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Bast fibres (flax, hemp, jute, ramie, kenaf, abaca)

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2.1 Introduction

Nature in its abundance offers us a lot of material that can be called fibrous; fibres are found in plant leaves, fruits, seed covers and stalk. Fibres from these plants can be considered to be totally renewable and biodegradable. Bast fibres are soft, woody fibres obtained from stems of dicotyledonous plants (flowering plants with net-veined leaves). Such fibres, usually characterized by fineness and flexibility, are also known as 'soft' fibres, distinguishing them from the coarser, less flexible fibres of the leaf, or 'hard', fibre group. This chapter will discuss bast fibres from flax, hemp, jute, ramie, kenaf and abaca.

Green fibres like flax, jute, sisal, kenaf and fibres of allied plants, which have been used for more than 8000 years, are the present and will be the future raw materials not only for the textile industry but also for modern eco-friendly composites used in different areas of application like building materials, particle boards, insulation boards, food, fodder and nourishment, friendly cosmetics, medicine and source for other bio-polymers 'agro-fine chemicals and energy'. Potentially, under optimum cultivation conditions, they cause little or no detrimental effect on the ecosystem, they can grow in different climatic zones and they recycle the carbon dioxide in the Earth's atmosphere.

Global trends towards sustainable development have brought to light natural, renewable, biodegradable raw materials, among them bast fibres. Science and technology continue to extend their use in textile and other industries. Recent achievements and new applications of green fibres and associated products made of bast fibrous plants can provide the background for the following conclusions:

- A fast-growing population and eco- and health awareness will create large market for future expansion of other natural cellulosic fibres as alternatives to cotton.
- Green fibres/bast fibrous plants will also be used in growing quantity in

a wide spectrum of biocomposite materials. Being lignocellulosic they can be combined with man-made or natural polymers to provide a wide range of useful composites in textiles (including geotextiles and nonwovens), in particle and other boards, in goods containing chemical and thermosetting polymers, in filters, in transportation, in the building industry and agriculture. In the future all biocomposites will have to be recyclable and fully biodegradable.

- Green fibrous plants provide valuable by-products such as seeds, waxes, fragrances, and pigments. These may be used for food, fodder, pharmaceutics, cosmetics, and body-care items. Especially important are linseed/hemp seed. They contain substances indispensable for our brain and nervous system as well as antisclerotic/anticarcinogenic lignans and unsaturated fatty acids. The Institute of Natural Fibres (INF) has developed valuable food additives from linseed/hemp seed, which are in high demand together with cosmetics/body-care products. This is a good example of providing jobs and raising living standards by promoting agriculturally based industries.

Resuscitation of these plants is very important because they provide a better agricultural balance on the Earth and they will reduce a deficit of cellulosic pulp for the twenty-first century when the population will grow to about 11.6 billion.

2.2 Flax

Flax (*Linum ussitatissimum* L.) has 15 pairs of chromosomes (2n = 30) and the spring cultivars of fibre and oil flax are economically important. Flax is the oldest textile fibre in the world, it has been grown since the beginning of civilization; the earliest trace of its use dates from 8000 BC. Linen fabrics have also been discovered in Egyptian tombs wrapped around the bodies of the pharaohs. The qualities of nobility and strength of this fibre were already renowned in 6000 BC. The Phoenicians, famous merchants and navigators, bought flax in Egypt to export it to Ireland and Britain. In this way the fibre of flax entered the European continent. Around 3000 BC flax was cultivated in Babylon and around 650 BC burial chambers depict cultivation and clothing from flax fibres. Hippocrates writes about using flax for the relief of gastrointestinal problems and Theophrastus recommends the use of flax mucilage as a cough remedy.

2.2.1 Economic importance of flax

Fibre flax is a plant grown mainly in wet temperate climates, and cultivated widely in Europe (Table 2.1). Outside Europe fibre flax is grown in China

Table 2.1 World fibre flax production in 2003

Country	Cultivation area (ha)	Total fibre yield (t/ha)	Total fibre production (t)
Argentina	2 700	0.70	1 900
Belarus	70 000	0.37	26 000
Belgium	19 250*	NA	NA
Chile	2 200	1.00	2 200
China	143 000	3.50	500 500
Czech Republic	7 000	2.53	17 700
Egypt	7 700	0.93	7 160
Estonia	107	0.64	69
France	86 351	1.00	86 000
Italy	3 000	0.15	450
Lithuania	9 500	0.66	6 270
Netherlands	4 500	5.56	25 000
Poland	5 100	1.96	10 000
Romania	200	1.50	300
Russian Federation	79 000	0.47	37 000
Slovakia	880	0.40	350
Spain	15 000	0.73	11 000
Ukraine	24 000	0.50	12 000
United Kingdom	18 000	1.56	28 000
Total (World)	497 488	1.27 (avg yield)	771 899

Source: FAO statistics (http:/apps.fao.org).
*INF data; NA – not available.

and Egypt. Flax fibre is used today as a valuable, environmentally friendly raw material for the textile industry. It is used to produce woven and knitted fabrics with exceptional health, hygienic and aesthetic qualities which ensure that linen never goes out of fashion! Linen woven and knitted fabrics ‘breathe’ with the skin. They absorb sweat and are good heat exchangers which cool us down in hot weather. An additional quality of flax fibre is that they do not collect an electrostatic charge, which is beneficial for human health and provides psychophysical comfort.

Traditionally, linen was used to produce table cloth, bed linen and upholstery fabrics. Recently, however, it is more and more frequently used as a raw material for clothes and for non-textile applications such as floor covering, geotextiles and in the automotive industry.

The processing of flax, besides fibre, also yields shive (50% of the harvested biomass) which is a good raw material for manufacturing lignocellulosic boards used in the construction and furniture industry.

Flax is a source of many other valuable raw materials used in the food and the pharmaceutical industries. Flax seed (linseed) can be added to bakery products (whole and ground) increasing its taste, nutritive value and prolonging its shelf-life. The linseed oil, containing polyunsaturated fatty acids, is a fast-drying oil and is a basic component in the production of paints and varnishes. It is also a precious dietetic and curative product. It has a beneficial effect on the peristaltic action of the intestine, prevents skin problems and shows anti-sclerotic action.

Oil flax is grown mainly in dry, warm and temperate climatic conditions. The major producers of oil flax are Canada, India, China, Argentina, USA and Europe (Table 2.2). The main crop is seed. The fibre is a secondary material used sometimes for quality pulp production and in non-textile applications.

Today, flax is facing strong competition from cotton and man-made fibres. To meet this challenge breeders try to improve its qualities by creating better cultivars. To obtain new cultivars by the classical method usually takes about 16 years but this process can be accelerated by implementing modern breeding techniques, for instance from molecular biology and biotechnology. Research at the INF has succeeded in breeding haploid plants through anther culture, which shortens the breeding cycle to only 8 years. During the experiments a new variety of fibrous flax was developed and called *Alba 2*, which is characterized by higher resistance to Fusarium wilt in comparison with the initial variety *Alba*.

Applying modern biotechnological methods in plant breeding will bring further development progress in the production of both food and other products. Continuous development of the research has resulted so far in three generations of genetically modified plants.

To ensure successful breeding, regardless of the method used, breeders must have access to gene banks as the source of genetic variability indispensable for breeding. The best source is the IPGR gene bank, which holds 7934 accessions (47% is represented by fibre type, 10% by linseed type, 6% by combined type, 1% by other type and about 36% is not specified) [1].

2.2.2 Anatomy of the flax plant

Flax seed is oval in shape and flat (slightly convex) with one end round and the opposite end with a sharp beak-like tip. The colour of the seed is mostly brown (in a wide range of shades, from almost black to light brown). Some cultivars (mainly oil ones) have yellow (golden) seed. Flax has a tap root system reaching approximately to the depth corresponding to the height of the plant, namely 60–100 cm. The size of the root system depends strongly on the conditions the plant is growing in. In good soil/moisture conditions the root system is weaker. The stem is composed of three main parts: root neck, non-branched (in fibre flax) or branched (oil flax) stem and an inflorescence – panicle. Leaves are small, narrow, lanceolate, arranged spirally on the stem, without petioles. Usually there are fewer leaves at the top of the stem than at the bottom of the stem. Leaves have three main parallel nerves and are covered with a thin layer of wax.

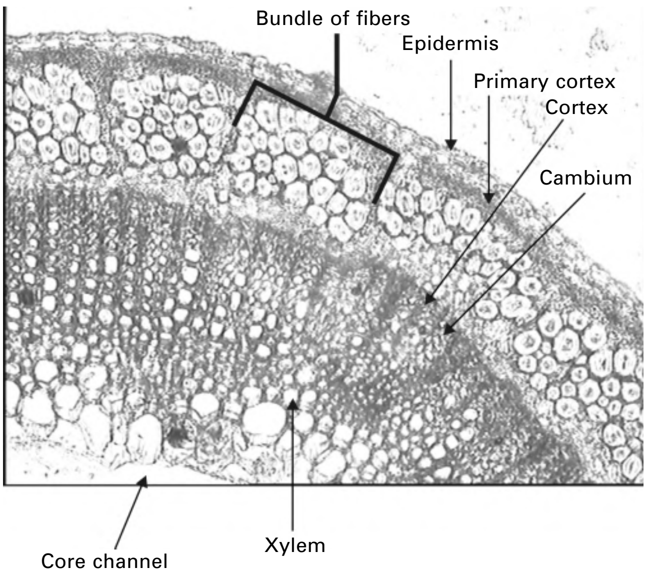
Table 2.2 World linseed production in 2003

Country	Cultivation area (ha)	Linseed yield (t/ha)	Linseed production (t)
Argentina	13 800	0.82	11 250
Australia	7 000	0.86	6 000
Bangladesh	70 000	0.71	50 000
Belarus	70 000	0.20	14 000
Belgium	20 232	0.67	13 460
Brazil	11 000	0.66	7 300
Canada	728 400	1.04	754 400
Chile	1 150	0.90	1 035
China	390 000	1.19	466 000
Czech Republic	5 344	0.91	4 848
Denmark	221	0.31	68
Ecuador	90	0.40	36
Egypt	17 000	1.53	26 000
Eritrea	341	0.59	200
Estonia	107	0.92	98
Ethiopia	98 595	0.52	51 052
France	77 124	0.69	52 941
Germany	16 000	0.63	10 000
Hungary	1 000	1.00	1000
India	459 200	0.38	172 600
Iran, Islamic Rep of	800	0.88	700
Italy	3 000	0.67	2 000
Kazakhstan	650	1.00	650
Kenya	800	1.00	800
Kyrgyzstan	6 000	0.63	3 800
Lithuania	9 500	0.28	2 700
Netherlands	4 500	1.00	4 500
New Zealand	500	2.00	1 000
Pakistan	6 200	0.48	3 000
Peru	1 000	0.75	750
Poland	740	0.99	733
Romania	1 561	0.96	1 498
Russian Federation	62 800	0.88	55 000
Slovakia	1 635	0.82	1 333
Spain	11 145	0.34	3 800
Sweden	3 600	1.83	6 600
Tunisia	2 200	2.14	4 700
Turkey	350	0.31	110
Ukraine	24 000	0.25	6 000
United Kingdom	34 000	1.74	59 000
United States of America	235 930	1.12	264 830
Uruguay	2 600	1.19	3 100
Total (World)	2 399 116	0.86 (avr. yield)	2 068 892

Source: FAO statistics (http://apps.fao.org).

The cross-section of flax stem reveals eight main elements (Fig. 2.1 [2]):

- epidermis – an outer part of the stem formed by a single layer of epidermal cells covered with cuticle;
- primary cortex – a tissue formed of 2–7 layers of parenchyma cells;
- layer of bast fibres – bundles of fibres in the form of a loose ring;
- cortex – a layer of secondary cortex made of tiny cells forming vascular bundles;
- cambium – a layer of parenchyma cells separating cortex from xylem;
- xylem – a thick layer of thick-wall cells;
- core – inner part of the xylem;
- core channel – an empty space inside the middle part of the stem along the whole length of the stem.



2.1 Flax stem cross-section [2].

The clusters of fibre called fibre bundles are located in the layer of cortex. Fibre flax is characterized by a high number of bundles with compacted structure. The lower number of loosely arranged bundles is characteristic of oil flax.

The inflorescence of flax is a panicle or a hanging bunch. The flower is self-pollinating with five petals, five-petal calyx and five-petal corona. The colour of the flower varies in different cultivars from white to different shades of blue. Five crochet-shaped, 2–5 mm stamens are joined at the bottom. The pistil is composed of a five-chamber ovary and five free necks, on top of each forming club-shaped stigma [3].

The following main development phases can be distinguished in flax [4]:

0 Germination.
1 Leaf development, young plant elongation.
3 Shoot development.
5 Inflorescence emergence.
6 Flowering.
7 Development of flax capsules.
8 Ripening of flax capsules.
9 Senescence.

2.2.3 Cultivation of flax

Flax is a temperate climate plant; the best weather conditions for flax are high temperature and high relative air humidity. The sum of rainfalls during the vegetation period should lie within 110–130 mm (600–800 mm annually). Flax consumes 400–600 ml of water to produce 1 g of dry matter. The best soils for flax cultivation are loess soils in good culture, medium-heavy, clay-sandy and sand-loamy soils. The flax should be cultivated on soils of good structure, with the ability to hold water and release it in dry conditions. The best soils for flax cultivation are the soil of IInd and IIIrd class, sometimes IVa [5].

