Chapter 6
Kenaf Fibre Crop for Bioeconomic Industrial Development

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Abstract Kenaf (*Hibiscus cannabinus* L.) is a high yielding fibre crop that can be utilised as raw material in many industrial applications ranging from traditional fabrics, yarns and ropes to new applications in building materials, composites and lightweight car parts. Kenaf competes in some applications with other bast fibre crops such as jute, hemp and flax and with wood or wood residues in other markets such as in wall panels and pulp and paper applications. Traditional gunnysack markets switched over to cheap synthetic manmade fibres based on fossil oil, resulting in a decline of demand and production of jute and allied fibres over the past decades. This declining trend may be reversed, only when the different new markets for fibre crops described in this chapter can be established on a viable scale. When the policies for the transition from a petroleum-based economy to the biobased economy are to be implemented, increased demand for these kind of cellulose resources has to be anticipated for. This provides opportunities to develop kenaf-based industries and increased kenaf cultivation, especially in regions with limited supplies of wood.

6.1 Introduction

Climate change and globally dwindling forests with resulting shortage of wood supply are the urgent drivers for the search for sustainable biomass resources and new bioeconomic industrial developments. The search for alternative resources for cellulosic fibre production to manufacture paper pulp and other consumer products is inspired by the broad public debate on climate change and the prospects of the transition towards CO_2 neutral production. The bioeconomic developments for up-scaled production of biofuels and the design of novel biorefineries for the production of green chemicals involves the identification of sustainable solutions for supplies of resources and conversion technologies (Boeriu et al. 2005;

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van Dam et al. 2005; Vellema et al. 2010). Existing applications of lignocellulosic resources are expected to find increased competition on the markets for fuel and energy (e.g. energy crops) (Keijsers et al. 2012). In the past decades, several extensive surveys have been conducted to find alternative feedstock for paper production (Nieschlag et al. 1960a; van Berlo et al. 1993; Atchison 1995; Pande 1998; Saijonkari-Pahkala 2001).

Kenaf (*Hibiscus cannabinus* L.) has been identified as one of the fibre crops that have potential as high yielding crop in non-wood pulp production and other industrial uses such as building materials and lightweight car parts. Plant fibres traditionally find a wide variety of applications such as fabrics and yarns, ropes, twines, nets, etc. Most important industrial conversion technologies for non-wood fibres used to be the spinning and weaving processes of fibres into textile fabrics for clothing, sacking and netting. Competition with cheap synthetic fibres on these markets has eroded the market share of most commodity fibre crops in the last half century. By far, the most important textile fibre crop is still cotton. Other fibre crops of commercial interest for textile production include jute and kenaf, flax, hemp and ramie (Table 6.1).

Extensive research has been carried out on the application of kenaf fibre in pulp and paper applications after it had been identified by United States Department of Agriculture (USDA) as the most promising non-food crop for pulp production (Nieschlag et al. 1960a, 1961). Several large-scale trials and a demonstration project resulted in commercialisation plans for the Kenaf Rio Grande newsprint mill (Kugler 1988, 1996). However, overproduction of pulp and low market prices made the financing of the planned mill at that time not attainable. Private entrepreneurs and USDA started then searching for less capital intensive, smaller scale markets for both the core and bast fibres from kenaf.

Table 6.1 Global production volume of fibre crops (2010)

Cellulosic fibres	kton/year	Percentage of total fibres	Major producing countries
Cotton	23,500	80.1	China, Brazil, India, Pakistan, USA
Jute	3,055	10.4	Bangladesh, India
Coir	1,100	3.7	India,Vietnam, Sri Lanka
Flax	620	2.1	EU, China
Kenaf	390	1.3	China, India, Thailand
Sisal	350	1.2	Brazil, Kenya, Tanzania
Ramie	120	0.4	China, Laos, Philippines
Kapok	100	0.3	Indonesia, Thailand
Hemp	70	0.2	China, DPR of Korea
Agave	34	0.1	Colombia, South America
Cellulosic fibres	29,330	100	Total world

Source FAO STAT (FAO 2010a) and personal communication

In the early 1950s, in response to a shortage of vegetable fibres, trials were conducted in growing kenaf in Queensland in Australia. However, this work was discontinued when adequate supplies of this commodity came available on the market. In the late 1960s, the pulping studies in the USA led to a renewed interest in kenaf in Australia and agronomic and pulping studies were undertaken (Wood 1981). Agronomic studies were also conducted in Argentina (Ayerza and Coates 1996) and in South-Europe (Alexopoulou 2008).

One paper mill that used kenaf on commercial scale was the Phoenix pulp mill in Thailand. From 1981, this mill operated a whole stem kraft pulping process with a capacity of 200 ton/day (Taylor 1993). Situated in an agricultural area combined with a shortage of timber, kenaf pulping was expected to be competitive. In 2006, this mill converted plantation-based eucalypt, besides kenaf. However, currently this mill does not advertise using kenaf anymore.

In spite of these unsuccessful attempts of creating large-scale markets for kenaf fibre other than textiles, research and development efforts are persisting. In the last decade most of the published research on kenaf applications shifted to Asia, especially to Malaysia and China. There the urge is felt by the governments to search for new sustainable crops that can substitute the declining traditional crops and can supply the market with alternative fibres. The Malaysian Government is strongly promoting the R&D on kenaf as an alternative crop (Edeerozey et al. 2007; Adnan 2010).

The strong economic development of the newly industrialised Asian and Latin American countries during the past decades also creates higher pressure on the planet's natural supplies and the environment. Demands on sustainable CO_2 neutral alternatives are increasing and biorefinery of biomass crops has become a worldwide topic of research. In this perspective, these new kenaf R&D initiatives have therefore a higher chance of success than the previous efforts.

6.2 Kenaf Applications and Properties

6.2.1 Positioning Kenaf Among Other Crops

Plant fibres are the structural building elements in all higher plants. They are composed of cellulose fibrils that are embedded in a non-cellulosic polysaccharide matrix (hemicellulose, pectin) and lignin (Willför et al. 2011). In commercial production of cellulose products and paper pulp, mainly wood and cotton are used as resources in industry today. Only about 10 % of the world's virgin paper pulp is made from non-wood sources from which 87 % are pulped in Asian countries (China, India and Pakistan) where there is an increasing lack of timber resources and a high demand for paper products. Paper can be made in principle from any fibrous plant material, including many annual plants and agricultural crops or residues such as cotton (linter), hemp and flax (tow), cereal straws, bamboo or sugarcane bagasse. China is producing about 70 % of the total world production of non-wood pulp

(FAO 2010a, b). Of the 13 million tons of non-wood pulp produced in China in 2008, straw had a share of 62 %, reed 12 %, bamboo 11 % and bagasse 8 % (Huang 2010).

Commercially important plant fibres that may compete with kenaf fibre in some applications are classified according to their use in textile fibres (cotton, and soft fibres: ramie, flax, jute, hemp), ropes and twines (hard fibres: sisal, coir, abaca, hemp, henequen), brush and mat fibres, stuffing and upholstery materials (coir, kapok) or papermaking fibres (straw, bamboo). The commercial value depends on the nature of the fibre with respect to length, fineness, strength and stiffness (Tables 6.2 and 6.4). The embedding of fibre cells in the surrounding plant tissues affects the ease of extraction to a large extent, which dictates the commercial value and fibre quality characteristics.

Traditionally, more coarse and hard cordage fibres are used for making ropes and twine for tying, netting and matting (Fig. 6.1, Tables 6.2 and 6.5)

Non-wood materials that are used in paper making can be categorised into two distinct groups (Han and Rowell 1997). Several non-wood crops are specifically grown for the production of specialty paper products, with a higher market value. For example, pulps made of the long fibres of abaca, hemp, flax and cotton are used for manufacturing of paper products with high strength (security papers, banknotes) and cigarette paper. Other common non-wood paper pulps are produced from the residues derived from the agricultural food production. Cereal straws

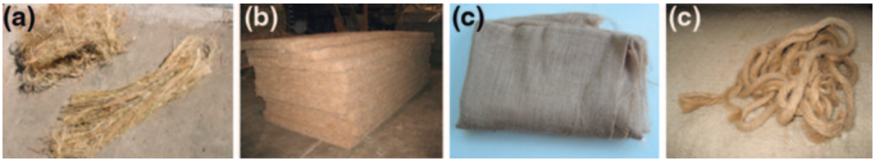

Fig. 6.1 Kenaf fibres (**a**), insulation mats (**b**), textile (**c**), ropes (**d**)

Table 6.2 Examples of kenaf dimensions and quality ratings compared to some other cellulosic fibre sources. Adapted from (Ververis et al. 2004; Roy and Chattopadhyay 2012)

	Fibre length, L (mm)	Diameter, D (μm)	Lumen, d (μm)	Cell wall thickness, w (μm)	Slenderness ratio, L/D	Flexibility coefficient, 100 × d/D	Runkel ratio, 2 × w/d
Kenaf bast	2.32	21.9	11.9	4.2	106	54	0.7
(range)	(2.3–2.9)	(17–25)					
Kenaf core	0.74	22.2	13.2	4.3	33	60	0.5
(range)	0.6–0.8	22–33					
Jute bast	2.8	18	7.6	5.2	155	42	1.6
(range)	1.9–3.2	16–20					
Roselle	2.9	19			152		
(range)	2.6–3.3	19–20					
Hard wood	1.0	13–22			45–75	55–70	0.4–0.7
Soft wood	3.5	20–40			95–120	75	0.35

(mainly wheat and rice) and sugarcane bagasse together with bamboo are the most important non-wood fibre sources.

6.2.2 Botany of Plant Fibres

Vegetable or plant fibre is defined differently by botanists or other specialists, using plant fibres. The fibre is considered botanically to be an individual cell, which is part of sclerenchyma tissue and is characterised by a relatively thick cell wall and high length to diameter ratio (Table 6.2). The sclerenchyma is providing mechanical integrity to the plant. Spindle-shaped cells with tapered ends are a characteristic feature of the fibre cell. According to this definition, cotton fibre—the most well-known plant fibre—is not a fibre, but a trichome or seed hair—the extrusion of epidermal tissue.

The sclerenchyma fibre cells occur usually in bundles, possessing distinct tensile strength, elasticity and flexibility by which they can be discriminated from the other plant tissues and can be extracted for industrial purposes. Such fibre bundles occur in the dicotyledon bast fibre crops of commercial interest known as soft fibres (flax, hemp, jute, ramie and kenaf). The fibre bundles run longitudinally along the stem from bottom to top and reach almost the full length of the plants, which may be up to 3 m or more for hemp, jute and kenaf (Fig. 6.2).

The lignified fibre cells in the fibrovascular woody tissues or xylem of plants form another class of fibres. Wood is a mixture of dead and living cells of many different cell types, including fibre tracheids and libriform fibres. Actually, tracheids are not fibres, as their major function is conducting water and the cell shape is not typical for a fibre, though it has relatively thick cell walls. Both tracheid fibres and libriform or xylary fibres have emerged from tracheids in the course of evolution. Intermediate forms can be easily found (van Dam and Gorshkova 2003). This type of fibres are utilised in large quantities by the pulping industries for cellulose extraction and papermaking. Dicotyledon bast fibre crops including kenaf yield also a woody core (shives, hurds) that contain this class of short lignified fibres (xylem).

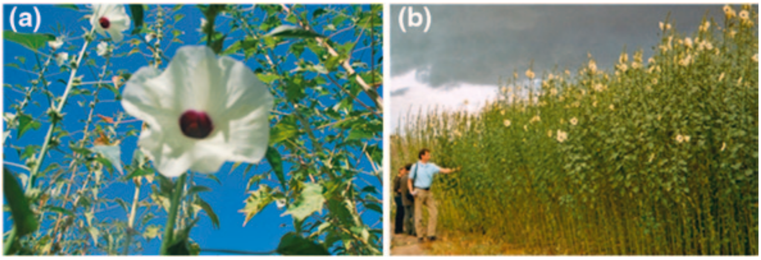

Fig. 6.2 **a** Kenaf flower and **b** crop inspection in the field

6.2.3 Plant Morphology of Kenaf

The Kenaf plant is a member of the Malvaceae (Mallow) family and belongs to the genus *Hibiscus* that comprises various species that yield fibres from their stem. Kenaf, an old cultivated crop supposedly originating from West Africa, can be grown in tropical and subtropical areas (Dempsey 1975). Kenaf is a crop with photoperiod (daylight) sensitivity and consequently only produces fertile seeds in lower latitude regions (between 37° N and 37° S) (Petrini et al. 1994). The plant is very similar to Roselle (*Hibiscus sabdariffa* L.) that is originating from tropical Africa. It is possible that growers do not always differentiate between the two species. In India, the common local names 'Ambari hemp' or 'Mesta' and 'Bimli' are used for both crops (Catling and Grayson 1982). In China, the crop is known as Yangma (Jinma, or Zhongma).

The different cell types observed in transverse section of *H. sabdariffa* were described and depicted in detail in a schematic reproduction (Fig. 6.3).

The bast fibres of kenaf contain a significant amount of lignin (Table 6.3), as can be visualised as brown–red staining in microscopic transverse sections of the stem (Fig. 6.4). In Fig. 6.4, each dot in the outer bast layer represents a fibre bundle consisting of a number of elementary fibres, as can be seen at higher magnification (Fig. 6.5).

