m. The seeds are contained in capsules or pods that are picked and broken open with mallets. The floss is dried and the fiber is separated by hand or mechanically. A nondrying oil is produced from the seeds with properties similar to cottonseed oil. The fiber is exceedingly light, with a circular cross section, thin walls, and a wide lumen. Kapok fibers are moisture resistant, buoyant, resilient, soft, and brittle, but not suitable for spinning. The traditional uses were in life jackets, sleeping bags, insulation, and upholstery; however, synthetics have replaced most of the applications as filling material and now kapok is mainly used for life preservers. Kapok-filled life preservers can support up to three times the weight of the preserver and do not become waterlogged.

3.4. Palm and Other Fibers. *Piassava and Crin Vegetal.* These palm (palm family, Arecaceae) fibers are obtained from the palm leaf base of *Attalea funifera* growing in Brazil and the palm leaf segments of *Chamaerops humilis* growing in North Africa. The former are used for cordage and brushes, the latter for stuffing.

Broom Root and Broom Corn. Broom root fiber is obtained from the root of the bunch grass, *Muhlenbergia macroura* (Poaceae), found in Mexico, where it grows 1–3 m high. The long fibers are bleached in fumes of burning sulfur before grading according to length. They are used in stiff scrubbing and scraping brushes and whisk brooms.

Broom corn is the fiber obtained from the flower head of another grass, *Sorgum vulgare technicum*, grown in the United States. The fibers are less stiff than those of the broom root and are used in brooms.

4. Economic Aspects

The principal bast and leaf fibers are produced in yields of 2–5%, with some exceptions such as flax (15%) and kapok (17%), on a green plant basis. The world production of several cordage (leaf) and textile (bast) fibers is given in Table 6. Vegetable fiber production on the world market has dropped substantially because of periods of economic recession and synthetic fiber replacements. The U.S. imports of vegetable fibers have also dropped in recent years for similar

Table 6. **World Production of Major Vegetable Fibers in 2002, 10^3 metric tons**[a]

Fiber	Major countries		World production
flax (fiber and tow)	China	221	647
	France	77	
	Egypt	63	
	Russia Fed.	62	
	Benelux	30	
hemp(fiber and tow)	China	15	55
	Korea (Dem.)	13	
	Romania	8	
	Spain	7	
jute and jute-like	India	1,875	3,107
	Bangladesh	860	
	China	136	
	Myanmar	42	
	Nepal	16	
ramie	China	175	179
	Philippines	2	
	Brazil	1	
sisal	Brazil	177	331
	Mexico	27	
	Kenya	25	
	Tanzania	21	
	Madagascar	15	

[a]Source: http://apps.fao.org

Table 7. **Uses of Vegetable Fibers**

Uses	Leaf fibers				Bast fibers					Seed, fruit, and other fibers		
	Abaca	Cantala	Henequen	Sisal	Flax	Hemp	Jute	Kenaf	Ramie	Sunn	Kapok	Coir
Textiles and woven goods												
fine household, clothing					X	X			X			
coarse household					X	X	X	X	X			
bags and sacks			X				X	X				
thread, yarn					X	X	X		X			
canvas, sailcloth							X	X	X	X		
carpet backing, matting[a]	X	X	X	X	X		X	X				X
rugs, hammocks, belting, hose		X	X	X	X		X	X	X			
Cordage and twine												
industrial ropes	X		X			X			X	X		
marine ropes	X					X						
binder, baling twine		X	X	X								
nets									X	X		
twinesa	X		X		X	X	X	X	X	X		
Upholstery and stuffing												
mattresses, furniture			X	X					X		X	
sleeping bags, life preservers											X	
Other uses												
brooms, brushes												X
pulp for papermaking	X			X	X	X	X	X				
biobased composites	X			X	X		X	X				

[a]Also phormium leaf fibers.

reasons (with the exception of flax wastes). The precipitous decline in jute exports from India are shown in Figure 2. Although most vegetable fibers are converted to lower cost commodity products, some of the fibers are converted into the most expensive products in their respective industries, eg, U.S. currency (paper).

5. Uses

Vegetable fibers have application in a broad range of fibrous products, including textiles and woven goods, cordage and twines, stuffing and upholstery materials, brushes, paper and new biobased composites (Table 7). The uses for each of the specific fibers have been discussed in the designated sections. The traditional uses for the vegetable fibers have been eroded by substitution with synthetics on the world market. The declining uses include cordage, mats, filling material, brushes, etc. However, the unique properties of the bast fibers have allowed continued use in such specialty papers as bank notes, some writing papers, and cigarette papers.

Work at the USDA and Kenaf International (Texas) during the past decade demonstrated the potential of both growing and processing kenaf fibers for newsprint and other paper products in the United States (15). Another promising use for vegetable fibers is in the new biobased composites that are now marketed in various parts of the industrialized world (1). The vegetable fibers are mixed with thermoplastic or thermosetting resin matrices and either extrusion or compression molded into a variety of useful shapes. Such products are already utilized in the automotive industry for automobile interior door and head liners and as trunk liners. Although vegetable fibers will continue to provide indigenous populations with traditional uses, new innovative applications need to be developed to maintain international markets for the fibers.

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