Flax is susceptible to the preceding crop. In intensive agriculture the best forecrops are cereals, while in more extensive conditions sugar beet, and on weaker soils legumes. It does not tolerate growing on the same field the following year. The suggested break is 6–7 years [5]. Important elements in tillage are mechanical treatments controlling weeds in spring and in autumn and reducing evaporation from the soil (in spring). Besides basic nutrients (N, P, K), more and more important is the application of magnesium and calcium and microelements (B, Zn, Cu, Mn and Mo).

There are several diseases that are a problem in flax. The most dangerous ones are Fusarium wilt, anthracnose, gray mildew, polysporosis, rust, rhisoctoniosis, powdery mildew and pasmo [6], but to some extent the diseases (especially Fusarium wilt) can be controlled chemically with fungicides. The most dangerous insects for flax are flea beetles (two species) and thrips. Flea beetles are most dangerous from the beginning of germination till plants are about 5 cm tall. When the population of flea beetles reaches 5–10 insects m^{-2} the plants should be sprayed with insecticide.

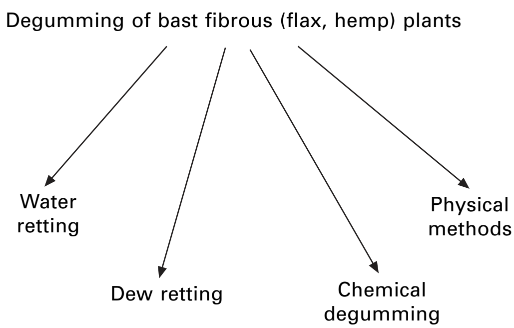
The optimal time for harvesting flax grown for fibre is the early yellow maturity of straw (green–yellow maturity). In this stage the stems are yellowish on approximately 1/3 of length (from the bottom of the plant), the stem has no leaves up to about a quarter of its length; the bolls begin to turn yellow.

Flax grown for seeds should be harvested at yellow maturity when stems are completely yellow, leaves have fallen off from 2/3 of the stem and the bolls are yellow. Seeds are fully developed and begin to turn brown.

Harvesting of flax in the first stage of this operation is done by pulling machines. These are mostly self-propelled machines that pull out straw and swath it in the field for the retting process. When retting is half-advanced, the straw must be turned over to secure uniform retting. This operation is performed by special turning machines which usually also harvest seeds. Sometimes seeds are harvested during the pulling operation [7]. For the reasons mentioned in Chapter 1 on hemp, most of the cultivated flax is dew-retted. When retting is completed straw is picked up from the field with rolling presses. Retted straw is delivered for processing which generally is similar to processing of hemp except that most flax straw, unlike hemp straw, is processed for long fibre. Therefore, the majority of flax straw is processed by scutching lines.

2.2.4 Degumming of flax and hemp

The process of loosening the bond between the fibre bundles and surrounding tissue (decomposing the natural adhesive pectin) is called degumming. There are several degumming methods (Fig. 2.2); however, only two are commonly used, water and dew retting.



2.2 Degumming methods.

Water retting

In the past flax and hemp were retted in industrial conditions in so-called retting mills. Straw was water retted in special basins (tanks) in warm or cold water. The retting process was conducted by bacteria (*Bacillus amylobacter*, *Bacillus felsineus*, *Granulobacter pectinovorum*, *Clostridium felsineum*, *Bacillus comesii rossi*) [8], in anaerobic conditions. Due to high costs of the process in terms of energy (required for heating water up to 30°C) and waste water (20 tonnes of water per tonne of straw and 10 tonnes for washing and rinsing) it is a considerable threat to the environment and it is not used any more in many countries. However, in hotter countries where no heat is required for warming water and with a more ‘flexible’ approach to environmental protection, water retting is still used.

Dew retting

Today, in most countries where flax and hemp straw is retted, it is by dew retting. This method involves the action of fungi, mainly *Cladosporium herbarummand* and also other species like *Mucor stoloniter*, *Mucor hiemalis*, *Mucor plumbens*, *Aspergillus niger*, *Fusarium culmorum*, *Epicoccum nigrum* and *Rhizopus sp.* [8]. Unlike water retting this process is aerobic. In rainy conditions the action of bacteria is also involved. In the retting process, regardless of which organisms are involved, the principle is to decompose the plant glue (pectin) that bind both the elementary fibres together and also conglomerates of fibres in the form of strands to woody fractions (shive, hurds).

When dew retting is half-advanced, the straw should be turned over. This allows the straw to be retted evenly and prevents the unwanted vegetation to grow through the swath. The time to break the retting is crucial for the quality of the fibre, especially when it is to be used for clothing. If the process is stopped too soon the fibre will be rough, stiff and it will be difficult to separate from the hurds. If retting takes too long, the fibre becomes weak and breaks into shorter and shorter fragments causing losses. It may also finally rot if wet weather conditions persist.

Both processes involve the action of enzymes used by retting organisms to dissolve pectin. Enzymes can also be used directly to degum the straw. For flax a pectolytic activity (°PM) of 210 U cm^{-3} is required.

Chemical degumming

In chemical degumming straw is exposed to the action of chemicals, such as ethylene, oxalic acid, sulfuric acid, sodium hydroxide, acid and sodium carbonate, oxygenated water, soda, sodium sulfite, etc.

Physical methods

Several physical methods of straw degumming have been developed; all involve the application of physical techniques leading to the separation of fibre from surrounding tissue. Among these techniques the following are mostly used: ultrasound oscillation, electron radiation, steaming with application of pressure methods, steam explosion, flash hydrolysis, steam hydrolysis, osmosis degumming, high-power electromagnetic pulses.

Among these methods, osmosis degumming is especially worth mentioning as practically the only one that can be used more widely, at least as a laboratory method of retting for evaluation of content and quality of fibre, especially in the case of new cultivar breeding. In this method, the degumming of fibre from straw is based on the physical laws of nature: water diffusion, osmosis and osmotic pressure. In this process, fibrous plants are subjected to treatment with water which flows continuously in order to extract fibres from plants without influencing the natural properties of the fibre formed. The fibre obtained in the above method is characterized by a colour, delicacy and thinness appropriate to the raw input material. The best results are obtained under the following conditions:

- temperature: 25–35°C,
- time of process: from 72 to 168 hours;
- constant, regular and controlled water flow.

2.2.5 Straw processing (flax and hemp)

When the retting is complete, the stems are collected and dried. The straw containing below 19% moisture can be processed. Straw can be supplied to the retting mill in four forms depending on the technology applied:

1. Whole threshed stems bound in bundles.
2. Stems without tops cut into sections and baled.
3. Baled decorticated fibre (bast).
4. Raw non-retted straw.

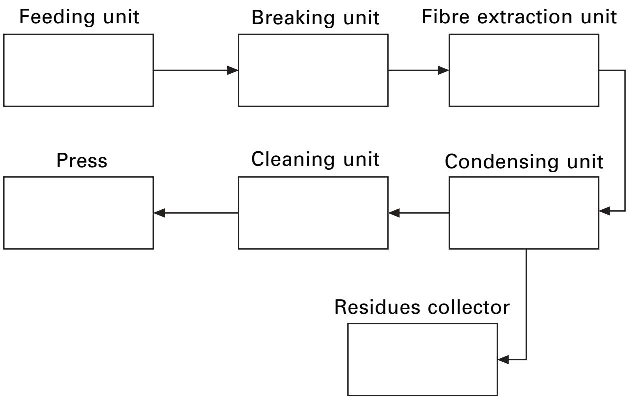
Basically, the objective of primary processing of straw is to weaken the bond between the fibre and shive and to separate the fibre. This objective is achieved by carrying out a series of breaking, shaking and scutching operations repeated several times until the fibre is satisfactorily extracted and separated from the shive. Depending on what kind of fibre is to be obtained, the straw is processed on a scutching line producing long fibre and waste short fibre (tow) or on a tow producing unit.

The scutching line comprises breaking machines which break the stem and crush the woody part of the stem thus causing preliminary separation of the fibre. Next, the crushed stems are scutched by scutching drums which hit the stems and knock off the shive.

The tow line is used for producing tow, also called homomorphic fibre in this case as there are no two different kinds of fibre in this process. To achieve this objective the processing line is assembled of three main units: breakers, scutchers and shakers.

Breakers, typically, are a set of riffled pairs of cylinders. The straw is inserted between them and crushed. It is the crushing action of the breakers that loosens the stem and allows the knocking down of the woody part of the stem (shive) in the following stage of processing (scutching and shaking). Scutchers can be similar to the scutching drums used in the processing of flax straw or are built similarly to the breakers with specially shaped teeth. Shakers are basically the sets of needles and sieves allowing for separation of loosened hurds from the fibre still remaining after scutching.

The technologies described above serve to process retted fibre. The raw straw needs much more intense operation (decortication) to loosen the bonds between hurds and fibre and yield fibre that requires extensive further processing to make it spinnable into yarns. This technology employs, as previously described, the decortication unit together with a set of several machines applying cyclically repeated actions of breaking, scutching and shaking (Fig. 2.3). The straw or bast obtained as a result of initial decortication should be dried to below a 15% moisture content before being fed into the aggregate.



2.3 Scheme of decortication line.

Flax and hemp straw due to the specific structure of fibre finds its application mainly through the traditional flax spinning method. Linen and hemp textiles are usually thicker than cotton, wool or chemical fibres. Traditional flax spinning technology is highly labour intensive, inefficient and uneconomical.

The physical parameters of simple flax and hemp fibres are similar to those of cotton. This, for quite a long time, has been a reason for the interest in the possible utilization of bast fibres, properly modified, for manufacturing yarns blended with cotton and chemical fibres. The principle of modification of flax and hemp fibres (cottonization) is to make hemp fibres resemble cotton fibres. The following three types of cottonized hemp fibres can be obtained:

- mechanically cottonized fibre;
- chemically cottonized fibre;
- enzymatically cottonized fibre.

Mechanical production of flax and hemp cottonized fibre for spinning by a cotton system involves the following operations:

- double breaking of fibre (tow or homomorphic fibre) on a breaker equipped with 32 pairs of rollers;
- fibre wetting and conditioning;
- forming reels;
- carding on a carding machine;
- cutting a sliver into 40 mm sections;
- single or double processing of cut sliver on a carding machine adopted for processing of flax and hemp by the Institute of Natural Fibres in Poznań.

The chemically cottonized fibre can be produced using similar operations as mechanically cottonized fibre. The only difference is that the sliver is cut or broken into 60 mm sections and next boiled in a solution of sodium hydroxide followed by acidifying, rinsing, centrifuging, drying and double processing on a carding machine. The retted fibre, cottonized chemically, mechanically or enzymatically, may be used for production of thin, pure linen and hemp yarns or yarns blended with cotton, wool and other fibres. Such modified fibre allows for the production of yarns having 50–100 tex of linear mass by pneumomechanical spinning system.

2.2.6 Spinning flax

As mentioned earlier flax is spun mainly by flax spinning equipment. The spinning of flax comprises various operations that make it possible to transform the fibres into yarn. The techniques vary according to the raw materials used and type of yarn to be produced. In short, the spinning process involves drafting and doubling, or carding and drawing out the long or short fibres into sinuous ‘ribbons’ which are then plied together on spinning looms in various weights and thicknesses. The fine yarn is ‘wet spun’ to impart a smoother, shiny appearance. The tow is commonly ‘dry spun’ yielding a less regular and napped yarn.

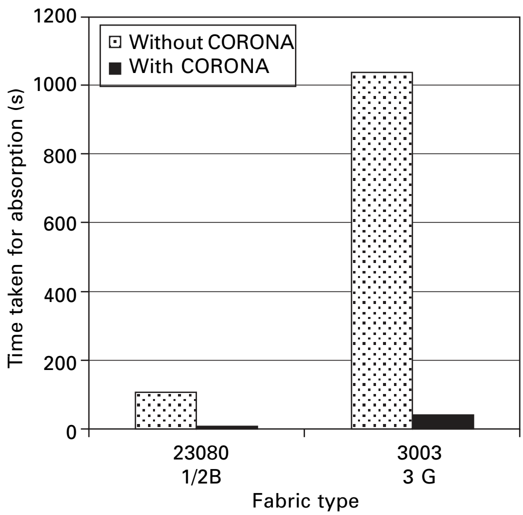
Linen can be used to make a very wide range of fabrics, for many applications. A few years ago, the weaving of linen was the work of a few specialist weavers; today the evolution in equipment and the quality of the yarn available on the market have allowed a great part of the textile sector to use linen in the development of increasingly competitive products. The development of products in pure linen or majority blended linen has continued to grow in response to the new trends in fashion and the expectation of consumers.

Linen is known for numerous advantages, but has also some disadvantages, the most problematic being susceptibility to creasing. This disadvantage, however, can be overcome by special fabric finishing in liquid ammonia. The cellulosic clothing materials, such as linen or cotton, that are treated serially with liquid ammonia show a remarkable shrink-proof or shape-retention property and crease resistance. This finishing changes the crystal structure of cellulose making it more elastic.

A new quite promising finishing for linen and other lignocellulosic fibres is CORONA treatment. The CORONA discharge is produced between two electrodes, at high voltage with frequency of 20–40 Hz. It affects the surface of a substrate moving continuously between electrodes at ambient pressure and temperature. For natural fibres such as cotton and linen, superficial changes are high enough to obtain good effects in textile processing and the material's properties.