Kenaf as typical dicotyledonous plant contains in its stem both bast or bark tissues with long fibre bundles (Fig. 6.6) that are running along the full stem length (phloem) 1.5–3.5 m tall, and a woody core (xylem) fraction composed of short fibres (0.6–0.8 mm). In the plant, the fibre bundles act like the rig around the mast of a ship, without it the mast or the stem would easily break in the wind. Like in flax, hemp, jute and other phloem fibres, the fibre bundle itself is a conglomerate of elementary fibre cells (Fig. 6.7) and the cell wall of these elementary fibres exists of microfibrils (Fig. 6.8). Jute and kenaf have the same microfibrillar angle (Feng 2001), varying between 7 and 12° (Taib 1998). In kenaf, both primary and secondary phloem fibres are found in different ratios, depending on the stem section (Ayre et al. 2009). The fibre cells are polygonal in shape. The fibre bundles are more meshy (interconnected at some points) and irregular than in jute. The long fibre bundles are extracted for applications such as textile, ropes and non-wovens. The fibres used in papermaking are the short elementary or ultimate fibres. The length of the elementary fibres is reported in a broad range (Table 6.2) with an average of 2.9 mm (Catling and Grayson 1982). The average width of these fibre cells was 25 μm within a range of 7–35 μm. The same length distribution of the fibres was found by others, but the thickness then was on average only 12.5 μm (Calamari et al. 1997). These differences may be related to maturity or growing conditions and variety of the crop. The woody core fibres had an average length of 0.6 mm and width of 33 μm (White et al. 1970). For comparison, the fibre length of softwoods is around 3.5 mm and of hardwoods around 1 mm (Rydholm 1985). So kenaf bast fibres are longer than most hardwood pulp fibres, but shorter than softwood fibres while the core fibres are even shorter than hardwood fibres. Beside the fibrous tissues, kenaf stem contains a non-fibrous tissue in the centre, called pith.

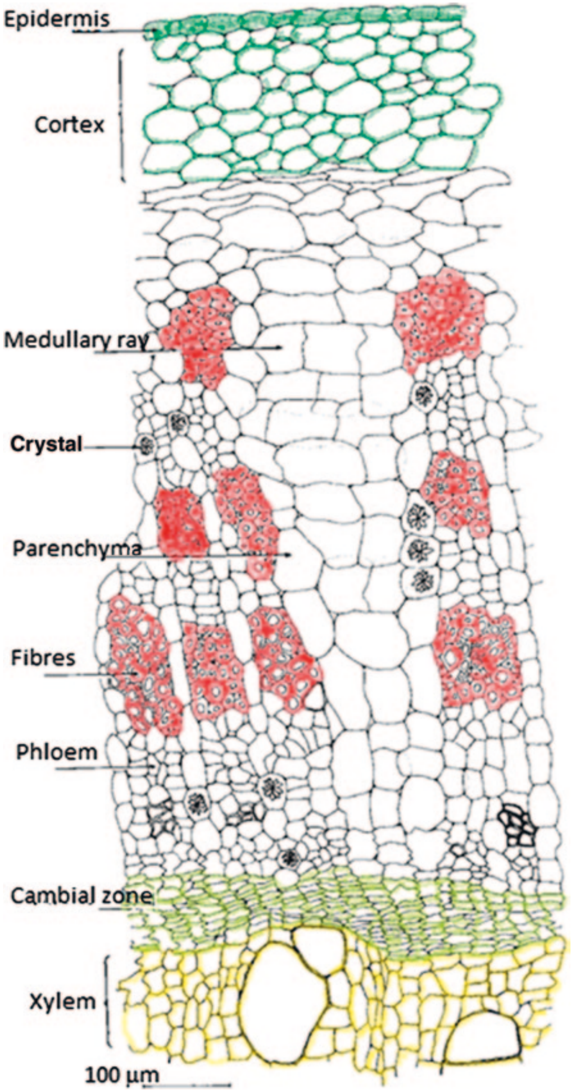

Fig. 6.3 Transverse section of *H. sabdariffa* stem (after Catling and Grayson 1982)

6.2.4 Fibre Properties and Composition

The fibre properties of kenaf are often compared with jute, but considered to be coarser or harder and less lustrous and a little better resistant against degradation (Kirby 1963; Rowell and Shout 2007). Kenaf is considered to be slightly inferior in quality to jute as coarser fibres are spun from it, e.g. jute can be spun into yarns of 13–27 denier, while kenaf yarns will count ca. 50 denier. Quality differences between fibres are related to physical properties (Table 6.4) and dimensions (Tables 6.2 and 6.3) of the fibre cells,

Table 6.3 Fibre bundle morphological characteristics and average composition

Common name	Fibre dimensions			Chemical carbohydrates composition			
	Bundle	Elementary fibres, (mm)		Cellulose	Pectin	Hemicelluloses	
	(cm)	length (mm)	width (μm)	(%)			Lignin
Flax, bast	30–90	13–60 (30)	12–30	72	2	18	<1
Shives	–	0.1–0.5	10–30	37	3	25	30
Ramie	>150	50–200	15–80	68–76	2	13–15	1
Hemp, bast	100–300	5–55 (20)	16–50	70	3	15	3
Hurds	–	0.5–0.6	15–40	40	3	25	25
Jute, bast	150–350	0.8–7 (2.5)	5–25	62	1	22	13
Kenaf bast	150–350	1.5–11 (2.6)	14–33	55	4	13	12–14
Core		0.6		40	7	19	19
Sisal	60–100	0.8–8 (3.0)	10–40	73	1	13	8–11
Abaca	100–200	3–12 (6.0)	12–36	70	1	22	9–13
Coconut	5–20	0.3–1.0	12–24	33	5	13	33
Cotton	–	20–60	12–25	90	–	6	1
Linter	–	1.0–2.0	–	80–85	–	–	–
Stalk	–	1.0–1.5	–	–	–	–	–
Sunn hemp	–	2.5–3.5	–	69–80	–	–	5–10
Roselle	–	–	–	32	–	–	10.4

(Kocurek and Stevens 1983; van Dam et al 1994; Atchison 1995)

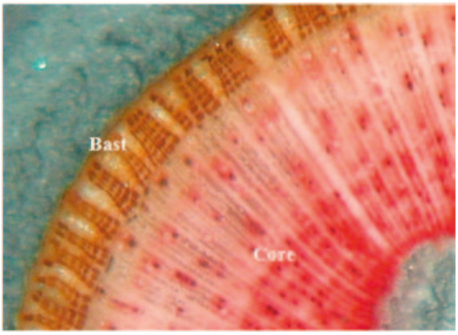

Fig. 6.4 Transverse section of the kenaf stem stained for lignin

which may vary significantly, even within one plant. Fibres from the top of the plant or from the bottom may differ in fineness. Moreover, the chemical composition of the cell wall and microfibril layered structure of the oriented cellulosic crystals are affecting the stiffness and flexibility, tensile strength and elongation. Besides cellulose, the cell walls are for the major part composed of polysaccharides, the so-called hemicelluloses and pectins, and polyphenolic lignin.

Detailed analytical data of the composition of different kenaf cultivars after warm water retting are all found in the same range. On average, the purified bast fibre samples contain 55 % w/w glucose, which is assigned to cellulose (Table 6.3). The typical hemicellulose sugar composition of kenaf bast includes xylose (12 %), mannose

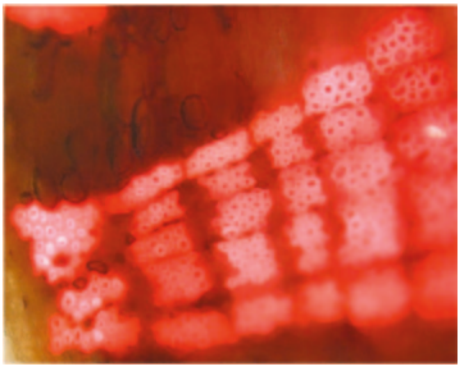

Fig. 6.5 Fibre bundles in the transverse section of the *bast layer* (lignin stain)

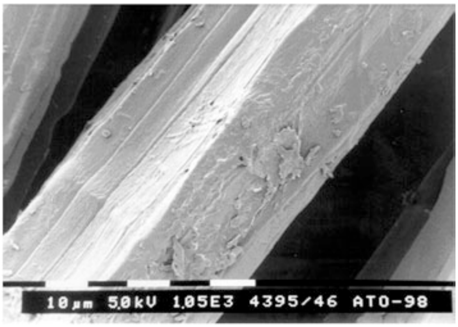

Fig. 6.6 Fibre bundle of kenaf

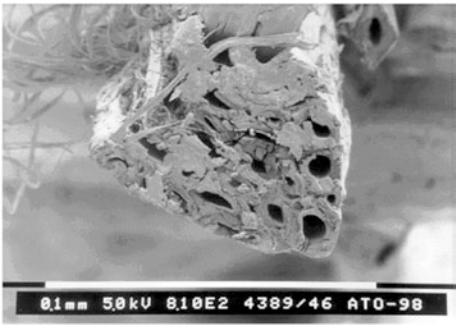

Fig. 6.7 Fracture surface of a fibre bundle

(0.7 %) and galactose (0.4 %), while pectic sugars are arabinose (0.2 %), rhamnose (0.2 %) and uronic acid (3 %). On average, 12 % lignin was also present in those fibres (Reinerink et al. 1998). The woody core contains the same sugars in different proportions: glucose (40 %), xylose (17 %), mannose (1.4 %), galactose (0.7 %), arabinose (0.6 %), rhamnose 0.5 %), uronic acid (6.0 %) and lignin (19 % w/w).

Kenaf bast fibre contains 12–14 % lignin, which is relatively high when compared to flax, ramie and hemp, but comparable with jute. Compared to most

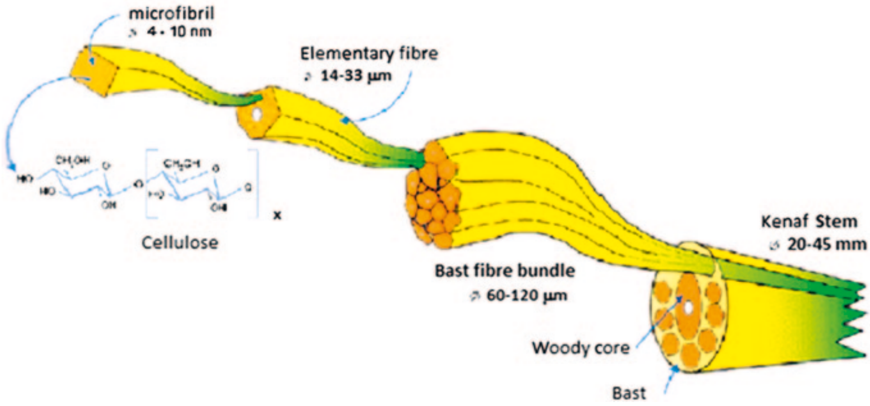

Fig. 6.8 Schematic structural composition of kenaf stem and *bast fibre*

Table 6.4 Mechanical properties of different cellulosic fibres (Reinerink et al. 1998; Eichhorn et al. 2001)

Fibre	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)
Cotton	287–597	5.5–12.6	7.0–8.0
Flax	345–1035	27.6	2.7–3.2
Hemp	690	–	1.6–2.2
Kenaf	580– 750	–	1.3–2.3
Jute	393–773	26.5	1.5–1.8
Ramie	400–938	61.4–128	3.6–3.8
Sisal	511–635	9.4–22.0	2.0–2.5
Abaca	925–1035	–	3.0–4.0
Coir	175–203	4.0–6.0	26–30

woody fibres, this percentage is low. The lignins in the bast fibre and the woody core are different in composition (Seca et al. 1998). Lignin isolated from kenaf bast was shown to be acetylated and have a typical high syringyl to guacyl ratio with predominantly ether linkages (Ralph 1996). Also differences in lignin content are observed between top and bottom of the stem (Nishimura et al. 2002). Other phenolic constituents found in the bast fibres are lignanamides (Seca et al. 2001).

6.3 Processing Kenaf Fibre for Market Products

6.3.1 Kenaf Markets (overview existing applications and trends)

In this chapter, the various traditional and novel applications are reviewed of kenaf fibre fractions in composites, building materials, non-wovens, paper and board and absorption particles. The various post-harvest processes of kenaf stems will be discussed as schematically depicted Fig. 6.9.

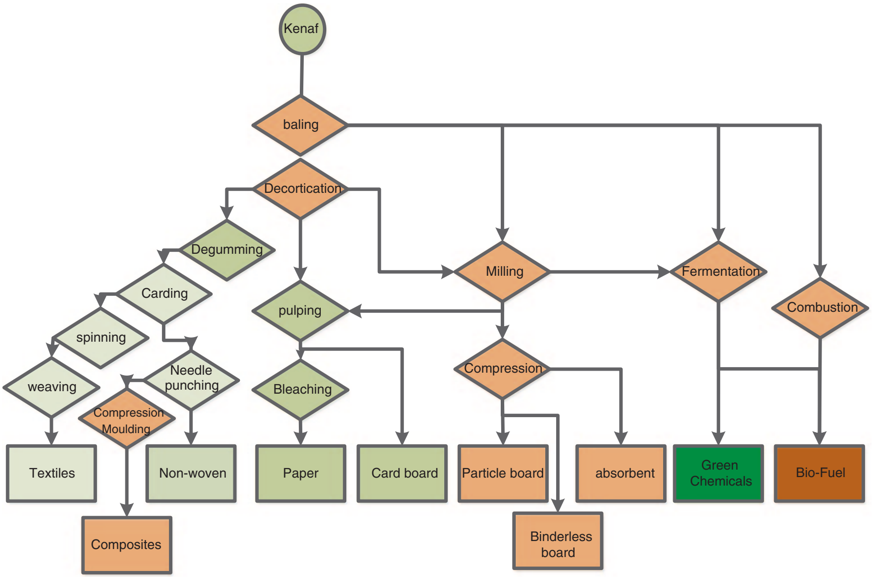

Fig. 6.9 Flow scheme of kenaf fibre processes and products

Table 6.5 Market kenaf products

Product	Fibre form	Fibre price range (€/ton)
Sacking, hessian, canvas	Woven fabric/textile	High 800–2000
Ropes, cordage	Twined	500–900
Composites	Fabric/non-woven/chopped fibre	300–500
Non-woven tissue	Non-woven	200–400
Geotextile	Nets, non-woven	–
Insulation	Non-woven	–
Paper and board	Pulped	400–650
Fibre boards	Refined/milled/chipped	–
Absorbent (moisture/oil)	Core particles/non-woven	–
Green chemicals	Fermented and biorefined	50–100
Bio-fuel, activated carbon	Combustion and carbonised	–
Mulch, compost	Composted	50–100
No data available		

The various commercial outlets for kenaf fibre are listed in Table 6.5. The different applications are clustered according to the fibre form that is utilised and ranked roughly according to their relative market values (Keijsers et al. 2012). Kenaf fibres are suitable and already used for automotive applications for a price of about €500 per ton of cleaned short bast fibres.