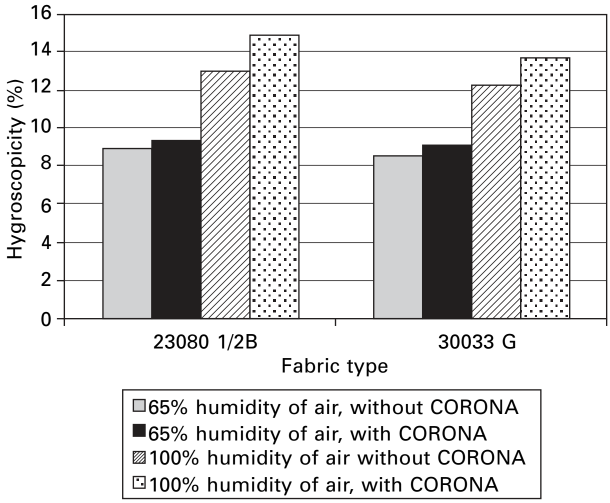
The processing of linen fabrics by CORONA treatment has an effect on some physical and mechanical properties of fabrics, namely in:

1. significant increase of water sorption (Fig. 2.4); and an
2. increase of hygroscopicity (Fig. 2.5).

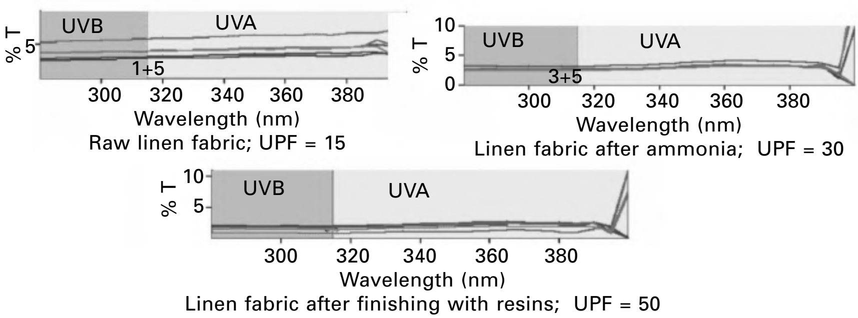


2.4 Speed of water absorption – drop method.

Apparel made of linen also ensures safety during sunny days, protecting us against hazardous ultraviolet radiation. Natural fibres containing natural pigments and lignin absorb ultraviolet rays very effectively. Linen and hemp fibres contain lignin as a part of their structure and therefore can be classified as excellent protectors against UV rays (Fig. 2.6). More dense structure of linen fabric with a lower level of clearance guarantees the user the best protection against ultraviolet radiation.



2.5 Hygroscopicity of fabrics.



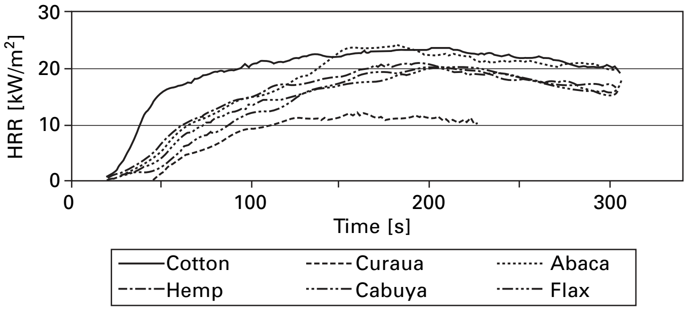
2.6 Protective effect of linen against UV radiation.

2.2.7 Applications of flax

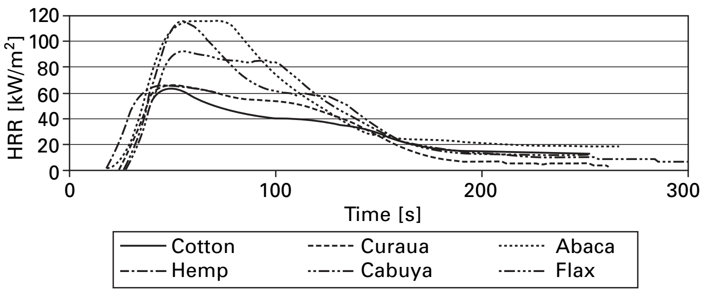
Textiles

Application of flax fibre in textiles cover both the clothing and non-clothing sectors. Flax is a well-known textile raw material used for exclusive and healthy clothing, woven and knitted. The non-clothing textile sector covers mainly table, bed linen and curtain fabrics. Some textiles may need fire retardant treatment. Fortunately cellulosic fibres, contrary to common belief, are quite safe in this respect as compared to other polymers (Figs. 2.7 and 2.8). Flax production and processing is the source of valuable by-products such as seeds, shive and waste fibres.

Flax seed as a by-product of bast fibrous plant is a rich source of valuable fatty acids, lignans, cyclolinopeptides, mucilage, waxes and other 'agro-fine



2.7 Heat release rate of cellulosic bast fibres (heat flux 35 kW m^{-2}).



2.8 Heat release rate of cellulosic bast fibres (heat flux 50 kW m^{-2}).

chemicals' making it an excellent source of valuable nutrients (Table 2.3). Shive constitutes 50% of processed straw and has numerous applications. The most common are particle board with different densities (Table 2.4; Fig. 2.9). Flax fibres are used also for non-textile applications, for instance in floor covering, and more and more often used as filling or reinforcing fibre in composites. Flax fibres display high tensile strength and much better tenacity than glass fibre. These properties make them an excellent choice for the automotive industry. Additionally, composites reinforced with natural fibres become biocomposites, which are a lower burden on the environment.

Table 2.3 Nutrient composition of flax seed

Nutrient	% by mass
Ash	4–5
Oil (90% polyunsaturated fatty acids)	28–45
Protein	24–30
Soluble dietary fibre (mucilage)	6–10
Insoluble dietary fibre	18–22
Total dietary fibre	27–31
Total carbohydrates	20–23
Lignans (phytoestrogens)	0.3

Table 2.4 Density range of particle boards from different annual plant residue

Density (kg m^{-3})	Low density			Medium density		
	300	400	500	600	700	800
Flax		■	■	■	■	
Hemp	■	■	■	■		
Jute	■	■	■	■		
Bagasse		■	■	■		
Flax and sawdust				■	■	■
Rape (canola)	■	■	■			

Source: Kozlowski, Mieleniak and Przepiera (1994) INF, Poland.

2.9 Lignocellulosic particle boards, *left to right* hemp, jute, vetiver root and flax.

2.3 Hemp

Hemp (*Cannabis sativa L.*) has ten chromosomes (2n = 20); it is an annual, dioecious, allogamic and wind-pollinating plant. Among hemp, three botanical varieties are found: var. *vulgaris* – regular hemp, var. *indica* – Indian hemp and var. *ruderalis* – wild hemp. Hemp is the only species found within the genus *Cannabis*; however, they are enormously rich in forms. Hemp can be divided into the following groups (types): northern hemp, middle European hemp (intermediate hemp) and southern hemp. The northern hemp is characterized by a short growing period (60–75 days), has high yields of seeds and low yields of poor quality fibre. The southern hemp gives high yields of vegetative biomass, including good quality fibre and low yields of seeds; they also have a long growing period (over 150 days) [9]. The group of intermediate hemp is characterized by factors lying between these values.

2.3.1 Economical importance of hemp

Hemp is a cosmopolitan plant found all over the world. Hemp is indigenous in Middle Asia, from the foothills of the Himalayas, from where it migrated to Eastern and Southern Asia. Hemp was first cultivated in China 5000 years ago and from there it spread to the whole world. Hemp was grown and still is grown mainly for fibre and seed but also as a source of narcotics. It is or was grown in the recent past on all continents except Antarctica from the tropics to Northern Europe (as far as 70° north altitude). Today, hemp is grown for fibre mainly in China, Europe (Russia, France, Ukraine, United Kingdom, Germany, Poland, and Finland) and also in North America (Canada). The area of cultivation, however, is much smaller than for other crops (Table 2.5).

Table 2.5 World hemp production in 2003

Country	Cultivation area (ha)	Total fibre yield (t/ha)	Total fibre production (t)
Bulgaria	8	0.00	0
Chile	4 300	0.95	4 095
China	15 000	2.53	38 000
France	200	1.80	360
Hungary	60	2.00	120
Italy	296	4.33	1 281
Korea, Dem. People's Rep.	18 500	0.69	12 800
Korea, Republic of	120	1.87	224
Poland	70	0.71	50
Romania	600	3.33	2 000
Russian Federation	15 000	0.47	7 000
Serbia and Montenegro	50	0.40	20
Spain	11 000	1.36	15 000
Ukraine	2 000	0.50	1 000

Source: FAO statistics (http://apps.fao.org).

In the past, before cheap fibres like cotton and, later, chemical fibres become available, hemp fibre was commonly used to produce technical items (ropes, sail fabric, twine, tarpaulin, etc.). After the Second World War, hemp cultivation was prohibited in the USA and Western Europe (except France) because of its narcotic properties.

In recent years, because of the search for alternatives to food crops in Europe and alternative sources of renewable resources, hemp is again of interest. Besides the traditional textile application of hemp numerous new directions emerge:

- building and isolation materials – particle board, MDF boards, cement boards with additional fibre, acoustic insulation materials, thermal insulation materials, light structural elements, bricks, upholstery material, nonwovens, etc.;
- composite materials – pressed elements for the automotive industry, coatings for clutches and brakes, filling material for injection moulding;
- special cellulose – special papers such as banknote, cardboard, cartographic, paper, cigarette and tea bag tissue, cellulose 'plastics';
- clothes, home textiles – wear, bed linen, towels, tablecloths;
- technical textiles – for laminates, tarpaulin, sail fabric, ropes, nets, etc.;
- geotextiles and agricultural textiles – nonwovens, felt, mats, embankment reinforcement material;
- oil-based products – paints, varnish, lubricants, cosmetics, food oil, dietetic foods, nutraceuticals, etc., and essential oils;
- items for agriculture and horticulture – animal bedding, flower beds.

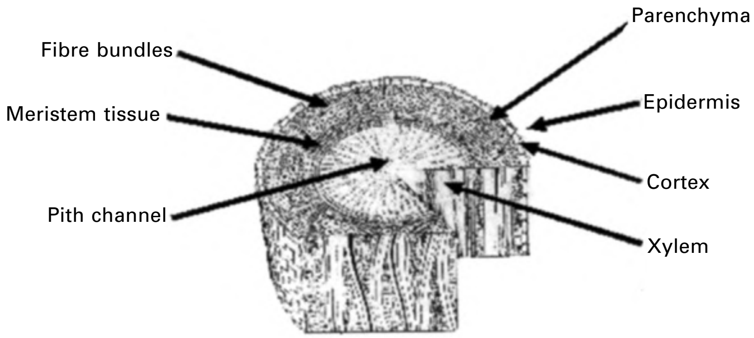
2.3.2 Anatomy of the hemp plant

Anatomically, the hemp nut consists of lignified ovary, seed shell, and embryo with cotyledons, apical bud, radicle and endosperm [9]. The main chemical components of a seed are: fats (25–38%), protein (about 25%) and carbohydrates (25%) [9]. Hemp has a strong tap root system, reaching 1.5–2 m deep into the soil. For 80 cm of depth the roots branch strongly, following side branch levels, spreading perpendicularly reaching about 1 m from the main root. The main root mass is located about 20–40 cm from the top of the soil. The development of the root system depends on, among other things, ground water level; hence the depth of root system of hemp growing in peat soils is only 50–60 cm.

A stem of hemp grown for fibre (at higher sowing densities) does not branch and has about 10–13 mm diameter. At low sowing densities, on seed plantations and especially in the case of single plants, the stem strongly branches. The height of plants varies from 150–200 cm to 400 cm and even more.

The internodes on the stem produce one pair of leaves. The palmatipartite leaves grow on leaf petioles and are divided into lancet-shape sections. The number of sections (5–11) differs, depending on the location on the stem. The closer to the top of the stem, the lower the number of sections. On the top of the male plant, the leaves consist only of a single section. In the bottom and middle part of the stem, the leaves are arranged opposite, while within the inflorescence, alternately. The leaves fade gradually and fall off the plant as the plant matures [9].

The anatomy of hemp stems is characteristic of this species. It consists of a cortex, collenchymas, a ring of primary bast and rings of secondary bast and wood. A layer of bast in hemp, which becomes fibre after proper processing, lies directly under the cortex. It is arranged in bundles of tidily adhering cells of bast glued with a pectin and joint with so-called anastomosises [9]. The fibre is not distributed regularly in the stem. The highest concentration of fibre is found in the middle part of the stem. At the very bottom of the stem, at the so-called root neck, it is strongly lignified and has no technological value. At the top of the stem, the concentration of fibre decreases and in the middle of the inflorescence it is so low that the top of the stem can be easily broken. Therefore, the section of the stem from the root neck to the middle of the inflorescence is called a 'technical' length to distinguish it from the total length of a hemp plant. The fibre in the stem is arranged in the form of rings of primary and secondary fibre. The latter can be found mainly in the bottom part of the stem, while there is no secondary fibre in the top part of the stem. The highest concentration of primary fibre can be found in the middle part of the stem (Fig. 2.10 [10]).



2.10 Hemp stem cross- and longitudinal section.

The secondary fibre is formed later in the development of the plant and decreases the technological value of the fibre while it is strongly lignified, stiff and difficult to divide. The quality and amount of fibre in the stem is an outcome of the effects of numerous natural and agricultural factors, mostly on the cultivar (genetic potential), type of soil and fertilizer supply, sowing density, time of harvesting, etc.