In the following chapters, the various aspects of kenaf processing and commercialisation are described.

6.3.2 *Kenaf Bast Textiles and Non-wovens*

6.3.2.1 Textiles

Traditionally, kenaf bast fibre has been processed and used much the same as jute in textile industries to manufacture coarse technical fabrics. Kenaf bast fibre bundles are relatively long and can be processed into yarns and fabrics that are comparable to well-known jute or burlap products such as hessian and gunny bags (Fig. 6.10). For this purpose, they have to be cleaned thoroughly from adhering core (shive) and cortex tissues. Therefore, the stem needs to undergo decortication and retting or degumming processes.

To improve the properties of kenaf in yarn production, the effects of the different retting methods have been investigated (Ramaswamy et al. 1994; Yu and Yu 2010). Removal of the adhering gum or non-cellulosic polysaccharides, without damaging the cellulose fibre structure integrity is important. Traditional water retting in rivers or tanks results in pollution of the surface waters and therefore alternative environmentally sound methods are of interest. Besides microbial methods, enzymatic and chemical degumming processes (alkaline and acidic degumming) have also been described for kenaf fibre extraction. The quality of the fibre bundles (strength, consistency) depends strongly on the method of fibre extraction. Strong fibre bundles are produced when traditional extraction methods are applied after water retting. However, this method is labour intensive and polluting when operated in open ponds. Cheaper separation can be achieved if whole stems are hammer milled followed by separation of the bast and core fibres. This green decortication process affects the strength of the fibre bundles very much due to the harsh mechanical action. The method of harvesting, storage and extraction determines the number of market possibilities. If the fibre bundles are weakened during these processing steps, then only non-textile applications, where strength of the fibre bundles is not important, are possible.

Oxidative degumming with strong oxidising agents was shown to be effective on delignification of kenaf fibre (Yan et al. 2011). The meshiness of the kenaf fibre is an obstacle for the carding process and the production of finer yarns. The resulting hairiness of the fibre is restricting its use to coarse technical textiles. To enhance the performance of the fibres in the spinning process, pre-treatments such as scouring (hot NaOH treatment in the presence of detergent) and addition of batching oils (mineral oil or castor oil) are commonly used.

Bleaching methods of kenaf for textile processing were investigated and described. Bleaching improves the appearance of the textile products and enhances the dyeability. However, it often affects the strength negatively. Mostly, hydrogen

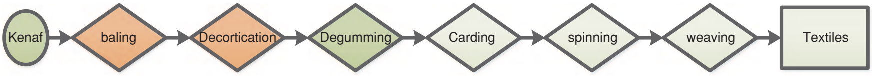

Fig. 6.10 Flow scheme kenaf to textiles

peroxide is applied in addition of surfactants and bleaching enhancers (Jinhua and Ramaswamy 2003). Chlorine bleaching is very effective but undesirable because of environmental restrictions for the use of chlorine bleaching. Softening of kenaf fibres and chemical treatments were performed to improve the blending with cotton in open-end rotor spinning experiments (Zhang 2003). The effects of chemical (alkaline $NaOH/NaHSO_3$) treatment enhanced the fibre fineness. Softness and the elongation at break were improved, but the fibre strength was weakened.

6.3.2.2 Non-wovens

Cleaned and opened kenaf bast fibres (free from core) can be used for the production of non-wovens or felts with or without addition of chemical binders (Moreau et al. 1995). Most common for kenaf fibre non-woven processing are using mechanical entanglement by needle punching or carded air-laid non-woven processes (Fig. 6.11).

Such non-wovens are used as agricultural/horticultural ground covering, filters, and absorbents or insulation mats. In the preparation of kenaf non-woven mats, the influence of pre-treatment was studied of the mechanically separated fibres by alkali (1–2 N NaOH/120 °C, 3 h) or emulsifying agents (vegetable oil) to soften the non-wovens. Both treatments resulted in less stiff kenaf mats (Tao et al. 1995, 1997). Alkali treatment results in finer and more flexible fibres.

Blended with thermoplastic fibres such as PP thermoforming composite products can be manufactured (see Sect. 6.3.5). Kenaf non-woven fibre mats are used for manufacturing of composite materials and automotive parts (Parikh et al. 2002). Sandwich and composite materials, based on Kenaf/PP (70/30) mixtures (Chen et al. 2005), have been tested and show good mechanical, thermal and wet properties. Uniform composites show better mechanical performance than the sandwich structures. In laminated structures, the kenaf non-wovens, blended with PP (80:20), can be applied as wall covering, upholstery cover and overlays (Ramaswamy et al. 2003).

6.3.3 *Kenaf in Building Materials*

Kenaf stems are separated into bast fibre and woody core. Both can be converted into building materials such as different types of fibreboards and insulation

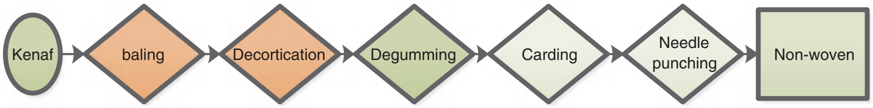

Fig. 6.11 Flow scheme kenaf to non-woven

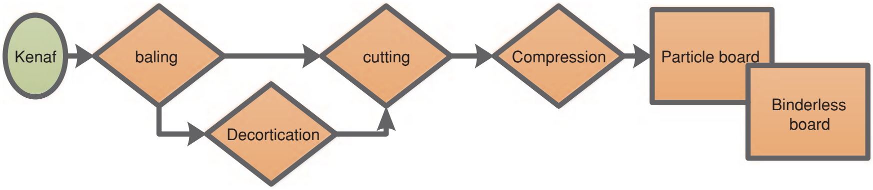

Fig. 6.12 Kenaf to fibreboards

materials. On relatively small industrial scale Kenaf based fibre boards are produced, for example in Malaysia (Fig. 6.12). There the Kuantan plant in Pahang (Panasonic Corp) consumes about 7,000 tons kenaf/year to produce fibre boards, laminated panels and particle boards. More than 90 % of its supply comes from Bangladesh with the remainder from Myanmar, Vietnam and Malaysia. Malaysia currently produces only 2,400 ton/year of kenaf. The factory produces kenaf fibreboard for wall panels and doors. These boards are exported to Japan where they are used as housing and building materials. Kenaf fibreboards are popular for their low weight, strength and eco-friendly characteristics (IJSG 2012a; Chen 2011).

6.3.3.1 Bast Fibre Boards

For fibreboard production, the fibres do not require such extensive cleaning as is common for textile processing. Like other bast fibres, kenaf is less suited for MDF production unless the fibres are refined. Without refining, the fibres are too strong and long and form entangled clusters that will give problems in homogeneous spreading and even mat formation. Kenaf bast fibre has another disadvantage in board manufacturing, being an absorbing fibre that is consuming high amounts of (expensive) glue to form a consistent board product. Therefore, kenaf bast fibre is considered less suitable for resinated fibreboard production.

6.3.3.2 Particle Boards

Particleboards are primarily made of wood residues from saw mills and lumber planing operations (Pearce and sellers 2000). Lightweight particleboards can be produced of separated woody core part or ‘shives’ of kenaf. The internal bond strength (IBS) of 100 % kenaf core board was found lower than reference wood particleboard, but addition of up to 50 % kenaf core to woodchips did not negatively affect IBS (unpublished results FAIR project). However, thickness swelling increased above 30 % substitution (Oliveros 1999). Technically satisfying building boards for interior applications can only be produced from 100 % kenaf core, if the amount of resin is increased substantially. The adhesive is the most expensive component in the manufacture of particleboard and hardboard (Okuda and Sato 2004).

The size distribution of the relatively large kenaf core particles lacks fines (as present in chipped wood and saw dust). This is a disadvantage for particleboard manufacturing, because sanding and trimming are more difficult and consequently lead to a rough surface of the board.

The well-known disadvantage of particleboards for its poor screw holding capacity and drilling is even more difficult with the low-density kenaf core particles. Screw holding capacity of kenaf panels was only 10 % of wood-based MDF panels and about 50 % of low-density particleboard (Sellers et al. 1995).

Kenaf core can be used in particleboard production as a light-weight additive combined with wood chips, especially in boards that do not require high strength; for instance, application in indoor acoustic and thermal insulation panels.

6.3.3.3 Medium-Density Fibreboards

Good strength properties are essential in MDF boards. Substitution of wood by refined kenaf core and whole stem material in the production of medium-density fibreboard (MDF) gave no significant differences in properties up until an addition level of 10 % kenaf core or 50 % whole stem. At higher content, delamination occurred (Oliveros 1999). So application of kenaf core in MDF is possible if added in small amounts, when it can be supplied cheaper than wood chips. The panels using up to 30 % refined whole stem fibres have properties that ‘fit for use’ in many of the key applications (Oliveros 2000).

MDF boards were investigated based on mixtures of kenaf and oil palm empty fruit bunch (EFB). Such boards can be used for furniture components such as table tops and shelves, wall partitions and door panels (Jamaludin et al. 2007). Kenaf-based panels were successfully tested using soybean-based resins, as alternative binders for formaldehyde (UF)-based resins (Soyad®) (Rao et al. 2012).

6.3.3.4 Hardboards

Thermomechanical refining (TMP) of the whole kenaf stem yields a suitable feedstock for hardboard production (Muehl et al. 1999). Hammer milling of the stems should be performed beforehand to facilitate process feeding and to avoid bast fibre clustering in the refiner. Hot pressing of the (7 %) phenol resinated fibres yields panels with satisfactory mechanical performance.

6.3.3.5 Oriented Strand Board

Oriented Strand Board panels were made of kenaf stalks blended with aspen. Boards made with 25 % kenaf, 75 % aspen flakes and 6 % resin were comparable with 100 % aspen boards and also met or exceeded SBA (Structural Board Association) standards (Chow and Bajwa 2005).

6.3.3.6 Laminated Boards

Three layer boards were produced from two rubber wood surface layers and kenaf stem particles in the middle layer. The boards meet the requirements of the Japanese Industrial Standard (Juliana et al. 2012).

6.3.3.7 Binderless Boards

Binderless boards can be produced with finely ground powders of kenaf core. The mechanical properties meet the requirements for MDF (grade 15 by JIS A 5905-1994), but thickness swelling and water absorption exceeded the maximum permitted level (Okuda and Sato 2004). A good internal bond was found, but a poor durability (Xu et al. 2003). Such boards can thus only be used in dry conditions as indoor panels, or in applications such as disposable trays. Outdoor exposure of experimental boards showed somewhat lower bond durability than the commercial MDF. The absence of an added chemical binder was considered to be an ecological advantage (Okuda and Sato 2008).

Kenaf core powder can be used as a natural plywood binder if particles have an average particle size of approximately 10 μm. A high pressing temperature is necessary to melt the solid–solid interfaces between the particles and to supply the activation energy for chemical reactions (Okuda and Sato 2007).

Low-density binderless particleboards from kenaf core showed thermal conductivity values similar to mineral wool. These boards show potential as panels for thermal and sound insulation (Xu et al. 2004). In these applications, binderless panels of kenaf core are more competitive with wood since these are light weight compared to wood.

6.3.3.8 Cement Fibre Boards

Wood(wool) and other cellulosic fibres have been studied in the fabrication of mineral bonded fibre composites. Cement, gypsum and magnesium with these fibres or particles make light weight building products, with good acoustic insulation properties (Simatupang and Bröker 1998). Without pre-treatments, the hydration of cement is seriously retarded when kenaf fibres are added (Ma et al. 2000). Kenaf fibre reinforced concrete (Elsaid et al. 2011) was produced containing 1.2 and 2.4 vol% kenaf. A higher toughness was observed and a good bond with the matrix was obtained. No commercial use of kenaf in mineral composite products is known.

6.3.3.9 Insulation Mats and Panels

Kenaf bast fibres can be processed into non-woven dry laid (needle punched) or resinated mats by conventional technologies. The performance of kenaf mats as insulation material in building application is comparable to other fibre non-woven products on the market (hemp and flax, cellulose). The application in thermal and acoustic insulation products are satisfactory, when precautions are taken for fire retardency, moisture absorption and sensitivity towards moulds and insects (Yachmenev et al. 2006). Thermal and acoustic insulation properties are important in automotive as well as building applications. Non-woven composites made with kenaf and polypropene (PP) show excellent thermal properties according to the ASTM C5188 standard (Yachmenev et al. 2004).

The Italian company KEFI manufactured kenaf insulation mats made of 80 % bast fibres and 20 % thermo-bonding polyester fibres. Such mats showed comparable thermal conductivity to flax fibre mats. However, application of fire retardant salts in the flax mats resulted in hygroscopic behaviour that eventually leads to accelerated microbial decay (Lips and van Dam 2007).

Experimental composite insulation boards of polyurethane (PU) reinforced with kenaf bast were found at a 50/50 mixture to be optimal. Alkali treatment improved the strength but increased water absorption (Ibraheem et al. 2011).

The life cycle impact of kenaf insulation boards was compared with LCA's of various competing insulating products such as polyurethane foam, glass wool, flax non-woven, mineral wool and paper wool. Highest impacts are assigned to synthetic materials, while mineral wools appear to have the lowest. However, kenaf fibre-based products have the least impact if a complete life cycle scenario is considered, including after functional life the incineration with energy recovery (Ardente et al. 2008).

6.3.4 Kenaf Fibre in Pulp Paper and Board

6.3.4.1 Kenaf as a Raw Material for Pulp and Paper Applications

To produce paper, a pulping step is followed by an optional bleaching (depending on the type of paper). The pulp is then transformed into a paper or cardboard sheet (Fig. 6.13).

Extended research has been carried out on the application of kenaf in pulp and paper applications after it had been identified by United States Department of Agriculture (USDA) as the most promising fibre crop for pulp production (Nieschlag et al. 1960a, b; Nelson et al. 1961; Nieschlag et al. 1961). The pulping studies in the USA led to a renewed interest in the 1960s in kenaf in Australia, resulting in agronomic and pulping studies (Wood 1981). In the last decades, research on the use of kenaf for paper pulp production has been continued in Thailand, Malaysia, Indonesia, Iran and China. Shortage of long fibrous wood (softwood) in these countries is a strong motivation for this research (Ang et al. 2010; Dutt et al. 2010; Mossello et al. 2010a, b, c). The Malaysian Government has allocated RM 12 million for research and future development of kenaf-based industry (Edeerozey et al. 2007). In recent years, several authors from Iran published their work on kenaf (Resalati 2009; Shakhes et al. 2011; Zeinaly et al. 2011). The recent research covers chemical and mechanical pulping processes, but also the use of whole kenaf and separated fibre fractions.

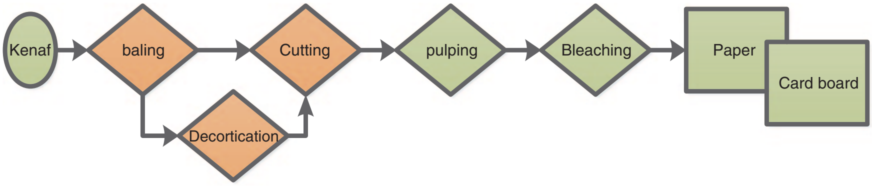

Fig. 6.13 Kenaf for pulp and paper application

6.3.4.2 Pulping Processes

For the conversion of wood or plant fibres for papermaking purposes, these fibres have to be liberated from the embedded structure. Different types of pulping processes are used in industry to purify the lignocellulosic fibre. Most frequently applied are the chemical pulping processes, such as kraft, sulphite and soda pulping. In these processes, the lignin is dissolved and removed from the plant tissue by cooking in alkaline, sulphide or sulphite solutions. After bleaching, this pulp can be used for printing and writing papers. If the bleaching step is omitted, the fibres can be used as wrapping paper. Chemical processes have yields of around 50 % and the produced paper has a high brightness (if bleached) and is strong.

In mechanical pulping processes, fibres are liberated from their plant or wood structure by mechanical forces. With this process, the fibres are damaged heavily, fibre shortening takes place and a lot of fine fibre particles are created. Chemicals and higher process temperatures can be used to optimise fibre properties. As lignin is not removed in substantial amounts, all these pulps have high yields ranging from 85 to 95 %. The presence of lignin causes yellowing of the papers. But these pulps are used in newsprint, where yellowing is not a problem, or in light-weighed coated paper, where the coating prevents yellowing.

Application of fibres in paper production is not unambiguous because hundreds of types of papers are distinguished, all with their own specifications. To reach these specifications, papermakers make their choices from a variety of paper pulps originating from a variety of raw materials. Different pulps are mixed to reach the specifications in the most cost-effective way. Whether a specific fibre such as kenaf is suitable as a raw material strongly depends on the type of paper one wants to produce.

Kenaf chemical pulping

Whole stem kenaf can be transformed to pulps and bleached papers with physical characteristics comparable to those of many woods. At the same dewatering rate on the paper machine (freeness levels), the strength characteristics were superior to hardwoods. Except for tear strength, the kenaf stem pulps were comparable with strength properties of softwood kraft pulps and superior to hardwood pulps (Clark et al. 1962). Yields varied between 45 and 48 % for unbleached pulps and 41–43 % for bleached pulps, which is about 5 % lower than the yields of wood pulps (Clark and Wolff 1965). In 1970, the technical applicability was demonstrated in a pilot run on a paper machine with a furnish of 60 % mixture of softwood and hardwood fibres and 40 % of kenaf kraft pulp (Clark 1970).

In soda and kraft pulping, core pulps showed low strength and could only be improved at unacceptable high drainage times. Bast fibre pulps showed good tensile strength and very good tear strength. Production of neutral sulphite semi-chemical (NSSC) kenaf pulps for linerboard was considered most economic. NSSC kenaf bast fibre pulps had excellent tearing strength and good bonding strength, comparable with those of chemical pulps, which makes these pulps suitable for linerboard (Gartside 1981). NSSC pulps from core showed lower tearing strengths but higher bonding strengths than most chemical pulps. Without blending these pulps with higher strength pulps, they can only be applied in corrugating papers. Because of the different behaviour of the two types of fibre in CTMP processes and PFI beating response, separate processing was recommended (Law et al. 2003).

Soda-Anthraquinone pulp of kenaf whole stem showed intermediate properties of core and bast pulps and close to those of unbleached softwood pulps but lower energy was needed for beating (Mossello et al. 2010a, b, c). Paper properties were found to be better and production costs of whole stalk pulps are considered more economic compared to separated bast and core fractions (Mossello et al. 2010a, b, c; Ibrahim et al. 2011). Continuous kraft cooking gave high yields of good quality whole stalk kenaf pulp. The pulp properties approached hardwood pulps and could be easily bleached (Yu et al. 2011).

Chlorine free bleaching of kenaf by pre-treatment of soda AQ pulp with white rot fungi (*Phanerochaete chrysosporium*) was studied. The biobleaching combined with alkaline extraction and peroxide treatment gave higher brightness, opacity, yield and strength as compared to conventional chlorine bleaching (Nezamoleslami et al. 1998).

Kenaf mechanical pulping

The advantage of mechanical pulping over a chemical process is that production scale can be much smaller. Because of the limited size of the refiners that are used in this process, large scales do not bring as much profit as with chemical pulping. Mechanical pulps have a high yield, but demand high input of (electrical) energy. Due to this high energy requirement, mechanical pulp mills are normally integrated in a paper mill. The surplus of steam generated in the refining process is used in the paper mill. Due to this integration of pulp and paper mills, the amount of mechanical pulps on the market is very limited. In 2011, only 3.2 million tons (8 %) of the total world production of 39 million tons of mechanical pulp was available for the market (FAO 2011).

The strength properties of pure kenaf Thermo Mechanical Pulp (TMP) were very poor, but peroxide bleaching of the TMP pulp greatly improved the strength properties (Touzinsky et al. 1980). This bleaching raised the brightness to newsprint level (Cunningham et al. 1979).

Handsheets made of a mixture of bleached kenaf TMP and 10–15 % of kenaf soda chemical pulp showed strength properties comparable with commercial newsprint. However, on a laboratory paper machine trial in 1977, this ratio of pulps formed a mat that tended to pick to the press and only sheets of high basis weights could be formed. By increasing the amount of this kenaf chemical pulp to about 35 %, a paper web with low basis weight and desired strength could be made (Bagby et al. 1979).

With kenaf bast, satisfactory Refiner Mechanical Pulps (RMP) pulps could be produced for use in furnishes for newsprint. A sulphite pre-treatment resulted in a small increase of the strength properties. Alkaline sulphite CTMP pulping of kenaf core resulted in much poorer pulps than bast fibre pulps. Alkaline sulphite CTMP pulping of the whole kenaf stem gave satisfactory pulps with a reasonable balance between strength properties and drainage rate (Puri and Higgins 1981). Whole kenaf RMP improves mechanical properties of newsprint (Mohta et al. 2004).

Alkaline peroxide mechanical processes (APMP) is one of the mechanical pulping processes. The addition of NaOH and H_2O_2 reduced the energy requirements to 50 % compared to TMP pulping (Lawford and Tombler 1982; Myers and Bagby 1995). The paper strength properties were between newsprint and printing and writing papers. Brightness was too low for printing and writing papers. APMP pulps from whole kenaf give higher paper tensile strength at the same density, or the same strength at a higher bulk than aspen pulp (Xu 2001).

Biomechanical pulping of kenaf, using fungal pre-treatments also reduces the energy demands with 38 % compared to RMP pulps, while the strength properties of the paper improved (Ahmed et al. 1999). The brightness was reduced, resulting in a higher hydrogen peroxide demand during bleaching.

6.3.4.3 Kenaf Paper Commercialisation

Commercial-scale paper machine trials

The commercialisation activities of kenaf in newsprint application in the USA were reviewed (Kugler 1988, 1996). In 1978, 22 tons of CTMP pulp of kenaf was produced at C.E. Bauer, Springfield Ohio. Severe erosion by metal, stones and sand required replacement of refiner parts already after 12 production hours (Hodgson et al. 1981). The kenaf pulp was sent to International Paper's Pine Bluff mill in Arkansas for a paper machine trial. The paper machine ran without problems on a mixture of the kenaf pulp and 8–25 % of kraft pulp. The strength of the produced kenaf paper was higher than that of the control. Smoothness was comparable and porosity was lower. The brightness of the sheet was considerably higher, with a corresponding lower opacity. Printing of the newsprint paper was successfully tested but the opacity and print through were identified as a problem (Hodgson et al. 1981).

Despite problems in the pulping stage, the paper and printing machine runs went well. This illustrates the importance of providing a clean raw material. Harvesting and handling of kenaf, needs to yield a clean quality product. Washing and cleaning also reduces the amount of metals that disturb the peroxide bleaching (Lawford and Tombler 1982). Cubing of the chopped kenaf to reduce transport costs will make the removal of contaminants in a later stage almost impossible.

Depending on soil and fertilizer use, the ash content of clean kenaf varies between 2 and 6 % (D'Agostino et al. 1996; Neto et al. 1996), whereas the ash content of wood is much lower.

In 1981, a second commercial-scale newsprint trial was conducted at International Paper in Mobile,Alabama. It was the first time that kenaf fibre handling, pulping and newsprint manufacture took place in continuous steps. It demonstrated the feasibility of design and operation of a newsprint system based on kenaf (Kugler 1988; Taylor 1993).

In 1987, a new commercial-scale production trial was performed by Sprout Bauer (CTMP pulping) and CIP Inc (Canada) newsprint manufacturing. The paper was made of 82 % whole kenaf stem CTMP and 18 % kraft pulp (balsam and spruce). The paper had superior strength to southern pine newsprint and the opacity equal to or better than western newsprint. Printing of the paper went smoothly and the kenaf prints were brighter and had more contrast than the best quality newsprint normally used (Kugler 1988).

The economic and technological feasibility for a kenaf newsprint system was demonstrated (Kugler 1988). One of the major problems still remaining is to get the bulky kenaf to the mill and the space needed to store it for 6–8 months (Young 1987).

The 1990 ASRRC workshop (Wood et al. 1990) acknowledged that markets were available for the various kenaf pulps in Australia. However, entrenched conservatism of the pulp and paper industry would make it very difficult for a new product to penetrate the market unless it had significant advantages in either price or quality.

In 1990–1991, three mills in the US started mechanically separating the core and bast fibres and sell it for use in different products. Products range from high quality printing and writing paper from bast fibre to adsorbents and horticultural mixes from core fibre (Kugler 1996). Starting in 1992 Vision Paper produced tree-free printing and writing paper from kenaf bast fibres (Vision Paper 2010). The small scale and batch pulping make the kenaf paper more expensive than traditional printing and writing paper (Kugler 1996).

Different new efforts were made to build a kenaf newsprint mill (Pulp and Paper Online 1997; Rymsza 2000). In 1998, the planned capacity was increased to 110,000 tons/year (Pulp and Paper International Online 1998), however, due to financial problems the plans were abandoned.

Commercial application of chemical bast fibre pulp.

In the USA, Vision paper produced 100 % kenaf paper and paper made from a mixture of recycled paper and kenaf bast fibre chemical pulp on a small scale. The price of the kenaf bast fibre pulp, that is used, is more than three times as high as the price of wood pulp. Separation of the bast fibre is not complete as it still contains 20 % of core fibre. The small scale of this process together with the infant status of the kenaf industry were the major reasons for this price difference (Rymsza 1998a, b). The price of kenaf pulp is expected to drop due to yield improvements and adapted pulping technology.

Vision paper sells its paper products as tree-free total chlorine free printing and writing paper that has environmental benefits. Customers may agree on that, but only a small part is willing to pay the extra costs. High prices bring low volumes, but volumes must increase to lower the prices (Rymsza 1998a, b).

Some Japanese paper mills are known to use kenaf in one of their products (Vision Paper 1999). Globally, only ca. 15,000 tons of kenaf pulp (or 0.05 %) was used in the total production volume of 30 million tons of paper (Sato 2001).

Commercial application of chemical pulp from whole kenaf stem.

Phoenix pulp mill in Thailand started in 1981 with whole stem kraft pulping at a capacity of 200 ton/day (Taylor 1993). Situated in an agricultural area and lack of local forests, kenaf was expected to be competitive with wood. They experienced problems in getting a guaranteed supply of good quality at an affordable price. In the first operating years, the price went up to twice the amount that was estimated (Roberts 1996). The mill switched to other raw materials (Kaldor 1990) and in 2006 this mill converted plantation-based eucalypt, bamboo and kenaf to chemical pulps. However, kenaf pulp contributed only 5 % of Phoenix total pulp production (Phoenix 2004, 2008). The use of whole kenaf stem makes the raw material much cheaper than using separated bast fibre (Paul 1991).

Specialty papers

Specialty papers are produced in small quantities with very specific requirements. Examples of specially papers are cigarette paper, Bible paper, filter paper, banknote and security papers. The usual fibres used in those types of papers are cotton, flax, hemp and abaca. No actual use of kenaf in this type papers is known today. Schöller and Hoesch GmbH (Germany) conducted trials with kenaf and concluded that kenaf can be used for specialty cigarette and filter papers (Sholton 1981).

Cellulose dissolving pulp and nano-whiskers

Preparation of dissolving pulp from kenaf is technically possible, but not reported often in open literature. The dissolution and rheological behaviour of kenaf bast fibres in N-methylmorpholine-N-oxide (NMMO) was compared to other fibre pulps (Collier et al. 2000). The viscosity of kenaf fibre was lower than of dissolving pulps due to the presence of lignin and low molecular hemicellulose. Ionic liquids (e.g. various imidazolium salts) were combined with ultra-sonication for enzymatic assisted saccharification of kenaf (Ninomiya et al. 2012).

Isolation of kenaf cellulose assisted by ultrasound irradiation yielded ca. 25 % highly pure cellulose (Pappas et al. 2002). The crystallinity of ultrasonicated kenaf cellulose was only slightly lower (30 %) than found by traditional isolation methods (31 %). The X-ray crystallinity index of kenaf nanofibres (10–90 nm diameter) was determined to reach 81.4 %, while raw kenaf was only 48.2 % (Jonoobi et al. 2009).