The inflorescence of hemp is a panicle. Hemp, being naturally a dioecious species, is characterized by a clear dimorphism of sex. Male plants form loose, strongly branched panicles with a very low number of leaves while females produce compact panicles with lots of small leaves. A male flower has five stamens: anthers set on long filaments and five sepals. A female flower is located in green, rolled in the form of sheath bractlets and has a single-chamber ovary. The stigmas reach out from a narrow slit during flowering.

Hemp belongs to the plants with a very intensive growth, compared to other crops. In the fast growth phase it grows more than 10 mm a day making it very competitive to weeds which usually dispenses with the need for using herbicides in cultivation of hemp for fibre. The following development phases can be distinguished in hemp:

1. germination;
2. beginning of emergence;
3. full emergence;
4. fast growth phase;
5. inflorescence buds formation;
6. beginning of male flowers blooming or beginning of flowering (monoecious hemp);
7. mass flowering of male plants or full flowering (monoecious hemp);
8. milky maturity of seeds;
9. waxy maturity of seeds;
10. full (biological) maturity of seeds.

2.3.3 Cultivation of hemp

In Europe both mono- and dioecious cultivars are grown. Currently mostly Polish, Hungarian Ukrainian and French cultivars are available in the international market. Polish cultivars are well adapted to the climatic conditions of Poland. However, the warmer the summer, the higher the yields that can be obtained, provided there is sufficient water supply. Despite hemp being a warmth-liking species, Polish cultivars can stand light freezing conditions. It can survive the temperatures of –5 to –7°C better than flax.

Hemp has high soil requirements. The soils must be fertile, structural, with stabilized water conditions. Mostly the soils suitable for hemp cultivation are black earths, alluvial soils, loesses, lime soils rich in humus and well-meliorated peats. Hemp is very sensitive to the pH of the soil. The optimum pH for hemp is 7.1–7.6. Therefore, the soil should be limed when the acidity drops below these values. Hemp should not be grown on soils where the pH is below 6.0 [5].

Hemp is also a good crop to grow on soils polluted with heavy metals. An experiment has shown [11] that providing the soil shows good agricultural quality, hemp can extract and accumulate substantial amounts of elements such as copper, lead, zinc and cadmium with no detrimental effect on the quantity and quality of the crop. The total calculated, extracted and fixed copper and lead can reach 377 g and 141 g per hectare, respectively [12]. This results in gradual remediation of the soil and eliminates the threat of introduction of heavy metals to the nutritive chain of humans and livestock.

Hemp has no special requirements for the preceding crop. Hemp grows well after root crops grown on manure, legume crops; it even can be grown for a few years on the same field. When growing for seeds, special attention should be paid to weeds, especially to *Elymus repens* (L.) Gould. Hemp, especially when grown for fibre (at high sowing densities and sown in narrow row spacing), is very competitive to weeds, giving no chances for any weed to grow. It also improves the structure of the soil (deep root system) and leaves very good conditions for the following crops [5].

When growing hemp for fibre potassium and calcium are especially important for plant cell formation, while when growing for seeds it is phosphorus, which is taking part in seed formation, that is important. The N:P:K ratio in seed production should be 1:8:1, while in fibre production 1:7:1.5 [5].

As mentioned before, hemp is often considered a crop free of pathogens. Some authors suggest that the presence of essential oils in hemp, especially α-pinene and limonene, are responsible for it or stipulate that it is the cannabinoids content, especially in narcotic type hemp, that keeps the insects away [13]. Some experiments show that insects forced to feed on hemp slow down their development or are even killed. Another explanation for treating hemp as a pathogen-free crop may also be the fact that for decades it was a marginal or non-existing commercial crop in farming. This situation may change dramatically when hemp is grown to a bigger acreage. Geographical differentiation of pathogens can also have a lot to do with the opinion of hemp as a pathogen-free crop.

On the other hand, a considerable list of insects and also non-arthropod pests are mentioned that may be or actually are a problem in hemp [14, 15]. Some authors claim as many as 272 insects are associated with hemp and there is at least one of six arthropod classes depending on hemp to a greater or lesser extent [16]. Among the insects are the European corn borer (*Ostrinia nubilalis*) and the hemp borer (*Grapholita delineana*). These insects, or actually their larvae, feed inside the main stem and inside branches breaking the tops and wilting distal plant parts. These pests are especially dangerous as they destroy the stem and automatically a fibre which is currently the main purpose of hemp cultivation [15]. Another dangerous stem-boring pest in hemp can be the budworm (e.g. *Heliothis armigera* and *Heliothis viriplaca*) [15]. They can be a problem in hemp grown for seeds as they feed on flowering buds but have no effect on hemp grown only for fibre. Another insect threatening hemp, especially in the germination stage, is the hemp flea beetle (*Psylliodes attenuata*) [15]. This insect feeds on cotyledons and first true leaves. In years of heavy infestation it can destroy the plantation if not controlled.

Hemp can also suffer from fungi and diseases like Fusarium wilt, septoriosis and gray mildew are found especially in weather conditions promoting these diseases. Sometimes, especially if hemp is grown several times on the same stand, in may suffer from a parasitic plant, branched broomrape (*Orobranche ramosa* L.) [14]. Virus diseases may also sometimes attack hemp.

The time of harvesting depends on the purpose of cultivation of hemp. Hemp grown only for fibre should be harvested at the beginning of flowering. This allows for obtaining delicate and quite strong fibre suitable for textile production. Delaying harvest increases the fibre yield. Also, its strength is increasing when harvesting is delayed; however, this is also connected with stronger and stronger lignification of the fibre and such fibre is not suitable for textile production – it can only be used for technical purposes and for pulp production.

If hemp is grown for both fibre and seeds or only for seeds it should be harvested at full maturity phase, when the seeds in the middle part of the panicle are mature. The fibre obtained from hemp harvested at this time has no value for textile application. It can be used for twine and for other technical non-textile applications, including pulp.

Due to its exceptional productivity and the high bulk volumes of biomass to be harvested, hemp is quite difficult to harvest. Currently there is no modern and efficient technology available for hemp, especially for fibre. Harvesting is done either manually (Asia) using simple tools or mechanically using quite out-dated machinery (eastern Europe). There are numerous trials in many research centres to develop efficient harvesting technology, but with no major commercial success [17].

2.3.4 Degumming of flax and hemp

The degumming (retting) of hemp is discussed in Section 2.2.4. However, research has been conducted on hemp fibre into new retting techniques.

Enzyme degumming

Within research on utilization of enzymatic processes for fibre extraction two preparations of different bacterial laccases (NS 51002 and NS 51003) were used and the third enzyme used was *Pectinex 100L*. The laccases are oxidoreductases which react directly with oxygen; it is an important oxidant used in the paper industry to eliminate lignin from the pulp.

The research showed that optimal processing conditions during the application of laccase preparations for enzymatic degumming of raw hemp fibres required the following conditions:

- temperature 37°C
- pH 4.5
- time of treatment 48 hours
- dispersing agent *Sultafon UNS* in amount of 1g dm^{-3} and hydromodulus 1:25.

The fibre thinness after enzymatic processing varies from 8.21–9.03 Tex when treated with NS 51002 and 8.05–9.1 Tex when treated with NS 51003. The thinness for control treatment was 16 Tex.

The enzymatic process allows shortening of the fibre from 269 mm to 144–172 mm when treated with NS 51002, and 153–177 mm when treated with NS 51003.

Observed total mass loss shows that non-cellulosic components (pectin, hemicellulose, fats and waxes) are removed from fibre during enzymatic treatment, it has also been found that within the application of laccases followed by mechanical upgrading the mass loss is approximately twice as intensive as mechanical upgrading alone. The mass loss in a whole process is on the level of 20–21% for NS 51002 and 21–23% for NS 51003 while in mechanical processing it is only 11%.

Pectinex 100L is a treatment obtained from a selected strain of fungus, *Aspergillus niger*. The active enzymes in this preparation are pectinotransferase, polygalacturonase, hemicellulase and arabanase. Tests on *Pectinex 100L* in conditions of variable temperature, time, pH, and concentration of the enzyme were conducted to determine the optimum parameters of the processing of hemp fibre. However, the thinness of hemp fibre after treatment did not differ significantly from the control and was 14–16 Tex. Also the length of the fibre and the mass loss remained unchanged; the latter was 16%, as in the control treatment.

Electrolytic degumming

The effect of an electrolyic process on hemp fibre degumming was tested at the Institute of Natural Fibres, Poland. Experiments were conducted using an oxidation process and using a reduction process. In both cases 0.01M and 0.1M solutions of hydrochloric acid and sodium hydroxide were used as electrolytes.

The research found that application of sodium hydroxide in 0.1M concentration gave better results in both oxidation and reduction at the following treatment parameters:

- temperature 20–25°C
- time of treatment 48 hours
- voltage 4.5 V

Hemp fibre thinness after electrolysis with this electrolyte varied from 8.51 to 10.32 Tex (control treatment – 16.35 Tex). The mass loss in both oxidation and reduction processes calculated as a total for electrolytic and mechanical processing was 18.77–21.56% (control – 12.89–14.19%).

2.3.5 Straw processing

Straw processing is carried out as described in Section 2.2.5.

Table 2.6 Hemp fibre content in function of slenderness

Slenderness	229	174	169	163	144	118	116
Fibre content (%)	23.7	20.4	19.3	18.8	18.4	16.1	15.9

Besides yield, a feature that characterizes good hemp straw is slenderness (Table 2.6 [9]), namely the ratio of the technical length and thickness of the stem. Therefore the best results in processing are obtained when technical length of stem is 150–200 cm and thickness 4–8 mm.

The quality of raw material depends also on the length of internodes. The long internodes contain the fibre of longer elementary cells.

As mentioned before, the primary fibre (the most interesting material from a processing point of view) is distributed along the whole stem, with the highest concentration in the middle part of the stem. It is formed in the apex from the meristem before the end of flowering. The secondary fibre is contained mainly in the lower part of the stem and is formed later in the development. The parameters of the fibre and a comparison with flax fibre are presented in Tables 2.7–2.9 [9].

Table 2.7 Breaking strength of hemp fibre from different parts of the stem

Part of the stem	Breaking strength of hemp fibre (kg)
Bottom	11.3
Middle bottom	42.7
Middle	31.6
Middle upper	32.8
Upper	36.2

Table 2.8 Length of elementary fibres in different parts of the stem

Part of the stem (cm)	Length of elementary fibres (mm)
0–15.5	5.1
75.5–95.5	10.2
105.5–135.5	9.1
155.3–175.5	8.9
195.5–215.5	8.3
235.0–245.0	3.9

2.3.6 Chemical composition of fibre

The most important components of fibre are cellulose, pectin and waxes. Pectin is found in the middle lamella of the fibre cells and glues the elementary

Table 2.9 Comparison of elementary fibre of flax and hemp

Physical features	Flax	Hemp
Length of fibre* (mm)	2–120	2–90
Average length (mm)	20	15
Diameter of fibre (μm)	17–20	10–30
Thickness of fibre (nm (metrical number))	1500–9500	800–8500
Average thickness of fibre (nm (metrical number))	3620	3460
Self breaking (km)	23–72	27–63
Average self breaking (km)	49	46
Elongation of fibre – dry (%)	1.5	1.5

*Maximum length of secondary fibres reaches 5 mm.

fibres to form bundles. The lignin is an incrusting component of the fibre. It is incrusting cellulose and contributes to the hardness and breakability of fibres. It is allocated in the middle lamellae and fibre cells. Other components of hemp fibres are tannin, resins, fats, proteins, etc. The composition of hemp fibre is presented in Table 2.10 [9].

The content of additional substances (other than cellulose) is much higher in hemp than in cotton. Therefore, the processing of those fibres requires different technology of processing. The higher the content of cellulose the better the quality of fibre.

Table 2.10 The components of hemp fibre (%)

Component	% by mass
Water	6.60
Ash	1.2
Waxes	1.47
Water solubles	2.45
0.5% HCl solubles	0.89
Pectin A	1.35
Total pectin	1.42
Hemicellulose	6.08
Lignin	1.75
Cellulose	77.89
Protein	2.65

2.4 Jute

Jute (*Corchorus capsularis* and *Corchorus olitorius)* is one of the best known and most extensively used textile fibres of plant origin, with the exception of cotton. Jute was regarded by many early botanists as of Chinese origin, but the most widely cultivated species apparently is indigenous to India. On the Indian subcontinent, the jute plant has been utilized from time immemorial both as a vegetable and as a source of textile fibre [18].

After much debate, there seems to be agreement that white jute originated in the Indo-Burma region and tossa jute in Africa. China is also considered to be one of the places of jute origin. According to some academics, some provinces of the southern parts of China are the secondary centres of origin of tossa and white jute [19].

The various jute plants and hence the fibre and fabric made from it went under the name 'pat'. The word 'jute' may be traced to 'jhat', a term still used in India which was doubtless derived from the Sanskrit word 'yuta' (fibre). Jute, a bast fibre, means the fibre known as pat, kosta, nalita, bimli or mesta [18]. Jute is a natural fibre obtained as an extract from the bark of the jute plant. This fibrous plant in earlier days was also used by the inhabitants as a delicacy, which accompanied their staple diet.

Jute is a long, soft, shiny fibre that can be spun into coarse, strong threads. It is one of the cheapest natural fibres. Jute fibres are composed primarily of the plant materials: cellulose, lignin and pectin. Both the fibre and the plant from which it comes are called jute. It belongs to the family *Tiliaceae,* which belongs to the genus *Corchorus*.