Cellulose nanocrystals (CNC) were isolated from kenaf bast by subsequent alkali bleaching treatment followed by sulphuric acid hydrolysis (65 wt%, at 45 °C and 40 min). Crystals (CI 80 %) were obtained at relative high yields with dimensions of ca. 12 nm width and 150 nm length (Kargarzadeh et al. 2012). A stepwise procedure to obtain cellulose nanowhiskers with fibre length between 100–1,400 nm and diameters between 7 and 84 nm from kenaf bast was described (Shi et al. 2011).

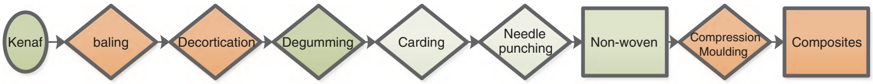

Fig. 6.14 Kenaf to polymer composites

6.3.5 *Kenaf Fibres in Polymer Composites*

Kenaf bast fibres are used as reinforcement or filler in polymer composite materials, where they compete with fibres such as flax, hemp and jute in quality and price (Summerscales et al. 2010). The automotive industries form an increasing market for natural fibre-based composites (Jeyanthi et al. 2011; Hao et al. 2012). Natural fibre composites are used in automotive applications primarily because of the light weight and end-of-life properties (recycling) (Jeyanthi et al. 2012). In this application, non-woven fibre mats are the basis of the interior automotive parts such as headliners, wall panels, trunk liners and hoods. Kenaf and jute fibre, compressed with thermoforming PP fibre, are often used in this industry, but the amount of kenaf is unspecified (Karus et al. 2006). In the last decade, much research on composites with different matrices were published. Besides polypropylene as reinforcement, kenaf fibre was tested in polyester (UPE), polyurethane (UR) (El-Shekeil et al. 2012) and epoxy (Yousif et al. 2012).

6.3.5.1 Technical Aspects

Interfacial adhesion between hydrophobic polymers and the hydrophilic cellulosic fibres of kenaf is critical for the mechanical properties of the composite products (Akil et al. 2011). The moisture content of the fibre is critical for the performance of most composite products. Different methods of composite manufacturing are applied in industries. Thermoplastic matrix fibre composites are manufactured by thermoforming, compression moulding or sheet moulding of multilayer polymer sheets and fibre non-woven mats (SMC) (Fig. 6.14). Alternatively compounded fibres and thermoplastic matrix granules are used for injection moulding parts. A compounding and injection moulding process for natural fibres and thermoplastics was developed (Snijder and Bos 2000; Snijder et al. 2003) and commercialised. Thermoset resins (PF, MUF, epoxies, polyesters, silicone) are processed most often by hand layup laminating procedures or by resin transfer moulding (RTM) (Rassmann et al. 2010) and pultrusion (Nosbi et al. 2010), followed by a high temperature curing.

Surface treatments such as NaOH extraction or silane coupling agents are widely used to improve the adhesion (Dittenber 2012). Treatment of the fibre with coupling agents (isocyanate/epoxidised soybean oil) improves the mechanical properties of compression moulded kenaf UPE composites (Ren and Li 2012).

6.3.5.2 Thermoset Resins

Epoxy resin with natural fibres is brittle, but addition of epoxidised natural rubber gave significant improvement of epoxy loaded with 20 % kenaf fibre (Abu Bakar et al. 2012). Other additives such as isocyanate cross linkers and MMT (Montmorillonite) filler have been studied to enhance the performance (Zuliahani et al. 2011). The mechanical properties of kenaf epoxy composites improve significantly by pre-treatment of the kenaf fibre with alkali (Abu Bakar et al. 2010).

Recycled PET (bottles) yielded unsaturated polyester resin (UPR) that was processed with different kenaf fibres (Farahani et al. 2012). Alkali treated fibre showed best interaction with the UPR. Sheet moulding compounds (SMC) of kenaf fibre reinforced with unsaturated polyester (UPE) show less impact strength than glass fibre SMCs (Du et al. 2010). The water absorption of such composites affect the mechanical properties dramatically (Rashdi et al. 2010). Drying of the fibres to 1–2 % moisture was performed for better curing of UPR kenaf composites manufactured by the RTM method (Rouison et al. 2004). Also fibre grafting with acrylamide N-methyol-acrylamide (NMA) enhanced the flexural modulus and water uptake of UPE composites (Ren et al. 2012).

Sandwich composites of kenaf fibre and (soy oil based) polyurethane foam were found suitable as substitutes for plywood in bus flooring applications (Munusamy et al. 2012).

6.3.5.3 Thermoplast

Compounding of kenaf fibre with PP by extrusion gives reduction of flexural strength, but enhances the modulus (Rozman et al. 2012). Compatibilising kenaf and the PP matrix has been achieved by using maleinated polypropylene (MAPP) (Law and Ishak 2011). Addition of MAPP as coupling agent increases mechanical properties of kenaf PP compounds significantly (Sanadi et al. 1995; Saad 2012). Also on kenaf thermoplastic elastomer composites with addition of impact modifiers (EPDM/TPNR) the addition of MAPP imparts mechanical effects (Anuar and Zuraida 2011). Maleic anhydride based compatibilisers (PE-g-MA) also had positive effects on the strength of polyethylene (LDPE) blended with sago thermoplastic starch composites with kenaf fibre reinforcement (Majid et al. 2010). The addition on the kenaf surface of zein as coupling agent was reported to have positive effects on the viscoelastic properties of the fibre PP composite (John et al. 2010). PP thermobonded kenaf fibre boards showed enhanced processability at high fibre loads (85 %) with the addition of small amounts of glycerine (Sanadi and Caulfield 2008).

6.3.5.4 Biopolymer Composites

Polylactic acid (PLA) as renewable and biodegradable polymer is gaining much attention as green product, also in combination with cellulosic reinforcements

(Nishino et al. 2003; Nyambo et al. 2010). Kenaf fibre PLA composites are prepared by melt blending and compression moulding, showing increase of flexural strength (36 %) and modulus (54 %) compared to pure PLA. The impact strength improved (60 %) at a maximum of 40 % kenaf fibre content (Tawakkal et al. 2012). Other studies show decrease of impact strength, but high tensile modulus at 20 % weight of kenaf in PLA (Graupner et al. 2009; Anuar et al. 2012). Alkali treatment of kenaf improved the fibre matrix interaction substantially (Neoh et al. 2012). Addition of low amounts of nano-cellulose improved mechanical properties of PLA kenaf fibre composites (Sukyai et al. 2012). Plasticising of PLA with PEG (10 % Polyethyleneglycol) shows decrease in tensile properties of kenaf PLA composites (Taib et al. 2010). Biodegradable composites were studied using kenaf fibre reinforced poly-L-Lactic Acid (PLA).

Thermoset resin composites of kenaf fibre with biobased poly(furfuryl alcohol) resin were studied (Deka et al. 2012) and shown to have good fibre matrix interactions and low water uptake. The mechanical performance of phenol formaldehyde (PF) thermoset resin composites with kenaf was studied with the addition of fiberfrax® ceramic fibre (Öztürk 2010).

Kenaf fibre has also been studied in combination with various other biodegradable or biopolymeric plastics such as PHA (Buzarovska et al. 2007), PBS (Liang et al. 2010) or ecoflex (Ibrahim et al. 2010). Biocomposites were also prepared from cellulose diacetate and kenaf fibres, sized with polyvinylalcohol, that gave better adhesion of the fibre to the matrix (Lee et al. 2010). Chitosan plasticised with glycerol and filled kenaf fibre gave flexible films (Julkapli and Akil 2010). Composites with natural rubber and kenaf fibre were investigated for the mechanical properties. The modulus is affected by particle size, fibre orientation and fibre content. This results in stronger and harder composite material (Raju et al. 2008).

The environmental impact of kenaf based composites was studied and compared in an LCA study on PHB-kenaf and PP-glass fibre used in automobile parts. Reduction of non-renewable energy and greenhouse gas emission savings are the main benefits, while impact factors such as photochemical smog, acidification, and eutrophication are higher than for glass fibre composites (Kim et al. 2008).

6.3.5.5 Economic Aspects

The use of agricultural fibres in the automobile industry is increasing. In a growing number of car parts, glass fibres have been replaced by natural fibres (Kaup et al. 2003). In Western Europe, ca. 25,000 tons of natural fibres are being used in compression moulded car parts (SMC). In this industry, from which 2/3 is applied in Germany and Austria (Fig. 6.15). Injection moulding technique for natural fibre composite production is gaining interest and used at ca. 4,000 tons/year in EU (Carus and Gahle 2008). This market is growing globally. When all cars produced would contain 5–10 kg of these natural fibres, the market potential would be exceeding 100,000 tons each year. The contribution of jute and kenaf to this application is substantial; however, distinction between those two is not made.

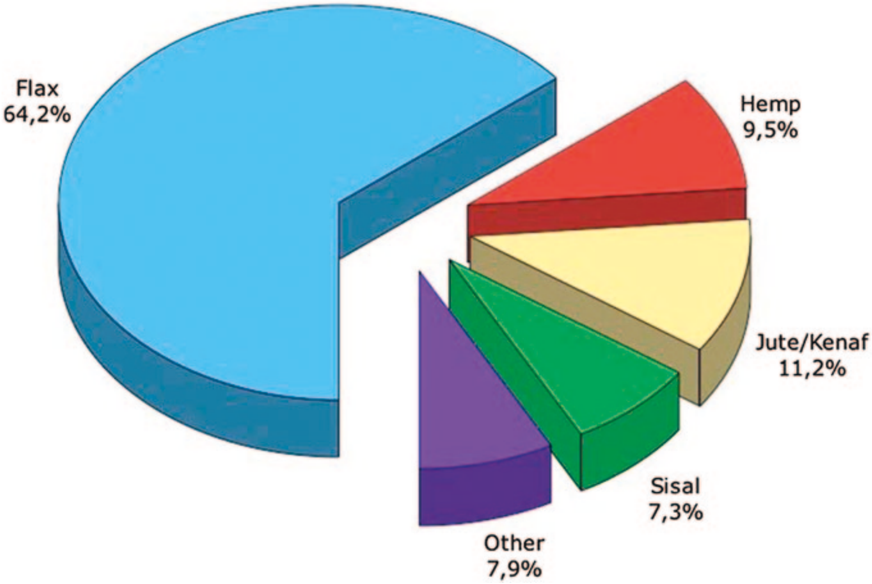

Fig. 6.15 The use of natural fibres for automotives in Germany (Kaup et al 2003, 2006)

The fibres that are commonly used in this industry are cleaned bast fibres of lower grades that are not long enough for textile spinning purposes.

For the production of compounds for the automotive industry the kenaf bast fibres are technically competitive with other natural fibres. They can also be competitive in price if production costs are low, i.e. by a high kenaf yield or low agricultural costs, high bast fibre ratio in the stem, or a high added value application of the core fibres, which forms the main part of the kenaf stem.

6.3.6 Kenaf Absorption Particles

If bast fibres are to be separated a profitable outlet for the kenaf core fibre is necessary to prevent that the bast fibre will become too costly. Separated core fibres are less suitable for the production of pulp and paper and one possible building application is found in insulation panels. Another likely application is the use of core fibres as absorption particles as animal bedding (Green-Natural-Fibres 2012) and as oil absorbent (Zaveri 2004).

6.3.6.1 Animal Bedding Material

Kenaf core fibres are used as bedding material for horses, cattle, and rodents (Watkins 1994). One of the criteria of bedding material is that the animals do not eat it (Green-Natural-Fibres 2012) (KEFI 2006). The core will absorb about 4 times its own weight of water, with the most coarse fraction absorbing the highest amount (Lips et al. 2009). Manually separated kenaf pith showed 20 times its weight of water absorption. Flax and hemp core fibres are also sold as horse bedding material. These bedding materials are pressed in small bales of 15–25 kg and packed in plastic, or delivered as bulk material. Transportation costs of this bulky product plays a major factor in the actual price and competitiveness of kenaf core to other available bedding materials. As animal bedding material must have a low dust content, the kenaf core has to be cleaned from fibre and dust.

6.3.6.2 Oil Absorbants

Kenaf core fibre can also be used as an oil absorbent. Kenaf fines are excellent sorbent materials comparable to commercial sorbent materials (Goforth 1994). Kenaf has the same sorption capacities and a higher retention capacity as polypropylene (Anthony 1994; Ghalambor 1995). Kenaf core performs as well as a polypropylene web does in sorption of high-viscosity oil from seawater (Choi and Cloud 1992). The US Naval facilities engineering service center recommended to preferably use kenaf absorbent where feasible (NFESC 1999).

Three different sized kenaf core particles were compared to straw, wood shavings and core particles of flax and hemp for their absorption of motor oil. The size of kenaf core particles affects absorption. When all these materials were milled to smaller than 2 mm kenaf core showed highest absorption capacity. The absorption capacity range of all milled materials was between 3.3 and 3.9 g/g (Lips and Dam 2007). Kenaf pith absorbed 6 g oil/g and by milling an increase to 25 g oil/g pith was realised, which is 6 times the core absorption.

Commercial kenaf bast fibre non-woven mats (density 31 kg/m^3), thermoformed with addition of 20 % polyester fibres, absorbed about 13 times their own weight of oil. Increasing the mat density enhanced the absorption capacity to maximum 15 times its own weight. Reuse of the standard commercial mats, after pressing out the absorbed oil, showed a loss of a quarter if its oil absorption capacity, because the oil could not be pressed out completely. When the soaking and pressing cycle was repeated four times, the absorption capacity remained constant during 10 cycles (Lips, unpublished data).

6.3.7 Lignocellulosic Biorefinery and Green Chemicals

Kenaf plays so far only a modest role among the biomass resources, which are studied concerning the developments related to biorefinery of biomass for energy and ‘green’ chemicals. Most attention goes here to abundant agricultural residues, such as sugar cane bagasse and corn cobs, rather than to non-food crops. Nevertheless, some research in whole crop utilisation and into thermochemical conversion of kenaf stems has been described. The fresh leaves are traditionally used as local vegetables and have value as nominal feed. The oil from the seeds is locally used as lubricant, and for the manufacturing of soaps, linoleum, paints and varnishes.

Alternative uses of kenaf stems and non-woven products in horticultural applications were reported. In the production of soilless turfgrass sod (Hensler et al. 1998), kenaf use was described. Kenaf-based growth media were tested as horticultural substrates, but showed inhibition of plant growth (Tsakonas et al. 2005). This property may have advantage in weed control and soil covering.

Thermochemical conversion and pyrolysis of kenaf is reported in several analytical assessments by pyrolysis combined with mass spectrometry. The heating value was assessed of kenaf process residues in fluidised bed gasification processes (Zhou et al. 2009; Irmak and Öztürk 2010) and considered of low efficiency for power generation. The relative high content of (carbon rich) ash was noted. In pyrolysis, the total oil yield is relatively high compared to other energy crops (like Miscanthus, Arundo, Switch grass, straw ~45–55 wt%), but low compared to wood (~70 wt%). Combustion of the kenaf oil may result in high NOx emissions (Alexopoulou 2008). Carbonisation of kenaf stems at 1,000 °C in inert atmosphere yields microporous carbon with high surface area (>1,000 m^2/g) (Inagaki et al. 2004). Such activated carbon from kenaf may be used for applications like heavy metal removal and filtering (carbonised char).

6.4 Kenaf Resources and Bioeconomic Prospects

Due to different market constraints, a serious decline of most natural fibre commodities other than cotton is observed in the past half century. The actual production of kenaf in recent years is mainly focussed in China, India and Thailand (Table 6.6), while the contribution from other countries is quite small. In other East Asian countries like Vietnam and Indonesia, some fluctuating kenaf production capacity is observed. The kenaf production data of Thailand reflect the dependency of primary production on the demand for supplies of raw material of the fibre processing industry. The dramatic decline since 1997 is reflected by the shift to a competing raw material in one relative small pulp mill. The capacity of a modern paper pulp mill is considered small when less than 200,000 ton/year pulp is produced. Non-wood pulping is commonly operated at smaller scales (35–70,000 ton/year), due to logistic constraints for annual crops that are harvested seasonally. Security of whole year round supplies of kenaf raw material is a big issue for bulk production of kenaf papers and other bulk market products. Issues of (dry) storage and contracts with farmers need to be solved.

In Latin America, a rather stable production of no more than 10,000 tons/year of kenaf is reported from Cuba which feeds the spinning mills for production of sacking. For bast fibre spinning mills (Jute spinning in Bangladesh), a production capacity of 10,000 tons/year is the average. In Brazil, the productivity is in the same modest range but has halved in recent years.

Table 6.6 World production of Kenaf and Allied fibre from 2003/2004 to 2010/2011 in 1,000 tonnes (1 tonne = 1,000 kg)

Kenaf and allied fibre	2003/2004	2004/2005	2005/2006	2006/2007	2007/2008	2008/2009	2009/2010	2010/2011 (provis.)
World	377.29	351.83	327.58	314.4	329.12	279.8	290.1	284.1
Dev. Countries	370.29	344.83	320.58	307.4	322.12	272.8	283.1	277.3
Far East	329.88	302.02	264.32	250.51	266.06	217.3	227.6	234.5
China	99.78	86.92	82.82	68.8	86.8	80	80	75.0
India	167	156.4	153	144	139.7	120	131.2	140.0
Indonesia	7	7	7	3.1	4	3.8	3.8	4.0
Thailand	41.33	35.66	4.6	3.6	2.2	2.9	1.8	1.8
Vietnam	12.5	14.2	15	10.6	31	8.8	9	12.0
Cambodia	0.65	0.65	0.65	0.83	0.85	0.3	0.3	0.2
Pakistan	1.62	1.19	1.25	1.59	1.51	1.5	1.5	1.5
Latin America	24.01	25.91	39.37	39.91	39.07	38.5	38.5	27.5
Brazil	10.5	12.65	26.1	25.95	25.66	25.1	25.1	15.0
Cuba	10	10	10	10	10	10	10	10.0
Other	3.51	3.27	3.27	3.96	3.41	3.3	3.3	2.5
Africa	12.7	13.2	13.19	13.29	13.29	13.3	13.3	11.7
Near East	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.6

Source Food and Agriculture Organization (FAO), (IJSG 2012b) website

Reported imports of kenaf fibre for automotive applications from Bangladesh are not found in the trade statistics and are included in the market data for jute productivity. The R&D promotion of the Malaysian Government to promote kenaf crop production so far has not yet affected the market demand on large scale.

6.4.1 Statistics Kenaf Production Trends

In most countries, a steady decline of production of jute and allied fibres can be observed over the past decades. For kenaf, the world production volume has declined from more than one million ton/year in 1990 to 290 k ton/year in 2009. The kenaf statistics indicate a dramatic decline (Fig. 6.16) of the world production to one-third of the productivity levels before 1990. Only when the different markets as described for kenaf in the previous paragraphs can be established on a viable scale, this declining trend may be reversed. When the policies for the transition from a petroleum-based economy to the biobased economy are to be implemented, increased demand for cellulose resources has to be anticipated for (Keijsers et al. (in print) 2012). Current innovation in the markets for natural fibre containing (composite) products has widened the scope of its use and that will be reflected in agro-industrial developments. Then it has the potential to become a major sustainable bioeconomic commodity again (van Dam 2009).

Kenaf, as one of the established high yielding fibre crops has the potential to recover to previous production levels of above one million tons/year. Therefore,

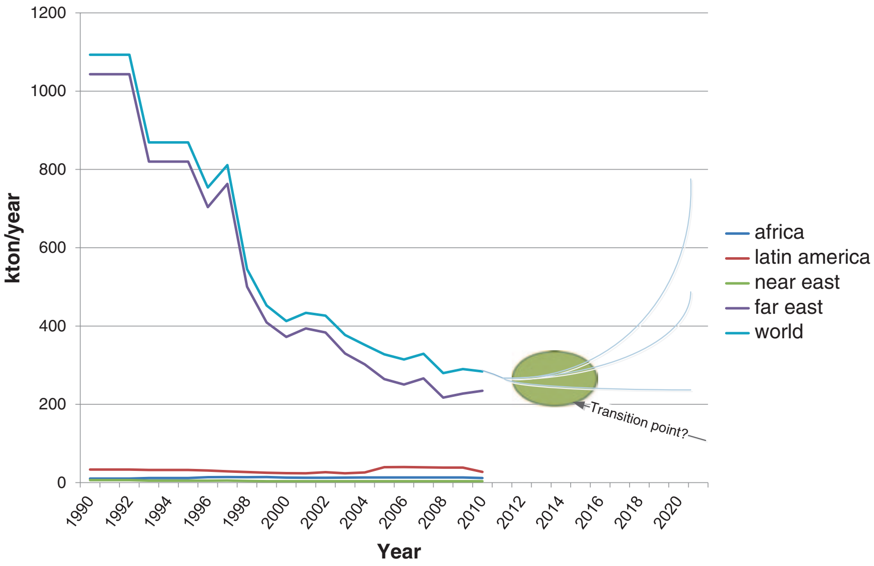

Fig. 6.16 The global kenaf production statistics and prospect scenarios for 2020

investments in modern industrial conversion processing needs to be promoted. This requires combination with the organisation of a qualified supply chain logistics and market product development. This means an organisation of quality grading of fibre products and half-products on international level combined with certification of the sustainable production chains.

6.4.2 Conclusions on Kenaf Markets

The markets with prospect of absorbing kenaf fibre crop in substantial volumes are ranging from the traditional textiles, non-wovens and paper pulp production, to fibre composites in building and automotive industries. In many applications, kenaf will have to compete on price with wood, while kenaf fibres also compete technically with the almost similar jute fibres.

Regarding application of kenaf in building materials, it can be concluded that different applications can be identified:

1. Kenaf bast fibre as such is considered less suitable for resinated fibreboard production.
2. In particleboards, kenaf core will not fulfil minimum strength requirements and will therefore not be competitive with boards made from wood.
3. In Medium Density Fibre (MDF) boards, substitution of wood by kenaf core is possible in small amounts (up to 10 %).
4. In MDF boards, substitution of wood by whole stem kenaf is possible up to 30 %.
5. Application of kenaf core fibre was shown to be technically feasible in binderless pressed panels for thermal and sound insulation.
6. Kenaf bast fibre is suitable for application in thermal and sound insulation mats.

Implementation of these products in building practice could absorb substantial volumes of fibre raw material.

Technically, it is possible to use kenaf raw material for production of different types of pulp and paper; however, the economics of using kenaf compared to wood are mostly in favour of wood (Myers and Bagby 1995). In spite of good prospects in applying kenaf as a raw material for high yield pulps, a persistent commercial-scale pulp mill has not been realised. High investment costs and the need for reliable supply of kenaf, result in high risks. Large-scale applications of kenaf in the softwood dominated pulp and paper industry are not likely to happen in the near future.

Cleaned kenaf bast fibres are already used in sheet moulding composites made from non-woven fibre mats and plastics for automotive industries. The current volume used in the German car industry is probably not exceeding 1,000 ton/year but increased use of cellulosic fibre composites is expected. Also the production of compounded granules from natural fibres and plastics has been commercialised. Lower quality fibre can be used in this process without affecting the quality of the composite. Kenaf fibre can be used for product manufacturing in the following market segments:

1. Automotive industry is using agrofibres as a substitute for glass fibre reinforcement in thermoplastic and thermoset composite parts, such as door panels, but also construction materials such as hoods, roofings and dash board panels.
2. Packaging materials such as crates, pallets, boxes, cases and trays for transport and export of agricultural products (mango's, fish, tea, etc.).
3. Engineering packaging for protection during the transport of consumer-electronics, refrigerators, etc.
4. Consumer plastics: toys, furniture and parts of electronics.

Kenaf and especially the core was shown suitable as bedding material for animals and as oil sorbent suitable for cleaning oil spills and is actually sold for these purposes.

So technically the use of kenaf in different consumer products has been demonstrated and when supplies of kenaf raw materials match the demand of industries, it may play a significant role in the bioeconomic developments.

References

Abu Bakar MA, Ahmad S et al (2010) The mechanical properties of treated and untreated kenaf fibre reinforced epoxy composite. J Biobased Mater Bioenergy 4(2):159–163

Abu Bakar MA, Ahmad S et al (2012) Effect of epoxidized natural rubber on mechanical properties of epoxy reinforced kenaf fibre composites. Pertanika J Sci Technol 20(1):129–137

Adnan H (2010) Kenaf plant has profitable business potential. http://biz.thestar.com.my/news/story.asp?sec=business&file=/2010/4/27/business/6121868

Ahmed A, Akhtar M. et al (1999) Biomechanical Pulping of kenaf. 1999 Pulping Conference Proceedings

Akil HM, Omar MF et al (2011) Kenaf fiber reinforced composites: a review. Mater Des 32(8–9):4107–4121

Alexopoulou E (2008) Kenaf booklet—prepared in the framework of the BIOKENAF project—EU contract QLK5-CT2002-01729 Biomass Production Chain and growth Simulation Model for Kenaf CRES-A&F and others

Ang LS, Leh CP et al (2010) Effects of alkaline pre-impregnation and pulping on Malaysia cultivated kenaf (*Hibiscus cannabinus*). BioResources 5(3):1446–1462

Anthony WS (1994) Absorption of oil with cotton products and kenaf. Appl eng agric. St. Joseph, MI: American Society of Agricultural Engineers, 1985. May 1994 10(3):357–361

Anuar H, Zuraida A (2011) Improvement in mechanical properties of reinforced thermoplastic elastomer composite with kenaf bast fibre. Compos B Eng 42(3):462–465

Anuar H, Zuraida A et al (2012) Improvement of mechanical properties of injection-molded polylactic acid-kenaf fiber biocomposite. J Thermoplast Compos Mater 25(2):153–164

Ardente F, Beccali M et al (2008) Building energy performance: A LCA case study of kenaf-fibres insulation board. Energy Build 40(1):1–10

Atchison JE (1995) Twenty-five years of global progress in non-wood plant fibre pulping. Historical highlights, present status and future prospects. Pulping Conference, Tappi Press, Chicago, USA

Ayerza R, Coates W (1996) Kenaf performance in northwestern Argentina. Ind Crops Prod 5(3):223–228

Ayre BG, Stevens K et al (2009) Viscoelastic properties of Kenaf bast fiber in relation to stem age. Text Res J 79(11):973–980

Bagby MO, Cunningham RL et al (1979) Kenaf thermomechanical pulp in newsprint. Nonwood plant fiber pulping progress report, Tappi vol 10, p 111

Boeriu CG, van Dam JEG et al (2005) Biomass valorization for sustainable development. Biofuels for Fuel Cells: renewable energy from biomass fermentation. In: Lens P, Westermann P, Haberbauer, M Moreno A (eds) IWA Publishing, London

Buzarovska A, Bogoeva-Gaceva G et al (2007) Crystallization behavior of poly(hydroxybytyrate-co-valerate) in model and bulk PHBV/kenaf fiber composites. J Mater Sci 42(16):6501–6509

Calamari TA, Tao WY et al (1997) A preliminary study of kenaf fiber bundles and their composite cells. Tappi J 80(8):149–154

Carus M, Gahle C (2008) Injection moulding with natural fibres. Reinf Plast 52(4):18–25

Catling D, Grayson J (1982) Identification of vegetable fibers. Chapman & Hall, New York

Chen E (2011) Fibrous kenaf could be Malaysia's third big crop. Green prospect Asia

Chen Y, Chiparus O et al (2005) Natural fibers for automotive nonwoven composites. J Ind Text 35(1):47–62

Choi HM, Cloud RM (1992) Natural sorbents in oil spill cleanup. Environ Sci Technol 26(4):772–776

Chow P, Bajwa DS (2005) Oriented strandboard (OSB) panels made from kenaf stalks and aspen. J Nat Fibers 2(1):83–89

Clark TF (1970) First bond paper made using kenaf pulp in the furnish. Paper Trade J 158(46):28

Clark TF, Nelson GH et al (1962) A search for new fiber crops: V pulping studies on kenaf Tappi J 45(10):780–786