At present the major producers of jute, kenaf and roselle fibres are India, Bangladesh, China, Myanmar, Nepal and Thailand.

2.4.1 Economic importance of jute

The advent of jute as a commercial commodity dates back to the eighteenth century. In the beginning, the jute fibre was made into ropes that were extensively used in wind- and hand-driven sea vessels. Later, it was learnt that jute can be spun and woven for the manufacture of carpets.

By 1838 newer technologies emerged and jute fibre was spun into better yarn and woven to make jute-cloth. Sacking bags and jute handbags were the initial developments and with that jute products started to enter people's daily lives. Applications in carpet making and packaging has also been dominated by jute ever since jute started to be woven into fabric form [20].

Other properties of jute fibre started to be noticed in the middle of the last century. The jute fibre and its subsequent processing might find application in new areas of use and also newer products.

Cultivation of jute plays an important role in maintaining soil quality; as the stem is cut during harvesting a major portion of the root remains within the soil. This in due course decomposes and disappears into the soil. Through this process of bio-degradation it enriches the soil by way of providing natural manure for other subsequent crops to be grown there.

In countries like India, some products such as petrochemical products, especially plastic bags, have become an indiscriminate menace on the environmental front. Soil pollution, visual pollution, choking of drains and blockage of natural water streams have all added to the problem. Jute bags and paper bags are thus regaining popularity. This alternative may not be as cheap as its plastic counterpart, but the price paid will still be cheap compared with the cost of saving the environment.

Jute products have a good market in India as well as in other regions like USA, Australia and Europe. The products generally in demand are jute shopping bags, wall hangings and floor coverings. New markets are being explored through increased consumer awareness and product promotion. It will not be surprising to find this natural fibre product becoming much more regularly used by consumers all over the world.

India, Bangladesh, China, Thailand, Myanmar and Nepal are the major producing countries with about 95% of the global production of jute and allied fibres (Table 2.11). India and Bangladesh produce mostly jute, China produces mostly kenaf, while Thailand produces kenaf and roselle.

Table 2.11 Area and yield of jute and allied fibre production in major producing countries

Country	Area (2002/2003) ('000 ha)	Yield (1998/99–2002/03) (Mt ha^{-1})
Bangladesh	500	1.79
China	56	2.53
India	1000	1.86
Myanmar	58	0.85
Nepal	11	1.13
Thailand	19	1.54

Jute cultivation is labour-intensive, but it requires relatively small quantities of other input, such as fertilizers and pesticides, and can be carried out in smallholdings. Jute competes for land with food crops such as paddy rice in Bangladesh and India, and cassava in Thailand. In general, producers attempt to adopt a multi-cropping strategy with jute in rotation with paddy.

Until the late 1990s, world production of jute fluctuated between 3 million and 3.7 million tonnes, with the notable exception of a record crop of over 6.0 million tonnes in 1985. Between 1998 and 2000, world production exhibited a marked decline to an average level of 2.6 million tonnes. This decline was the result of a decline in jute's competitiveness relative to polypropylene fuelled by decreases in the latter's price.

Assuming that weather conditions and yield per hectare of jute follow their normal patterns, world production of jute is projected at 2.4 million tonnes per year by 2010, well below the average production level of the past decade. This decrease in production in the medium term is expected to result from a weakening in price incentives due to declining global demand for jute fibre. In the medium term, the area under jute cultivation in the Far East is expected to contract by 3.1% per annum from an average of 1.6 million hectares in 1998–2000 to 1.2 million hectares in 2010 as producers adjust to market conditions through disinvestment. Production is expected to decline by 1.6% per annum from an average of 2.6 million tonnes during the years 1998–2000 to 2.3 million tonnes in 2010.

India is projected to increase its dominance of global jute production, accounting for 66% of the world production by 2010, compared to 58% during the period 1998–2000. In the medium term, the area under jute cultivation in India is expected to contract by 2.7% per annum, although production is expected to remain at approximately 1.6 million tonnes due to increases in yield. Between 1990 and 2000, yields increased from 1.60 to 1.86 tonnes per hectare and are expected to continue increasing to 2.1 tonnes per hectare by 2010.

In Bangladesh the area under jute cultivation is projected to contract from 447,000 hectares to 387,000 hectares by 2010, as producers respond to lower market prices and allocate land to competing food crops. The contraction of the land under jute will be partly offset by increased yields. Yields are projected to increase from the 1998–2000 average of 1.70 tonnes per hectare to 1.76 tonnes per hectare in 2010. As a consequence, production is expected to decline by 1.9% annually from 768,000 tonnes in 1998–2000 to 681,000 in 2010.

The area and production of jute in China are projected to continue to contract. Production declined from 726,000 tonnes to 126,000 tonnes in the course of the 1990s and is expected to continue to decline to 7000 tonnes by 2010 as more land is given over to food crops. During the same period, production in Thailand is also projected to decline to 17,000 tonnes, while in Vietnam production is expected to remain stable at 12,000 tonnes [21].

2.4.2 Cultivation of jute

Jute needs a humid climate with temperatures of between 24°C and 38°C, the optimum being around 34°C Celsius and humidity between 70% and 90%. This type of climate is prevailing in areas between 30° latitude north and south of the Earth. Minimum rainfall required for jute cultivation is 1000 mm. The most suitable growth for jute is in new grey alluvial soil of good depth receiving silt from annual floods. However, jute is grown widely in sandy loams and clay loams. Sandy soil and heavy clays are unsuitable for its cultivation. Loamy soil usually produces the best fibre. The clayey soil yields a short crop; the sandy soil produces coarse fibre.

Jute plants, after the shedding of leaves, are immersed in water for retting; gently flowing clear and soft water is ideal. Incomplete submersion and retting in stagnant water produce inferior quality fibre; most defects are due to faulty retting. Over-retting results in lustreless and weak fibre.

There are mainly two types of jute. They are *capsularis* (white) and *olitorious* (*tossa*), while the *capsularis* fibre is whitish in colour and *olitorious* fibre is finer and stronger than the *capsularis* and is yellowish reddish, greyish in colour. *Capsularis* is normally sown between February and May while *olitorious* is sown between April and mid-June.

Plants are cut from the bottom, leaves are stripped off from the top and accumulated in bundles. Structurally the jute stems are composed of epidermis, cortex, large phloem, cambium, wide xylem or wood and central pith tissues. The crop is harvested at different stages of maturity depending on various circumstances. The most common harvest stage is when 50% of the plants have produced pods. If the crop is harvested at this stage, both the yield and fibre quality are good.

2.4.3 Degumming of jute

Degumming (retting) is the process of extraction of the fibre whereby jute stalks or crude ribbons are immersed in water for a certain period of time. Bundles are then submerged in water for 7 to 10 days. Retting takes place due to the joint action of water, aquatic and plant surface organisms, mostly bacteria; in the beginning the process is aerobic, later anaerobic.

The combined action of water and microorganisms results in the softening and removal of pectins, gums and other mucilaginous substances, thus making the fibre easy to separate from the woody stem portion and bark. The minimum ratio of plant material to water in stagnant water should be 1:20. The important conditions for good retting are:

- the water should be non-saline and clear;
- the volume of water should be enough to allow jute bundles to float;
- bundles, when immersed, should not touch the bottom; and
- the same retting tank or ditch should not be used when water becomes dirtier.

Retting has been used for a long time as a method of fibre extraction from jute and allied vegetable fibre plants. If the stems are retted, the process is called stem retting; if ribbons are retted it is called ribbon retting. Retting is an important step in the production of good quality fibre, the retting process depending on a country and the practices can be variable. The retting process is finished when the bast layer can be easily removed from the woody stem and the bark readily washed off, leaving the clean fibre. The process is completed in about 10–30 days depending upon the temperature and movement of water, the amount of retting organisms in the water, age and size of the stems. If the water temperature is around 30°C, complete retting should take 10 to 12 days [18].

2.4.4 Processing jute straw

When retting is complete the straw is stripped, this process is accomplished by hand. The stripper holds the stem in one bunch and taps the root end lightly with a mallet, this frees the fibre at the foot of the stalk. The fibre is then grasped by lashing and jerking the stem in the water while the rest of the fibre loosens and comes off. Other methods of hand stripping retted stems are used, depending upon local tradition.

Jute fibres are kept hanging on makeshift hangers for drying; this process takes about 2 to 3 days. Grading becomes imperative depending on the fineness, colour, density, clearness etc., that are all taken into account. The crop then proceeds to the hands of buyer.

Dried retted jute as produced is usually tied in small or large bundles when offered for sale. Jute is then accumulated at the baling centres where preliminary grading is made. The bundles are scanned and jute fibres are categorized as per grades. Gradewise these are stocked at separate locations.

Graded bundles are subjected to machine press to convert them to bales. (The ropes used to tie the bales are prepared from the jute waste.) The bales are finally stored in the warehouse according to their grades, ready for sale.

The ribbons, fibres, leaves and stick contents of different JAF plants vary considerably. The fibre content of the *C. olitorius* jute plant is the highest and that of *H. sabdariffa* the lowest. The green leaf content of *H. sabdariffa* plant is the highest. The dry ribbon contents of both *C. capsularis* and *C. olitorius* plants are higher than those of *H. cannabinus* (Table 2.12).

Table 2.12 Physical compositions of different jute and allied fibre plants

Crop	Plant (t/ha)	Ribbons %		Leaf %		Sticks %		Fibres %
		Green	Dry	Green	Dry	Green	Dry	Dry
C. olitorius	46	38.7	11.7	11.0	2.7	50.3	16.6	6.8
C. capsularis	34	40.2	11.2	15.9	3.9	44.2	12.5	5.9
H. sabdariffa	48	35.2	9.6	16.3	3.6	48.5	15.0	4.8
H. cannabinus	36	34.0	9.5	14.2	3.3	57.8	15.9	4.9
Approx. avg	40	37.0	10.3	14.2	3.3	48.8	15.2	5.5

2.4.5 Fibre characteristics

Among jute, ramie, flax, hemp and cotton, jute has the shortest fibre length (0.5–6.0 mm) and ramie has the longest fibre length (125–126 mm). In the case of jute the average length of fibres from outer parts of the wedge is 0.3–2 mm and from the inner parts about 1–5 mm only (Table 2.13).

The quality of jute fibre is judged by its suitability for the production of various types of yarn and its behaviour in the manufacturing process.

The fibre that spins into the finest yarn is considered to be of very good quality. Jute fibre is marketed in bundles of fibre hanks. A fibre hank is composed of about 10–15 fibre reeds obtained from 10–15 plants. Each fibre reed is composed of thousands of fibre strands made of ultimate fibres with lignin and pectic substances, the cementing materials. Commercially, fibre

Table 2.13 Physical properties of jute and other fibres

Properties	Jute	Mesta	Roselle	Ramie	Flax	Comparative value for cotton
Ultimate cell						
Length (mm)	0.5–6.0	2–11	1.5–3.5	125–126	26–65	15–60
Length × breadth ratio	110	140	100	3500	1700	1300
Filament Tenacity (g tex^{-1})	30–45	30–45	25–40	40–65	45–55	20–45
Extension at break (%)	1.0–2	1–2	1–1.8	3–4	2.5–3.5	6.5–7.5

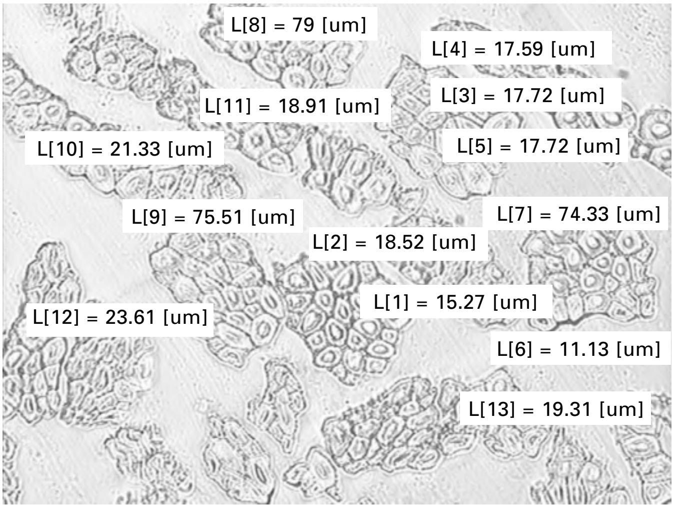
quality is assessed by taking a hank out of a lot, spreading the individual reeds on the ground and then assessing the different characteristics by 'look and touch' method.

The different characteristics of the fibre which are usually taken into consideration for the assessment of quality include root content, colour, lustre, strength, defects, etc. They are described below, and in Table 2.14 and Fig. 2.11 [22]:

Table 2.14 Jute fibre measurements in comparison with other fibres

Fibre origin	Technical fibres (bundle diameter)		Elementary fibres (single cell)	
	Surface area (S) (μm^2)	Diameter (L) (μm)	Surface area (S) (μm^2)	Diameter (L) (μm)
Curaua	2 833–11 554	62–119	30–39	8–9
Sisal	11 983–26 232	121–205	131–233	18–27
Abaca	6 672–52 659	90–347	166–274	22–30
Flax	1 252–2 801	38–85	111–272	15–22
Hemp	7 196–9 774	123	441–911	29–45
Jute	**2 349–4 087**	**63–85**	**299–780**	**26–30**
Cabuya	4 880–27 254	130–258	205–551	25–34
Lufa	–	–	244–885	28–57
Wool				18–60
Cotton				12–42
Silk				13–25

- **Root content**. These are hardy, incompletely decomposed basal or root areas of the fibre. It occurs more in white jute than in *tossa jute*. For processing in the factories and before export, these, constituting about 12.5 to 39.0 cm, are cut away and separately sold at a much cheaper price.
- **Length**. Differences in quality are generally associated with differences in the total length of the fibre strands. With increase in their average length, the mass of unit length of strands increases. It has been observed



2.11 Jute stem cross-section.

that the fibre that feels heavier in the hand tends to have higher spinning quality.

- **Colour and lustre**. The natural fibre colour of white jute is creamy white and that of *tossa jute* is golden. Any adverse deviation from the natural colour is considered to be bad. Lustre is a characteristic of shine when light falls on the fibre; the more the shine, the better the quality.
- **Strength**. This is a very important characteristic: the stronger the fibre the better the quality. No product can be made from weak fibre. The strength is divided into five levels *viz*. very strong, strong, sound, average and any strength.
- **Fineness**. The finer and stronger the fibre, the better the quality.

2.4.6 Jute and jute products, uses and applications and environmental advantages

Jute can be used not only in its traditional materials, but also for the production of other value-added products such as pulp and paper, geotextiles, composites and also home textiles. Jute has been employed for centuries as a packaging material. In recent times it is found to be a valuable aid to sound environmental management.

Jute is an annually renewable energy source with a high biomass production per unit land area, it is biodegradable and its products can be easily disposed of without causing environmental hazards. The roots of jute plants play a vital role in increasing the fertility of the soil; jute acts as a barrier to pests and diseases for other crops by rotating with other crops, and also provides a substantial amount of nutrients to other crops in the form of organic matter and micronutrients. The jute leaves after defoliation have fertilizer value and enrich the soil nutrients. Jute leaves are used as vegetables and have both nutritional as well as medicinal value. Jute sticks are used for fuel and shelter in jute-growing rural areas.

Jute is a fast-growing seasonal crop. Because the biological efficiency of jute is much higher than that of wood plants, the use of jute instead of wood to make paper pulp will lower substantially the cost of production of pulp and paper and save forest resources.

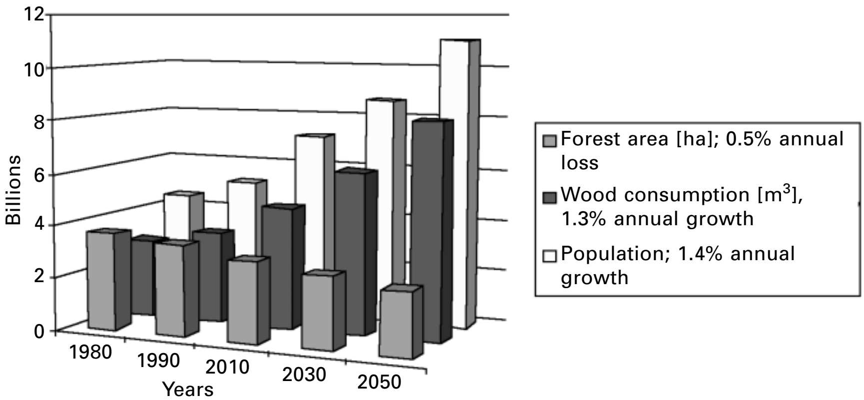
The production flow of jute agriculture involves: sowing, weeding/thinning, harvesting, defoliation, retting, fibre extraction, washing and drying. Processes of jute retting, fibre extraction and washing have drawn some concerns regarding solid residue and gaseous emissions that arise from such processes. Complaints about the unpleasant smell during retting are quite common, but the retting process is being improved using biotechnology (i.e. enzyme treatment) by volatile fatty acids (mainly butyric acid); the retting liquid contains the following volatile fatty acids: acetic, propionic, butyric, caproic and traces of caprylic acids. Butyric acid is the main component of retting liquor (*circa* 80%) [23].

Jute products manufacturing process involves several stages such as batching, softening with batching oil, carding, drawing, spinning, weaving and finishing. The use of mineral batching oils is being replaced in the case of bags for specific use like packaging of cacao and coffee for example.

The experiments to convert jute fibre and whole jute plant into paper pulp have successfully produced good quality pulp and paper. The growing demand of pulp and paper worldwide on a continuous basis and the increase of public awareness of environmental issues have created conditions to check depletion of forest resources through using jute/kenaf for producing pulp and paper. Jute can be also used for the production of good quality writing and other paper. Figure 2.12 shows the world population, forest area and wood consumption (for years 1980–2050).

Jute fibre also has the potential to compete with glass fibre as a reinforcing agent in composites and technologies exist that make it possible to incorporate jute fibre into polypropylene. Products made from jute-reinforced composites have the advantage of low cost, low density, renewability and biodegradability. These composites can be used in the packaging industry, i.e. the manufacturing of crates, boxes or cases used for storage and transportation of agricultural products; in the automobile industry, i.e. to replace glass fibre in car door panels; and as a construction material.

Applications of jute-reinforced composites are expected to have a significant positive environmental impact. Particle board made from jute, or the mixture of bast fibre and the core fibre can find a wide application as a substitute for wood. The availability of the technologies for producing particle board and



2.12 World population, forest area and wood consumption, years 1980–2050.

its high socio-economic value are solid arguments in favour of the future development of this product.

Jute geo-textile is another product with a potentially large-scale application. It can have several uses: soil erosion control, vegetation consolidation, agro-mulching materials, and road pavement construction.

Jute, for its versatility, rightfully deserves to be branded as the 'fibre for the future'. It is another natural option for a cleaner and healthier environment. The main jute products are:

- Yarns. The types of jute yarn manufactured can be classified according to the application to which they are put, i.e. fine yarns, hessian yarns, carpet/special yarns, sacking yarns, etc. These yarns can be further classified into warp and weft yarns, the warp yarns normally being superior to the weft yarns as they have to withstand the cycles of stress during weaving while the weft yarns act more as filler and undergo less strain during the weaving process.
- Twines, ropes and cordage are used for the purpose of tying, knotting and binding, particularly agricultural commodities. Jute yarns of various dimensions are plied together to make twines as per requirement and use.
- Fabrics, hessian, sacking, scrim, carpet backing cloth and canvas.
- The other areas where jute has started to find good markets are floor coverings, furnishing fabrics, handicraft, wall hangings and footwear.

The application of jute in many diverse areas is opening new perspectives for its usefulness. The jute sector is able to provide sizeable employment especially in the rural areas and among women. It also contributes to keeping ethnic art forms alive. Depending on the perfection and creativity of the artisans and craftpersons, these products find their way to their respective markets.

2.5 Ramie

Ramie* (*Boehmeria nivea* (*L.*) *Gaud.- Beaup.*) is the name of the product of one or more species of the genus *Boelimeria*, a member of the order *Urticaceae* and nearly allied to the stinging nettle genus (*Urtica*), from which, however, it differs in the absence of stinging hairs. Some confusion has arisen in the use of the various terms *China-grass*, *ramie* and *rhea*. Two plants are concerned: one, *Boehmeria nivea*, China-grass, has been cultivated by the Chinese from very early times under the name Tschou-ma; the other, probably a variety of the same species (*Boehmeria nivea,* var. *tenacissima*) though sometimes regarded as a distinct species (*B. Tenacissima*), is the ramie (Malay zamf) of the Malay Islands and the rhea of Assam. Ramie (*Boehmeria nivea* (L.) Gaud., *Boehmeria nivea* var. *tenacissima*) is also commonly known as white ramie; green ramie is one of the group referred to as the bast fibre crops.

Ramie fibre is classified chemically as a cellulosic, just like cotton, linen, etc. Leading producers of ramie are China, Taiwan, Korea, the Philippines and Brazil. Until recently ramie has been unknown in the ready-to-wear market, but it is appearing in more garments. It is often blended with cotton and available in woven and knit fabrics from those that resemble fine linen to coarse canvas.

2.5.1 Economic importance of ramie

Ramie is a plant fibre that has been used since ancient times; long before the introduction of cotton, ramie was well established as one of the principal fibres of the Far East. It was used in mummy cloths in Egypt during the period 5000–3300 BC and has been grown in China for many centuries. In those days main areas of ramie cultivation were China, Indonesia, India, Algiers and Congo. *Boehmeria cylindrica* was used by Indians of the New World as twine to attach spear and arrow heads to shafts. Ramie was introduced into Europe in 1733; the first cultivation trials were undertaken in Holland in 1808–09. However, according to Karpowiczowa [24], the first records of ramie cultivation are dated 1786 in Bologna, Italy.

The first attempts in mechanization of ramie processing were undertaken by the government of India in 1869 and then by the French government which led towards the design of a hand-fed raspador decorticator, patented in the United States in 1896.

Floridians found that hydrogen peroxide and lime could be used for degumming; these are much less harmful than chlorine and sulfuric acid currently being used. In these regions ramie is locally spun and woven into

*There are at least two acceptable pronunciations for the word. Some authorities call it *ra-me* ('RAY-mee') while others pronounce it *ram-e* ('rah-mee').

coarse cloth, often without degumming. In China it is also used to make fine oriental textiles.

Brazil began production in the late 1930s with production peaking in 1971 with about 30,000 tonnes. Production in the Philippines began in the early 1950s, peaking in the mid-1960s with 5500 tonnes.

Nowadays, the main producer countries are reported to be China, Brazil, Philippines, India, South Korea and Thailand, but the available statistics are not reliable. This is because production statistics for ramie are included in the Fibre Crops NES (Not Elsewhere Specified) in the official FAO Production Statistics (FAO 1995). Ramie usage in the US increased in the mid-1980s with the emphasis of fashion on natural fibres.

The main importing countries are Japan, Germany, France and the United Kingdom. Only a small proportion of production enters international trade as most is used in the country of production. Ramie, and garments made of more than 50% ramie, entered the United States without import quota limits. Legislation was passed in 1986 eliminating the quota-free status of ramie.

Advantages and disadvantages of ramie [25]

(a) Advantages

- Natural lignocellulosic fibres can be used as a substitute to flax and silk.
- Resistant to bacteria, mildew, and insect attack.
- Extremely absorbent.
- Dyes fairly easy.
- Increases in strength when wet.
- Withstands high water temperatures during laundering.
- Smooth lustrous appearance improves with washing.
- Keeps its shape and does not shrink.
- Can be bleached and dyed.

(b) Disadvantages of ramie

- Low in elasticity.
- Lacks resilience.
- Low abrasion resistance.
- Wrinkles easily.
- Stiff and brittle.

2.5.2 Anatomy of the ramie plant

Ramie is a member of the *Urticaceae* or nettle family and is a hardy perennial which produces a large number of unbranched stems from underground rhizomes. *Boehmeria nivea* is a shrubby plant with the growth of the common nettle, but without stinging hairs, sending up each season a number of straight shoots from a perennial underground rootstock. The long-stalked leaves recall those of the nettle in their shape and serrated margin, but their backs are clothed with a downy substance and have a silvery appearance. The minute greenish flowers are closely arranged along a slender axis. The small seeds are dark brown in colour, ovate and produced in very large quantity. Ramie stems are slender, sometimes striated and range in diameter from 8 to 16 mm at the base. They may attain a height of 2 to 2.5 metres in 45 to 60 days under ideal growing conditions. They are usually hollow at maturity, being filled with dried pith and may be readily crushed between the fingers.

The variety *tenacissima* differs in that it is more robust and has larger leaves, which are pale green on the face and a very much paler green on the back. They are not downy, however, and this affords a ready means of distinction from true China-grass. *Boehmeria nivea* is sometimes found wild in India, Malaya, China and Japan, and is probably a native of India and Malaya. China-grass and ramie are widely cultivated not only in China, Formosa and Japan, but also in Brazil, Mexico and the southern states of North America, and also in South Europe.

Ramie fibres are found in the bark of the stalk; the fibre is very fine and silk-like, naturally white in colour and has a high lustre. The process of transforming ramie fibre into fabric is similar to processing linen from flax.

2.5.3 Cultivation of ramie

Ramie plant differs from the other bast fibre crops in several important characteristics. It attains a height of from 1 to 2.4 m, and is grown from seed, cuttings or layers, or division of the roots. It is easy to cultivate, and thrives in almost any soil, but especially in a naturally rich, moist, light, loamy soil. Ramie grows best in open type soils, and requires a rich, warm, sandy soil that is very well drained. Also suitable are soils of volcanic origin, including pumaceous types and friable sandy loams, but it is intolerant of wet soils. The plant does best in areas with high temperatures and high humidity plus a rainfall of 1100 cm evenly distributed throughout the year. It tolerates a pH in the range 4.3 to 7.3, but prefers slightly acid soil conditions. Calcareous soils are totally unsuitable despite the high demand of ramie for calcium.

For the best growth a good and equally distributed rainfall is necessary. Sudden changes of weather result in irregularities in growth, and these have a tendency to produce plants whose fibres vary in strength.

Ramie is a hardy perennial which under suitable conditions can be harvested up to six times a year. Also, the useful crop life ranges from 6 to 20 years. The bark contains gums and pectins which necessitate a chemical or enzymatic treatment to recover the bast fibres.

The *Boehmeria nivea* is a dicot and angiosperm, is adapted to moist tropical climates and deep soils, is a perennial plant, occupies the land all year round and, when under cultivation, it is without branches (apical dominance, apical buds pinched off).