Clark TF, Wolff IA (1965) A search for new fiber crops: VIII sulfate pulping of kenaf. Tappi J 48(6):381–384

Collier BJ, Dever M et al (2000) Rheology of lyocell solutions from different cellulose sources. J Polym Environ 8(3):151–154

Cunningham RL, Touzinsky GF et al (1979) Brightening of kenaf thermomechanical pulp. Tappi J 62(4):69–70

D'Agostino D, Richard A et al (1996) Continuous steam explosion pulping: a viable alternative for pulping of non-woody fibers. TAPPI Pulping Conference, Nashville, Tennessee, USA

Deka H, Misra M et al (2012) Renewable resource based all green composites from kenaf biofiber and poly(furfuryl alcohol) bioresin. Ind Crops Prod 41:94–101

Dempsey JM (1975) Fiber crops. The University Press of Florida, Gainesville

Dittenber DB (2012) Effect of alkalization on flexural properties and moisture absorption of kenaf fiber reinforced composites. International SAMPE Technical Conference

Du Y, Zhang J et al (2010) Kenaf bast fiber bundle-reinforced unsaturated polyester composites III: statistical strength characteristics and cost-performance analyses. For Prod J 60(6):514–521

Dutt D, Upadhyaya JS et al (2010) Studies on *Hibiscus cannabinus*, *Hibiscus sabdariffa* and *Cannabis sativa* pulp to be a sunbstitut for softwood pulp-part1: AS-AQ delignification process. BioResources 5(4):2123–2136

Edeerozey AMM, Akil HM et al (2007) Chemical modification of kenaf fibers. Mater Lett 61(10):2023–2025

Eichhorn SJ, Baillie CA et al (2001) Review: current international research into cellulosic fibres and composites. J Mater Sci 36(9):2107–2131

Elsaid A, Dawood M et al (2011) Mechanical properties of kenaf fiber reinforced concrete. Constr Build Mater 25(4):1991–2001

El-Shekeil YA, Sapuan SM et al (2012) Influence of fiber content on the mechanical and thermal properties of Kenaf fiber reinforced thermoplastic polyurethane composites. Mater Des 40:299–303

FAO (2010) Production, Crops, FAO STAT

FAO (2010) Production, Forest, FAO STAT

FAO (2011) FAO paper and paperboard capacity survey 2010–2015. http://www.fao.org/docrep/014/i2285t/i2285t00.pdf

Farahani GN, Ahmad I et al (2012) Effect of fiber content, fiber length and alkali treatment on properties of Kenaf fiber/upr composites based on recycled pet wastes. Polym Plast Technol Eng 51(6):634–639

Feng D (2001) Effect of compatibilizer on the structure-property relationships of kenaf-fiber/polypropylene composites. Polym Compos 22(4):506–517

Gartside G (1981) Kraft, soda and NSSC pulping of kenaf. Kenaf as a potential source of pulp in Australia. CSIRO, Brisbane

Ghalambor A (1995) Evaluation and characterization of sorbents in removal of oil spills. University of Southwestern Louisiana, Louisiana

Goforth CE (1994, May 1994) The evaluation of kenaf as an oil sorbent. http://msucares.com/pubs/Variety/Kenaf/kenaf14.htm. Accessed from 2012

Graupner N, Herrmann AS et al (2009) Natural and man-made cellulose fibre-reinforced poly(lactic acid) (PLA) composites: an overview about mechanical characteristics and application areas. Compos A Appl Sci Manuf 40(6–7):810–821

Green-Natural-Fibres (2012) Nafcore—Kenaf horse bedding. http://www.bednarekquarterhorses.com/nafcore_basic_story.html

Han JS, Rowell JK (1997) Chemical composition of fibres. In: Rowell RM, Young RA Rowell JK (eds) Paper and composites from agro-based resources. CRC, Boca Raton

Hao A, Zhao H et al (2012) Kenaf fiber nonwoven composites as automotive interior material: mechanical, thermal, and acoustical performance. International SAMPE Technical Conference

Hensler KL, Baldwin BS et al (1998) Kenaf-based fiber mat as a substrate for establishing soilless sod. HortTechnology 8(2):171–175

Hodgson PW, Lawford WH et al (1981) Commercial paper machine trial of CTMP kenaf in newsprint. Tappi J 64(9):161–164

Huang S (2010) Overview on the Chinese pulp & paper market. http://www.internationalpulpweek.com/Pastconf/Susan_Huang2010.pdf?OpenElement. Accessed Aug 2012

Ibraheem SA, Ali A et al (2011) Development of green insulation boards from Kenaf fibres and polyurethane. Polym-Plast Technol Eng 50(6):613–621

Ibrahim NA, Hadithon KA et al (2010) Effect of fiber treatment on mechanical properties of kenaf fiber-ecoflex composites. J Reinf Plast Compos 29(14):2192–2198

Ibrahim M, Daud WRW et al (2011) Comparative properties of soda pulps from stalk, bast, and core of Malaysian grown kenaf. BioResources 6(4):5074–5085

IJSG (2012) World Jute Profile—Malaysia. http://www.jute.org/wjp/cp_malaysia.htm. Accessed Sept 2012

IJSG (2012) World production of Kenaf & Allied fibre from 2003/2004 to 2010/2011. http://www.jute.org/statistics_01.htm#2. Accessed Sept 2012

Inagaki M, Nishikawa T et al (2004) Carbonization of kenaf to prepare highly-microporous carbons. Carbon 42(4):890–893

Irmak S, Öztürk (2010) Hydrogen rich gas production by thermocatalytic decomposition of kenaf biomass. Int J Hydrogen Energy 35(11):5312–5317

Jamaludin MA, Nordin K et al (2007) The bending strength of medium density fibreboard (MDF) from different ratios of kenaf and oil palm empty fruit bunches (EFB) admixture for light weight construction. Key Eng Mater 334(335):77–80

Jeyanthi S, Purushothaman M et al (2011) Development of ecofriendly thermoplastics for automotive components. Proceedings of the international conference on green technology and environmental conservation, GTEC-2011

Jeyanthi S, Jeevamalar J et al (2012) Influence of natural fibers in recycling of thermoplastics for automotive components. IEEE-international conference on advances in engineering, science and management, ICAESM-2012

Jinhua W, Ramaswamy GN (2003) One-Step processing and bleaching of mechanically separated Kenaf fibers: effects on physical and chemical properties. Text Res J 73(4):339–344

John MJ, Bellmann C et al (2010) Kenaf-polypropylene composites: effect of amphiphilic coupling agent on surface properties of fibres and composites. Carbohydr Polym 82(3):549–554

Jonoobi M, Oksman Niska K et al (2009) Chemical composition, crystallinity, and thermal degradation of bleached and unbleached kenaf bast (*Hibiscus cannabinus*) pulp and nanofibers. BioResources 4(2):626–639

Juliana AH, Paridah MT et al (2012) Properties of three-layer particleboards made from kenaf (*Hibiscus cannabinus L.*) and rubberwood (*Hevea brasiliensis*). Mater Des 40:59–63

Julkapli NM, Akil HM (2010) Influence of a plasticizer on the mechanical properties of kenaf-filled chitosan bio-composites. Polym Plast Technol Eng 49(9):944–951

Kaldor AF (1990) Kenaf—a competitive fiber to plantation eucalypt- based on recent investigations in Thailand. 1990 Pulping Conference

Kargarzadeh H, Ahmad I et al (2012) Effects of hydrolysis conditions on the morphology, crystallinity, and thermal stability of cellulose nanocrystals extracted from kenaf bast fibers. Cellulose 19(3):855–866

Karus M, Ortmann S et al (2006) Use of natural fibres in the German automotive industry. Gummi, Fasern, Kunststoffe 59(3):144–145

Kaup M, Karus M et al (2003) The use of natural fibres in composites in the German and Austrian automobile industry, NOVA Institut

KEFI (2006) Natural fibres. http://www.kenaf-fiber.com/en/azienda.asp. Accessed Sept 2012

Keijsers ERP, Yilmaz G et al ((in print) 2012) The cellulose resource matrix. Carbohydr Polym 93(1):9–21

Kim S, Dale BE et al (2008) Life cycle assessment of kenaf fiber reinforced biocomposite. J Biobased Mater Bioenergy 2(1):85–93

Kirby RH (1963) Vegetable fibres world crops books. Interscience Publishers, London

Kocurek MJ, Stevens CFB (1983) Properties of fibrous raw materials and their preparation for pulping. Pulp and Paper manufacture, 3rd edn. Joint textbook committee of the paper Industry, Montreal

Kugler DE (1988) Kenaf newsprint: realizing commercialization of a new crop after four decades of research and development. A Report on the Kenaf demonstration project, United States. Cooperative State Research Service. Special Projects and Program Systems 13

Kugler DE (1996) Kenaf commercialization 1986–1995. In: Janick J (ed) Progress in new crops. ASHS Press, Alexandria pp 129–132

Law TT, Ishak ZAM (2011) Water absorption and dimensional stability of short kenaf fiber-filled polypropylene composites treated with maleated polypropylene. J Appl Polym Sci 120(1):563–572

Law K-N, Lanouette R et al (2003) Characterization of kenaf by chemimechanical pulping. Tappi J 86(6):57–67

Lawford WH, Tombler G (1982) Kenaf pulp for newsprint. Pulp Paper Can 83(12):99–103

Lee CK, Cho MS et al (2010) Preparation and physical properties of the biocomposite, cellulose diacetate/kenaf fiber sized with poly(vinyl alcohol). Macromol Res 18(6):566–570

Liang Z, Pan P et al (2010) Mechanical and thermal properties of poly(butylene succinate)/plant fiber biodegradable composite. J Appl Polym Sci 115(6):3559–3567

Lips SJJ, van Dam JEG (2007) Kenaf for industrial products—final report Agrotechnology and Food Innovations—EU contract QLK5-CT2002-01729 Biomass Production Chain and growth Simulation Model for Kenaf Agrotechnology and Food Innovations, The Netherlands

Lips SJJ, Iñiguez de Heredia GM et al (2009) Water absorption characteristics of kenaf core to use as animal bedding material. Ind Crops Prod 29(1):73–79

Ma LF, Yamauchi H et al (2000) Manufacture of cement-bonded boards from wood and other lignocellulosic materials: relationships between cement hydration and mechanical properties of cement-bonded boards. Wood–Cement Composites in the Asia–Pacific Region, Canberra

Majid RA, Ismail H et al (2010) Effects of polyethylene-g-maleic anhydride on properties of low density polyethylene/thermoplastic sago starch reinforced kenaf fibre composites. Iran Polym J (English Edition) 19(7):501–510

Mohta DC, Roy DN et al (2004) Refiner mechanical pulp from kenaf for newsprint manufacture. Tappi J 3(4):9–13

Moreau JP, Bel-Berger P, Tao W (1995) Mechanical processing of kenaf for nonwovens. Tappi J. 78(2):96–105

Mossello AA, Harun J et al (2010a) A review of literatures related of using Kenaf for pulp production (Beating, Fractionation, and Recycled Fiber). Mod Appl Sci 4(9):44–49

Mossello AA, Harun J et al (2010a) Evaluation of linerboard properties from Malaysian cultivated kenaf soda-anthraquinone pulps versus commercial pulps. BioResources 5(3):1595–1604

Mossello AA, Harun J et al (2010b) New approach to use of kenaf for paper and paperboard production. Bioresource 5(4):2112–2122

Muehl JH, Krzysik AM et al (1999) Performance of hardboards made from kenaf. Kenaf properties, processing and products. In: Sellers T, Reichert NA (eds) Mississippi State University, Mississippi

Munusamy S, Whitacre R et al (2012) Development of biobased sandwich structures for mass transit applications. International SAMPE Technical Conference

Myers GC, Bagby MO (1995) Feasibility of using kenaf chemi thermomechanical pulp in printing and writing paper. Tappi J 78:5

Nelson GH, Nieschlag HJ et al (1961) A search for new fiber crops: III laboratory scale pulping studies. Tappi J 44(5):319–325

Neoh KW, Tshai KY et al (2012) Micro palm and Kenaf fibers reinforced PLA composite: effect of volume fraction on tensile strength. Appl Mech Mater 145:1–5

Neto CP, Seca A et al (1996) Chemical composition and structural features of the macromolecular components of *Hibiscus cannabinus* grown in Portugal. Ind Crops Prod 5(3):189–196

Nezamoleslami A, Suzuki K et al (1998) Biobleaching of kenaf bast fibre, soda AQ pulp using white rot fungus. Tappi J 81(6):179–183

NFESC (1999) Evaluation of bio-based industrial products for navy and DOD use—Phase 1 Kenaf absorbent. Naval Facilities Engineering Service Center 16

Nieschlag HJ, Earle FR et al (1960a) A search for new fiber crops: II analytical evaluation continued. Tappi J 43(12):993–998

Nieschlag HJ, Nelson GH et al (1960b) A search for new fiber crops. Tappi J 43(3):193–201

Nieschlag HJ, Nelson GH et al (1961) A search for new fiber crops: IV kenaf composition. Tappi J 44(7):515–516

Ninomiya K, Kamide K et al (2012) Enhanced enzymatic saccharification of kenaf powder after ultrasonic pretreatment in ionic liquids at room temperature. Bioresour Technol 103(1):259–265

Nishimura N, Izumi A et al (2002) Structural characterization of kenaf lignin: differences among kenaf varieties. Ind Crops Prod 15(2):115–122

Nishino T, Hirao K et al (2003) Kenaf reinforced biodegradable composite. Compos Sci Technol 63(9):1281–1286

Nosbi N, Akil HM et al (2010) Degradation of compressive properties of pultruded kenaf fiber reinforced composites after immersion in various solutions. Mater Des 31(10):4960–4964

Nyambo C, Mohanty AK et al (2010) Polylactide-based renewable green composites from agricultural residues and their hybrids. Biomacromolecules 11(6):1654–1660

Okuda N, Sato M (2004) Manufacture and mechanical properties of binderless boards from kenaf core. J. Wood Sci 50:53–61

Okuda N, Sato M (2007) Finely milled kenaf core as a natural plywood binder. Holzforschung 61(4):439–444