Two to four harvests per year are possible depending upon the climate but, as already mentioned, under good growing conditions it can be harvested up to six times per year; it is harvested as the stems turn brown. Harvesting is done just before or soon after the onset of flowering, since there is a decline in plant growth at this stage and maximum fibre content is achieved. The timing of the harvest of a particular stem is important as fibre yields are reduced if it is immature; additionally, there are difficulties in removing the fibre if the stem is over-mature. According to Buchanan, the plant is best harvested as the female flowers open [26]. The outer bark is removed and then the fibrous inner bark is taken off and boiled before being woven into thread [27].

Stems are harvested by cutting just above the lateral roots or the stem can be bent, to enable the core to be broken and the cortex can be stripped from the plant in situ. Mechanical harvesters have been developed but are not used commercially. After harvesting, stems are decorticated while the plants are fresh as the bark gets harder to remove as the plant dries out. The bark ribbons are dried as quickly as possible to prevent attack by bacteria or fungi.

The dry weight of harvested stems from both tropical and temperate crops ranges from about 3.4 to 4.5 tonnes ha^{-1} $year^{-1}$; a 4.5 tonne crop yields about 1600 kg ha^{-1} $year^{-1}$of dry undegummed fibre. The weight loss during degumming can be up to 25% giving a yield of degummed fibre of about 1200 kg ha^{-1} $year^{-1}$.

2.5.4 Degumming of ramie

Raw ramie fibre produced either by hand scraping or decortication contains a fairly large percentage of gums and non-fibrous cells, or parenchyma (30–35%). These gums and cells are, for the most part, insoluble in water and must be removed before the fibre can be mechanically spun in fine count yarns. They are composed principally of arabans and xylans which are readily soluble in alkaline solutions.

Actually, they all follow a similar pattern consisting of the following basic steps:

(a) boiling of the fibre one or more times in an aqueous alkaline solution with or without pressure and agitation, and with or without penetrants or reducing agents;
(b) washing with water and neutralizing;
(c) bleaching with the dilute hypochlorite or hydrogen peroxide;

(d) washing with water and neutralizing;
(e) oiling with a sulphonated hydrocarbon.

This process may be carried out on the undried or dried fibre although Hoefer's [28] findings indicate the latter is preferable. Most of the processes involve a treatment with caustic soda to dissolve the residual pectins and gums. Ramie fibre, when properly degummed, is long and strong vegetable fibre. It is lustrous, possesses high tensile strength, is remarkably absorbent and gains strength appreciably when moist.

Although ramie fibre is usually degummed chemically, there have been promising developments in microbial degumming (retting). Additionally some researchers reports that the use of ultrasonic vibrations speeds up the degumming process. The enzymatic treatment seems to be promising.

Chemical degumming

Hot alkali is used to dissolve the pectic substances that bind the ultimate fibres into bundles. Some commercial processes, for reasons of cheapness, use sodium hydroxide almost exclusively as the alkali, though it is used sometimes in admixture with sodium carbonate. The main factors that affect the efficiency and economics of chemical degumming are:

- concentration;
- pH;
- volume and temperature of the alkaline liquor;
- the duration of degumming;
- agitation.

Degumming can be carried out both below ('low temperature') and above atmospheric pressure ('high temperature'); during the latter the yield of degummed fibre tends to be low (about 75% on washed decorticated fibre). This is because at temperatures above boiling point not only the pectic substances and adhering epidermal tissues are removed, but also hemicelluloses and, sometimes, some of the true cellulose [28].

Two further aspects require consideration if chemically degummed fibre is to be suitable for spinning. Firstly, care must be taken to avoid tangling of the fibre during degumming and subsequent washing, especially if much mechanical agitation is used. Secondly, thorough washing after degumming is very important. Most of the published chemical degumming methods use water as either the sole or the final washing agent.

Microbial degumming (retting)

This method involves the utilization of several mixed bacterial cultures isolated from different sources. Each of the mixed cultures contained several bacterial species, which grew in association with one another [29]. The researchers observed that attempts to separate an individual organism for isolation and identification failed since it did not grow separately, probably owing to its dependence on the metabolic products of other organisms in the mixed culture for nutrition and growth.

Microbial degumming with mixed bacterial cultures is thus a good alternative to chemical degumming; this process involves several treatments to obtain good-quality fibres. The mixed degumming method is simple and economical in that less alkali is required, the treatment is less drastic, and such fibre properties as softness, feel, and lustre are also much improved. The combined microbial and chemical method is simpler and more economical.

2.5.5 Ramie straw processing

After the degumming process the degummed fibre, or filasse, is fairly white; if pure white fibres are required, the filasse must be bleached. In the past the fibre was bleached before being made into yarn or cloth but nowadays it may be possible to bleach cloth. The result of bleaching is a small loss of weight and of fibre strength [30]; it should be carried out only when absolutely necessary.

Since degummed fibre may be stiff, harsh and dry, and not completely separated, it needs to be softened, before spinning, by the application of a suitable agent – for example glycerine, oil, fat, soap, paraffin, wax or tallow – and left for some time to condition. The fibres can be further softened and separated by passing them through a series of paired fluted rollers and then through a pair of smooth rollers; if necessary, they can be passed through several times [30].

2.5.6 Spinning ramie

In traditional spinning individual fibres are then spun together; the warp is spun on a spinning wheel; the weft is joined and given a slight twist by hand. Industrial spinning is a multi-stage process which consists of three basic steps:

- carding (combing the fibres into a mat);
- drawing (pulling the carded mat out to form a long thin strand, or sliver, of adhering parallel fibres);
- spinning (twisting the sliver so that the fibres lock each other into the strand).

Ramie may be combed and spun by several methods. The finest yarns are produced on the spun silk system developed by the Japanese, but this system requires much labour. In Europe, Brazil and the Philippines, modification is used. This produces coarser count yarn and much less labour is required. Ramie may also be spun on the worsted and long draft cotton systems, but in the latter case stapled noils are used and usually blended with cotton or synthetic fibres. Since ramie fibre is relatively coarse in comparison with cotton, it is never spun into fine count yarns on the cotton system.

It appears that the main difficulty in spinning ramie results from the combination of high tensile strength with the long fibre length; the breaker cards cannot break the fibre into staple length suitable for subsequent spinning. Thus, it is usually necessary to pass the fibre through a stapling machine: this is reported to break, rather than cut, the fibre into the staple length. The advantages claimed for this method of stapling include: reduced fibre loss, easier spinning resulting from the more uniform length within a given staple, and smoother yarn resulting from feathered as opposed to blunt ends.

The weaving of ramie yarn does not pose any problem and all kinds of linen and cotton looms are used for this purpose. The ramie can be dyed in tops, in yarn or in fabrics and its dyeing properties are similar to those of linen and cotton. Very rich in cellulose, ramie remains snow white after exposure to the sun. The textiles woven from ramie yarn show excellent wearing properties and cover a vast range, running from very fine shirting to heavy uniform suitings.

2.5.7 Properties of ramie fibre

The fibres are the longest known in the plant realm [31], the tensile strength is seven times that of silk and eight times that of cotton, and this is improved on wetting the fibre. The fibre of the ramie after the extraction and primary processing is strong and durable, ranking first among all vegetable fibres in this respect. It is the least affected by moisture and its tenacity even increases by 25% when wet. It has the special advantage of resisting rot when exposed to weather conditions or immersed in water. The fibre of ramie is exceptionally white, being comparable to bleached cotton, and has also a high lustre, exceeding linen in this respect.

Ramie requires a different technological process to cotton; therefore it is difficult to compare directly the properties of those fibres. However, to give some idea about the advantages of ramie, some of the physical and chemical characteristics of ramie, flax, hemp and cotton are compared in Table 2.15 [32].

The ultimate fibres are exceptionally long and are claimed to be the longest of vegetable origin, with one report claiming the fibres range up to 580 mm, averaging about 125 mm. Another report describes the ultimate fibre as ranging between 48 and 290 mm in length. It was also reported that the range of bark fibre length was 5 to 36 mm and the fibre width was 41.8 microns. The inner structure of ramie differs from the other plant fibres in

Table 2.15 Ramie fibre properties in comparison with other fibres

Characteristics	Ramie	Flax	Hemp	Cotton
Ultimate fibre length (mm)				
minimum	5	1	5	9
most frequented	120–150	13–14	15–25	20–30
maximum	620	130	55	63
Ultimate fibre diameter (μm)				
minimum	13	5	10	12
most frequented	40–60	17–20	15–30	14–16
maximum	126	40	50	20
Tensile strength (kg mm^2)	95	78	83	45
Moisture regain (%)	12	12	12	8
Chemical composition (%)				
Cellulose	*72–97	64–86	67–78	88–96
Lignin	0–1	1–5	4–6	0
Hemicellulose, pectin and others	3–27	14–31	18–27	4–12

*Minimum and maximum cellulose contents refer to decorticated and degummed ramie respectively.

that the physical form of the cellulose is rigid and crystalline like linen, but is a more porous sieve-like form [33], providing it with even better absorbency than other cellulose fibres. In addition, it is softer with better dyeability.

Ramie fibre is very durable, but like linen and cotton, ramie has poor resiliency and wrinkles easily; application of wrinkle-resistant finishes or blending with synthetic fibres can reduce the problem in woven fabrics. Because of its high absorbency, ramie is comfortable to wear, especially during warm weather. Other properties include resistance to alkali, rotting, light and mildew. Resistance to insects is good unless the fabric is heavily starched. Ramie is not harmed by mild acids but can be damaged by concentrated acids.

The fibre has some natural stain-resisting ability with ease of stain/soil removal similar to that of linen, which is better than cotton. Dyes appear to have good wet-fastness in laundering but there can be a tendency for crocking in dark or saturated colours. Dark colours may lose their vibrancy over repeated launderings.

2.5.8 Applications of ramie and ramie fibres

In textile applications, blends are more common than pure ramie with the most being typically 55% ramie/45% cotton. The uneven linen texture is generally apparent in the blend, but the lustre is lost. When polyester and other man-made fibres are included in the blend, it improves wrinkle resistance and helps provide easy care and shrinkage control. When used in admixture with wool, shrinkage is reported to be greatly reduced when compared with pure wool.

Advantages and disadvantages of ramie as a fabric

(a) Advantages: resistant to bacteria, mildew, and insect attack. Extremely absorbent. Dyes fairly easily. Increases in strength when wet. Withstands high water temperatures during laundering. Smooth lustrous appearance improves with washing. Keeps its shape and does not shrink. Can be bleached.
(b) Disadvantatages: low in elasticity. Lacks resiliency. Low abrasion resistance. Wrinkles easily. Stiff and brittle.

Medicinal uses

Antiphlogistic, astringent, demulcent, diuretic, febrifuge, haemostatic, resolvent, vulnerary and women's complaints. Used to prevent miscarriages and promote the drainage of pus [34, 35]. The leaves are astringent and resolvent [36, 37]. They are used in the treatment of fluxes and wounds. The root is antiabortifacient, cooling, demulcent, diuretic, resolvent and uterosedative.

2.6 Kenaf

Sources are not consistent regarding the origin of kenaf (*Hibiscus cannabinus* L.) except that Africa is the continent of origin, and it has been known and grown for over 4000 years. Due to its origin, the species is a short-day plant; however, there are also photo-insensitive cultivars available [38, 39].

2.6.1 Economic importance of kenaf

It is grown mainly in Thailand, China, India, Vietnam and Cuba (Table 2.16). Production of kenaf is fairly constant throughout recent years although many producers experienced a substantial decline in 1999. The biomass production ranges from 12–18 t ha^{-1} and the fibre content is 18–22% of the dry stalk weight. The fibre yield on average is 1–2 tonnes fibre ha^{-1}, rising to 3–3.5 t ha^{-1} under favourable conditions [40].

Today's interest in kenaf focuses on it as an alternative source of paper pulp although still on a very limited scale. Ultimately refined bast fibres measure on average 2.6 mm in length and resemble the best softwood fibres while core fibres are only about 0.6 mm long and are similar to hardwood

Table 2.16 Main producers of kenaf (thousand tons)

Country	1998/ 1998	1999/ 2000	2000/ 2001	2001/ 2002	2002/ 2003	2003/ 2004
China	248.00	164.00	126.00	163.00	155.00	165.00
India	182.16	198.18	198.00	203.40	202.14	198.70
Indonesia	7.20	7.50	7.00	10.20	6.80	7.00
Thailand	47.21	29.72	29.69	56.00	41.00	57.00
Vietnam	14.60	9.40	11.30	14.60	20.50	12.50
Cambodia	1.10	0.30	0.20	0.20	0.50	0.50
Pakistan	1.90	1.90	2.20	2.20	2.20	2.20
Brazil	8.60	7.90	7.30	7.20	10.20	10.90
Cuba	10.00	10.00	10.00	10.00	10.00	10.00

Source: Compendium of Statistics on Sisal, Jute, Kenaf, Abaca and Coir. Consultation on Natural Fibres, FAO.

fibres [41]. It contains about 40% of cellulose in the fibre and over three times less lignin (10%) than southern pine, which makes it easily and quickly pulped and bleached with less toxic chemicals (hydrogen peroxide versus chlorine) [42]. This, in combination with its annual renewability, makes kenaf a much more environmentally sound raw material than commonly used timber.

Today about 200 tonnes per year of kenaf pulp is produced in the USA and also in small mills in China, India, Thailand and Spain [41, 43]. Also, in Japan many paper companies use or have used kenaf in their products [44]. Although different pulping technologies have been tested the only one commercially used remains the sulfate (craft) process.