Okuda N, Sato M (2008) Bond durability of kenaf core binderless boards II: outdoor exposure test. J Wood Sci 54(1):36–44

Oliveros R (1999) Validation of raw material coming from kenaf; Progress report for the period of 01–01-98 to 31–12-98. Keninter, Madrid

Oliveros R (2000) Validation of raw material coming from kenaf; Consolidated report for the period of 01-01-99 to 31-12-99. Fair CT96 1697 progress report. Madrid, Keninter

Öztürk S (2010) Effect of fiber loading on the mechanical properties of kenaf and fiberfrax fiber-reinforced phenol-formaldehyde composites. J Compos Mater 44(19):2265–2288

Pande H (1998) Non-wood fibre and global fibre supply. FAO-Unasylva 193:66

Pappas C, Tarantilis PA et al (2002) Comparison of classical and ultrasound-assisted isolation procedures of cellulose from kenaf (*Hibiscus cannabinus* L.) and eucalyptus (Eucalyptus rodustrus Sm). Ultrason Sonochem 9(1):19–23

Parikh DV, Calamari TA et al. (2002). Refining of kenaf fibres for processing into automotive nonwovens. Beltwide Cotton Conferences, Atlanta

Paul PK (1991) Phoenix and its views about kenaf. Phoenix pulp & paper Co., Ltd, Bangkok

Pearce RJ, Sellers T (2000) Fiver different agr-based particleboards bonded with urea-formaldehyde resin. Am Kenaf Soc 25:23–30

Petrini C, Bazzocchi R et al (1994) Yield potential and adaptation of kenaf (*Hibiscus cannabinus*) in north-central Italy. Ind Crops Prod 3(1–2):11–15

Phoenix (2004) http://www.phoenixpulp.com/eng/news.asp. Accessed March 2004

Phoenix (2008) http://www.ogcorp.co.jp/en/operations/ppd/phoenix.html. Accessed Oct 2008

Pulp and Paper International Online (1998) Kafus leads the way in Spain

Pulp and Paper Online (1997) kenaf newsprint mill

Puri VP, Higgins HG (1981) Chemimechanical and chemithermomechanical pulping of kenaf. Kenaf as a potential source of pulp in Australia, Brisbane

Raju G, Said MM et al (2008) Properties of kenaf fibre reinforced natural rubber composites. J Rubber Res 11(4):187–195

Ralph J (1996) An unusual lignin from Kenaf. J Nat Prod 59(4):341–342

Ramaswamy GN, Ruff CG et al (1994) Effect of bacterial and chemical retting on kenaf fiber quality. Text Res J 64(5):305–308

Ramaswamy GN, Sellers T et al (2003) Kenaf nonwovens as substrates for laminations. Ind Crops Prod 17(1):1–8

Rao S, Coombs B et al (2012) Kenaf MDF panels: a statistical approach in parameter selection. Int Wood Prod J 3(1):15–20

Rashdi AAA, Salit MS et al (2010) Water absorption behaviour of kenaf reinforced unsaturated polyester composites and its influence on their mechanical properties. Pertan J Sci Technol 18(2):433–440

Rassmann S, Reid RG et al (2010) Effects of processing conditions on the mechanical and water absorption properties of resin transfer moulded kenaf fibre reinforced polyester composite laminates. Compos A Appl Sci Manuf 41(11):1612–1619

Reinerink EJM, van der Kolk JC et al (1998) Validation of raw material coming from kenaf; Individual progress report for the period of 01–01-98 to 31–12-98. ATO-DLO, Madrid

Ren X, Li K (2012) Investigation of vegetable-oil-based coupling agents for kenaf-fiber-reinforced unsaturated polyester composites. J Appl Polym Sci 125:2486

Ren X, Qiu R et al (2012) Modifications of kenaf fibers with N-methylol acrylamide for production of kenaf-unsaturated polyester composites. J Appl Polym Sci 125(4):2846–2853

Resalati H (2009) Kenaf CMP pulp; an alternative potential to supplement wood shortages for making newsprint. Proceedings Tappi Engeneering, Pulping and Environmental Conference 2009. Vol 3. pp 1462–1488

Roberts S (1996) Potential of the non-wood fibre paper sector. International Institute for Environment and Development, Brazil

Rouison D, Sain M et al (2004) Resin transfer molding of natural fiber reinforced composites: cure simulation. Compos Sci Technol 64(5):629–644

Rowell RM, Stout HP (2007) Jute and Kenaf. Handbook of fibre chemistry. In: Lewin M (ed) CRC Press, New York pp 405–453

Roy AK, Chattopadhyay SN (2012) Jute and alternative raw material for packaging paper. IPPTA 24(3):121–124

Rozman HD, Sobra Mulisa A et al (2012) A comparison study of lignocellulosic-thermoplastic composites prepared from different compounding techniques. J Appl Polym Sci 124(6):4547–4553

Rydholm SA (1985) Pulping Processes. Krieger publishing company, Malibar, Florida. reprint edition.

Rymsza TA (1998) Creating High Value markets for kenaf paper—a commercial experience. http://www.visionpaper.com/PDF_speeches_papers/982aks.pdf. Accessed Sept 2012

Rymsza TA (1998) Utilizing kenaf for high value paper applications in the U.S.A. http://www.visionpaper.com/PDF_speeches_papers/hppsjapan.pdf. Accessed Sept 2012

Rymsza TA (2000) Advancements of kenaf in the USA-Kenaf paper and nonpaper developments. http://www.visionpaper.com/PDF_speeches_papers/007anwpp.pdf. . Accessed Sept 2012

Saad MJ (2012) The effect of maleated polypropylene (MAPP) on: the mechanical properties of Kenaf core—polypropylene composites. J Sustain Sci Manag 7(1):49–55

Saijonkari-Pahkala K (2001) Non-wood plants as raw material for pulp and paper, Helsinki

Sanadi AR, Caulfield D (2008) Thermoplastic polyolefins as formaldehyde free binders in highly filled lignocellulosic panel boards: using glycerine as a processing aid in kenaf fiber polypropylene boards. Mater Res 11(4):487–492

Sanadi AR, Caulfield DF et al (1995) Renewable agricultural fibers as reinforcing fillers in plastics: mechanical properties of kenaf fiber-polypropylene composites. Ind Eng Chem Res 34(5):1889–1896

Sato N (2001) Kenaf popular as nonwood alternative for paper. Kyodo News Service Japan Economic Newswire, Japan

Seca AML, Cavaleiro JAS et al (1998) Structural Characterization of the Bark and Core Lignins from Kenaf (*Hibiscus cannabinus*). J Agric Food Chem 46(8):3100–3108

Seca AML, Silva AMS et al (2001) Lignanamides and other phenolic constituents from the bark of kenaf (*Hibiscus cannabinus*). Phytochemistry 58(8):1219–1223

Sellers TJ, Miller GDJ et al (1995) Lignocellulosic-Based Composites Made of Core From Kenaf. Ann Agric Crop. IUFRO 1995 World Congress. Tampere, Finland

Shakhes J, Zeinaly F et al (2011) The effects of processing variables on the soda and soda-AQ pulping of Kenaf bast fiber. BioResources 6(4):4626–4639

Shi J, Shi SQ et al (2011) A chemical process for preparing cellulosic fibers hierarchically from kenaf bast fibers. BioResources 6(1):879–890

Sholton EJ (1981) Specialty paper from kenaf. Kenaf as a potential source of pulp in Australia, Brisbane

Simatupang MH, Bröker FW (1998) Properties and hygroscopic isotherm of cement-bonded particleboards and fiberboards made by carbon dioxide injection method and conventional methods. Holz als Roh Werkstoff 56(4):275–276

Snijder MHB, Bos HL et al (2000) Reinforcement of polypropylene by annual plant fibers: optimisation of the coupling agent efficiency. Compos Interfaces 7(2):69–75

Snijder MHB, Bos HL et al (2003) Extruder for continuously manufacturing composites of polymer and cellulosic fibres. U Patent US 6(565):348

Sukyai P, Sriroth K et al (2012) The effect of bacterial cellulose on the mechanical and thermal expansion properties of kenaf/polylactic acid composites. Appl Mech Mater 117–119:1343–1351

Summerscales J, Dissanayake NPJ et al (2010) A review of bast fibres and their composites. Part 1—fibres as reinforcements. Compos Appl Sci Manuf 41(10):1329–1335

Taib RM (1998) Cellulose fiber reinforced thermoplastic composites: processing and product charateristics. Virginia Polytechnic Institue and State University, Virginia

Taib RM, Ramarad S et al (2010) Properties of kenaf fiber/polylactic acid biocomposites plasticized with polyethylene glycol. Polym Compos 31(7):1213–1222

Tao W, Moreau JP et al (1995) Properties of nonwoven mats from kenaf fiber. Tappi J 78(8):165–169

Tao W, Calamari TA et al (1997) Characterization of kenaf fiber bundles and their nonwoven mats. Tappi J 80(12):162–166

Tawakkal ISMA, Talib RA et al (2012) Mechanical and physical properties of kenaf-derived cellulose (KDC)-filled polylactic acid (PLA) composites. BioResources 7(2):1643–1655

Taylor CS (1993) Kenaf: an emerging new crop industry. Wiley, New crops, New York, pp 402–407

Touzinsky GF, Cunningham RL et al (1980) Papermaking properties of kenaf thermomechanical pulp. Tappi J 63(1):53

Tsakonas A, Stergiou V et al (2005) Kenaf (*Hibiscus cannabinus* L.) based substrates for the production of compact plants. Ind Crops Prod 21(2):223–227

van Berlo JM, Bakker H et al (1993) Papier uit hennep van Nederlandse grond: eindrapportage van vier jaar henneponderzoek. Wageningen, s.n

van Dam JEG (2009) Natural fibres and the environment: environmental benefits of natural fibre production and use. Symposium on natural Fibres, Rome

van Dam JEG, van Vilsteren GET et al (1994) Increased application of domestically produced plant fibres in textiles, pulp and paper production and composite materials. European Commission, Brussels van Dam JEG, Gorshkova TA (2003) Plant growth and development: plant fiber formation, Chapter MS 46. Encyclopedia of applied plant sciences. In: Thomas B, Murphy DJ, Murray BG (eds) Elsevier, Amsterdam

van Dam JEG, de Klerk-Engels B et al (2005) Securing renewable resource supplies for changing market demands in a bio-based economy. Ind Crops Prod 21(1):129–144

Vellema SR, Bos HL et al (2010) biobased industrialization in developing countries. The biobased economy: biofuels, materials and chemicals in the post-oil era. In: Langeveld H, Sanders J, Meeusen M (eds), Earthscan London pp 214–228

Ververis C, Georghiou K et al (2004) Fiber dimensions, lignin and cellulose content of various plant materials and their suitability for paper production. Ind Crops Prod 19(3):245

Vision Paper (1999) "Kenaf and the 21st century current developments and trends. http://www.visionpaper.com/PDF_speeches_papers/992aks.pdf. Accessed July 2012

Vision-Paper (2010) Vison Paper. http://www.visionpaper.com/. Accessed Aug 2012

Watkins R (1994) The use of kenaf as bedding for horses and laboratory animals. Mississippi Agricultural & Forestry Experiment Station, Mississippi State University, Mississippi

White JA, Cunningham DG et al (1970) Cultural and harvesting methodes for kenaf, an annual crop source of pulp in the south east. USDA produktion research report no 113

Willför S, Alén R et al (2011) Chemical pulping Fibre Chemistry and Technology Chapt 1—Raw materials. Paper making science and technology book 6 (part1) Å. A. Pedro Fardim. Helsinki, Paperi ja Puu Oy

Wood IM (1981) Kenaf for paper pulp: research and development around the world. Kenaf as a potential source of pulp in Australia, Brisbane

Wood IM, Chudleigh PD et al (1990) The 1990 Kenaf workshop: summary of the conclusions and recommendations from the discussion sessions. In: Proceedings of workshop development of a Kenaf Industry in Australia, Brisbane

Xu EC (2001) APMP pulps from non-wood fibres Part 1: kenaf and straw. Appita J 54(5):444–448

Xu J, Han G et al (2003) Development of binderless particleboard from kenaf core using steam-injection pressing. J Wood Sci 49:327–332

Xu J, Sugawara R et al (2004) Manufacture and properties of low-density binderless particleboard from kenaf core. J Wood Sci 50:62–67

Yachmenev VG, Calamari TAJ et al (2004) Thermal insulation properties of kenaf and cotton non-woven composites for automotive application Beltwide Cotton Conferences. San Antonio

Yachmenev V, Negulescu I et al (2006) Thermal insulation properties of cellulosic-based nonwoven composites. J Ind Text 36(1):73–87

Yan TT, Gu WY et al (2011) Research on kenaf degumming with oxidation process. Adv Mater Res 332–334:1109–1113

Young J (1987) Kenaf newsprint is a proven commodity. Tappi J 11:81–83

Yousif BF, Shalwan A et al (2012) Flexural properties of treated and untreated kenaf/epoxy composites. Mater Des 40:378–385

Yu H, Yu C (2010) Influence of various retting methods on properties of kenaf fiber. J Text Inst 101(5):452–456

Yu DM, Chen KF et al (2011) The study of Kraft continuous cooking of knenaf. Adv Mater Res 236–238:1212–1215

Zaveri MD (2004) Absorbency characteristics of kenaf core particles. Master of science. North Carolina State University, North Carolina

Zeinaly F, Shakhes J et al (2011) Multistage alkali peroxide bleaching in low kappa kenaf bast pulp In: International Pulp Bleaching Conference 2011, IPBC 2011, Portland, OR, United States, 5–7 October 2011. pp 542–552

Zhang T (2003) Improvement of kenaf yarn for apparel applications. Master, Louisiana State University, Baton Rouge

Zhou Z, Yin X et al (2009) Research on the gasification characteristics of the industrial residues of kenaf. In: Goswami DY, Zhao Y (eds) Proceedings of ISES world congress 2007 (Vol I–V), Springer, Berlin pp 2397–2399

Zuliahani A, Rozman HD et al (2011) Preparation of epoxy-Kenaf nanocomposite based on montmorillonite. Adv Mater Res 264–265:469–474