Other uses of core kenaf fibre include also soil-less potting mixes, animal bedding, oil absorbents, packing material, organic filler for plastics, drilling mud binder, grass and flower mats, decorative fibres and insulation as well as animal feed and human food [41]. Bast fibre is also blended with cotton and used in textiles [41]. The bast fibre of kenaf can also be mixed with plastic for injection moulding.

2.6.2 Anatomy of the kenaf plant

Kenaf seeds are produced in 1.9 to 2.5 cm long and 1.3 to 1.9 cm in diameter fruits called seed capsules that contain many (20–26) small seeds, ranging in colour from brown to black [40, 45]. The plant has a long taproot system with relatively deep, wide-ranging lateral roots making the plant drought tolerant [46]. The stem is straight and poorly branched when cultivated for fibre and can reach up to 6 m in height in favourable conditions; usually the most desired height is 3–4 m. A cross-section of kenaf stem reveals three main parts: an epidermis; a thin layer of bast and wood filling; and the inner part of the stem. The two latter tissues are considered the source of two different kinds of fibre, the bast and the 'core'. The bast comprises roughly 40% and the core 60% of the stalk's dry weight [41]. Leaves are individually stalked and lobate to a different degree, depending on the cultivar [40]. Kenaf plants produce large, light yellow or creamy coloured flowers that are bell-shaped and widely open. The flowers of many cultivars have a deep red or maroon coloured centre [45].

2.6.3 Cultivation of kenaf

Kenaf is cultivated for its fibre and also as a fodder plant and has a relatively wide range of adaptation to climate and soils. With the exception of some early types developed for the Asiatic regions of the former USSR, most of the current kenaf cultivars grow best under tropical and sub-tropical conditions where mean daily temperatures are greater than 20°C [47]. Water demand varies but on average lies between 75 and 125 mm per month during the first 100 days of vegetation [41].

Kenaf can be successfully grown in a wide range of soils, from high organic peat soils to sandy desert soils [41]. The best effects are obtained on well-drained, fertile soils with a neutral pH; however, it can withstand late season flooding, low soil fertility, and a wide range of soil pH values [41]. Kenaf also has shown excellent tolerance to drought conditions.

Although some studies show that kenaf requires no fertilizer supply, it seams reasonable to secure the proper nutrient balance for the entire crop rotation planned. The rates of N, P and K should be about 100–130, 35–50 and 110–140 kg ha^{-1} respectively, depending on the soil nutrient content [47].

Where local weather conditions make kenaf growing impossible due to cool weather it can be planted once the soil has warmed to 13°C and the threat of frost is past [45]. Depending on local conditions, for fibre, 185,000 to 370,000 plants ha^{-1} or even 300,000 to 500,000 plants ha^{-1} is optimal, which can be accomplished sowing 8 to 25 kg ha^{-1} of seed [45, 47]. The row spacing should be about 50 cm with plants 3–4 cm apart within the row. The seeds should be planted 2–3 cm deep and about 1 cm deeper in moisture deficiency conditions [45, 48].

Kenaf is fairly resistant to pest and diseases; however, locally, cut worms, leaf miners, and other chewing/sucking insects are potential problems. The only pest problem most likely to be experienced almost anywhere kenaf is grown is plant parasitic nematodes, especially root-knot nematode (*Meloidogyne* spp.) [40, 48]. Kenaf can also be infected by anthracnose (*Colletotrichum hibisci*) [45]; however, choosing resistant cultivars can help solve this problem.

In a large-scale plant production manual harvesting is an unacceptable harvesting method. Although kenaf has gained the interest of market-oriented farmers around the world, few very efficient harvesting methods have been developed. Whole stalks can be harvested; plants are cut and laid down in an orderly fashion at right angles to the row, stalks are allowed to dry for around two weeks and are then gathered by a machine that picks up the stalks and arranges them in large bundles; the bundles are transferred to field trailers. Another method is to use forage choppers to harvest the crop. This method can be used in colder areas where the crop is allowed to dry after being killed by frost or by a desiccant. This method has been used in Mississippi [41]. The chopped kenaf is stored and transported in cotton modules with the same equipment used for harvesting cotton [48]. The crop may also be chopped and baled with forage equipment and, if covered, can be stored as large round or rectangular bales on field edges.

2.6.4 Processing of kenaf straw

Before straw is processed and fibres extracted, it has to be retted. In Asia, Africa and Latin America kenaf is still retted in ponds. However, this process is labour intensive and leads to serious contamination of waterways [47, 49], therefore, like many other bast fibre yielding crops, kenaf can be dew-retted. The second stage of processing involves a series of decortication machines that break the stem and separate core and bast fibres [50].

2.7 Abaca

Abaca or Manila hemp (*Musa Textilis Nee*) is a herbaceous plant that belongs to the family of *Musaceae*. Its appearance is similar to the banana plant, but it is completely different in its properties and uses. Abaca and other *Musa Textilis* mixtures, with different levels of quality and resistance, are produced and successfully marketed in several countries.

Abaca is indigenous to the Philippines, but has been introduced to Borneo, Indonesia and Central and South Americas. The origin of the abaca plant is in the southern part of the Philippines where there are rainforests and highly humid atmospheric conditions. The Philippines is the world's largest source and supplier of abaca fibre for cordage and pulp for specialist paper. While abaca fibre has been used in cordage manufacturing for many years now, fibre for pulp in specialist paper manufacturing came into commercial use only in the 1930s. In the Philippines, there are three regions that produce abaca on a commercial scale: Mindanao, Visayas and the Bicol regions. Each of these regions supplies different varieties and hybrids. Although each variety has certain advantageous qualities, not a single variety can be considered perfect. It was produced exclusively in this region until the Second World War, when the Japanese army cut off production and producers looked for new places to establish and grow it. An excellent place to grow abaca was found in countries such as Ecuador.

Abaca is a versatile plant with several uses. Because its fibres are particularly resistant to saltwater, abaca has been commonly used for fishing nets. Abaca fibre is used mainly in the production of tea bags and meat casings; it is also a substitute for bark, which was once a primary source of cloth. In addition, it is considered an excellent raw material in the processing of security and high quality paper, diapers, napkins, machinery filters, hospital textiles (aprons, caps, gloves), and electrical conduction cables, as well as some 200 other different finished products.

Fibres are removed from the abaca's stalk to make ropes, clothing, and paper-based materials. These plants thrive well in shaded and cool habitats and resemble the banana plant in many respects.

2.7.1 Economic importance of abaca

Table 2.17 shows recent distribution of the global production of abaca, according to the Abaca Growers Corporation of Ecuador (CADE), whose production represents 42% of the national total; the Philippines has never lost its predominant place in the global production of abaca. Abaca in Ecuador is processed with special equipment that separates the raw material and fibre; in contrast, in the Philippines the process is still performed manually, resulting in a lower yield and quality. The quality of the abaca plant in Ecuador is 12.5% (1.1% hard fibre and 11.4% soft fibre or bagasse).

Table 2.17 Abaca global production 1998

Country	Distribution (%)	Production (Mt)
Philippines	79.00	65 570
Ecuador	17.00	14 110
Costa Rica	1.50	1 245
Indonesia	1.02	845
Equatorial Guinea	0.98	815
Kenya	0.50	415
TOTAL	100.00	83.000

Source: Abaca Corporation of Ecuador (CADE).

While almost all production is sold directly from the producers to the exporters, a small amount is still sold through third parties. Before being exported, the fibre is taken to warehouses to be classified. All the companies have their own warehouses located in central locations. The maximum moisture allowed is 8% and the cellulose percentage ranges from 70 to 80%. The classification system is based mainly on colour and measurement of the fibre's diameter. Variation in fibre length, which normally goes from 1.8 to 6.0 metres, is considered in the classification. This classification has five and sometimes six grades, ranging from a white fibre, which would be considered grade 1, to a dark brown fibre, which would be considered grade 5. The rule for measuring quality based on the fibre's diameter is simple: the thinner the better.

2.7.2 Anatomy of the abaca plant

The abaca plant can grow to more than 6 m in height and is found in several varieties. Not all varieties are grown commercially. Abaca has a perennial production cycle; at the beginning, it takes 18 to 24 months to produce fibre and after that, the product can be harvested every two to three months. Abaca should be grown in regions with optimum conditions in order to get the best results possible. The best regions to grow abaca are those with humid tropical weather and temperatures from 22 to 28°C. Additionally, rainfall is extremely important; abaca must have from 1,800 mm to 2,500 mm of well-distributed rain during the year. One more element to consider is the altitude; the optimum altitude is between 100 and 140 metres above sea level. Rain and sunlight are both essential factors in the production of abaca: excess sunlight combined with a lack of rain may adversely affect the development of a regular plant to the point of making the production worthless. In a good growing environment, an abaca plantation can commercially produce fibre for 15 to 20 years.

2.7.3 Cultivation of abaca

The most appropriate time for planting is at the beginning of the winter season; however, abaca can be planted in another season if the soil has enough moisture. The abaca plant propagates itself through suckering, or the growing of shoots from the roots. When all the leaves have been formed from the stem, flower buds develop, at which time the plant has reached maturity and is then ready for harvest.

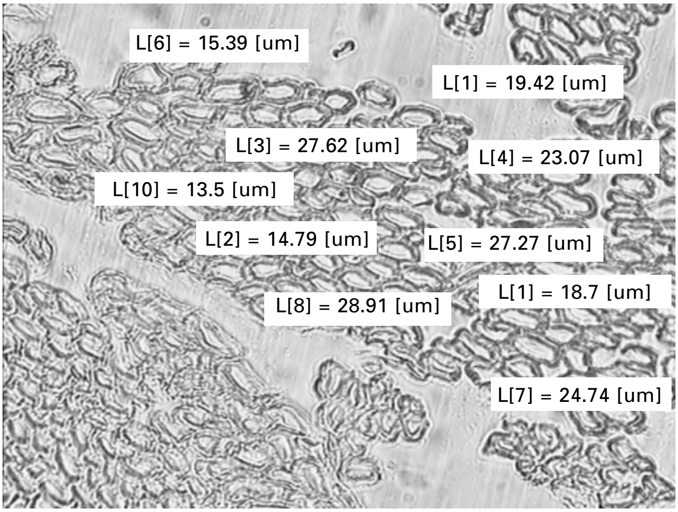
The time that a plantation lasts, between planting and harvesting, depends on various factors such as the nature of the property, the variety of abaca planted, seed selection, weather conditions, maintenance activities, etc. In general, the time between planting and harvesting is 18 to 24 months. The adequate moment to initiate the harvest is when the flower begins to develop. The stalks are considered mature and are harvested when the flag leaf appears. Harvesting is not recommended before or after this stage because the quality and the amount of fibre is reduced.

2.7.4 Processing abaca straw

The fibre extraction process is conducted by a shaving system; the operator surrounds the rod with one part of the tuxie (slice of the plant) while the other part is held between the blades. The blades are closed and with one movement or stretch, the fibre is separated from the tuxies. The other part of the tuxie that surrounds the rod is handled in the same way. A fibre extractor produces an average of 120 kg, with an optimum of 200 kg. In the Philippines, 90% of the fibre extraction is conducted manually by means of a set of knives placed in a special wood frame. The fibre that is obtained has a high percentage of moisture which makes it necessary to dry it at the farm in cane structures specially designed for this purpose. The drying period can last from a couple of hours to days, depending on weather conditions. At the same time that this activity is conducted, a preliminary classification is conducted depending on the colour that the fibre presents. After drying, the fibre is piled in dry places that can be covered and that have adequate ventilation, because even after drying the fibre holds a certain percentage of moisture and without ventilation, the fibre can change colour and lose quality.

2.7.5 Fibre physical properties and chemical composition

Abaca fibre measurements can be seen in Table 2.14 (see page 66) and in the cross-section of the fibre bundle (Fig. 2.13). Chemically, abaca comprises 76.6% cellulose, 14.6% hemicellulose, 8.4% lignin, 0.3% pectin and 0.1% wax and fat.



2.13 Abaca stem cross-section.

Table 2.18 Comparison of physical parameters of natural fibres

Fibre	Elementary fibres (single cell)		Ultimate stress (Mpa)	Elongation (%)	Young's modulus (GPa)	Density (kg m^{-3})	Specific stress (MPa m^3 kg^{-1})	Cellulose (%)	Lignin (%)
	Surface area S (μm^2)	Diameter (μm)							
Flax	110–270	15–22	900–1200	2.0–3.0	100	1540	0.58–0.80	71	2.2
Hemp	440–910	29–45	400–700	1.6–2.5	35	1480	0.27.0.47	70–88	3.0–4.0
Jute	300–780	26–30	400–700	1.5–2	2.5–15	1450	0.28–0.48	63–70	12.0
Ramie	400–900	40–60	800–1000	1.7–3	50–80	1560	0.51–0.64	70–80	0.5–1.0
Kenaf	150–700	14–33	350–600	2.5–3.5	40	1500	0.22–0.40	75–90	–
Abaca	166–274	15–30	–	–	–	–	–	77	8.4

Source: Institute of Natural Fibres, Poland, Department of Textile Raw Materials and Products Metrology.

Abaca is considered the strongest of natural fibres, being three times stronger than sisal fibre, and is far more resistant to saltwater decomposition than most of the vegetable fibres. Compared to synthetic fibres like rayon and nylon, abaca fibre possesses higher tensile strength and lower elongation in both wet and dry states.

2.8 Comparison of fibre properties

By way of summary, the physical properties of the six bast fibres discussed in this chapter are given in Table 2.18.

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