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Andrea Monti
Efthimia Alexopoulou *Editors*

# Kenaf: A Multi-Purpose Crop for Several Industrial Applications

## New Insights from the Biokenaf Project

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# Foreword

With ever increasing amounts of information coming forward from scientific research and ever changing market demands, the need for an overarching view which encompasses all aspects of a crop and integrates them in a ‘digested’ form into a meaningful entity for the end user and producer has never been greater. This applies to most crops that are currently in usage. There is always the concern that individual papers produce perfectly valid results in their own context but could result in problems being raised in other production or utilization components of the production cycle of the crop in question. Examples of this have been reported several times in recent years.

Modeling is an excellent way of linking together what is known in a meaningful way, yet at the same time identifying areas of lack or weakness in information. So models can help to identify future R&D priorities as well as optimizing production or utilization of the crop in question, based upon best use of existing knowledge. Further, the question of sustainability can only be answered through an integrated approach to knowledge and its applications. Hence integrated information in some format, including modeling, becomes an essential feature of long-term sustainable production and utilization of any crop or crop component.

Kenaf as a crop is of course not new. However, its use in parts of Europe as an industrial crop are relatively new and to an extent, underdeveloped. Additionally, the crop may well expand in EU as climate change/global warming alters potential production areas. Further focus on the need for bio-based industrial crops will be promoted through the recent policy decision within European Commission to progress the ‘Bio-Economy’. Undoubtedly this development will enhance demand for more efficient production and utilization of crops or their components, sometimes as food and non-food feedstock providers and in others as non-food feedstock providers only.

So this book, *Kenaf: A Multi-Purpose Crop for Several Industrial Applications* with new insights from Biokenaf Project, is particularly timely in its production and should make a significant contribution to decision making about and sustainable production of kenaf. Perhaps it forms the background ideotype for information on sustainable production of other crops?

Wolverhampton, UK
January 2013

Melvyn F. Askew

# Preface

On re-reading this book, it is difficult for us to understand why kenaf is still practically absent as a crop in Europe. Its multiple uses, as pointed out by Steef Lips and Jan van Dam (Chap. 6), such as fabrics, yarns and ropes, building materials, textiles, bio composites, bedding material, oil absorbents, to name but a few, seem not only interesting but also highly feasible. They certainly make kenaf one of, if not the most, fascinating opportunities for the growing European market of natural fibers, especially in regions with limited supplies of wood.

This was why we decided to ask some of the world's leading experts on kenaf to contribute to a book covering the most interesting and up-to-date aspects regarding this crop, in order to understand what the future developments of kenaf might be and how they can be carried out, not only in Europe but in other countries too.

We are certain that readers will be fascinated by the potential of this plant and will agree with us about the many opportunities that kenaf can offer. Readers will also agree that actually finding out about these opportunities and potential uses can represent a major limitation, and publications like this book can be of great help in making sure that this crop finally gets off the ground!

However, while on one hand the book describes the considerable potential of kenaf, on the other it confirms that rapid answers are needed to some specific critical aspects of this crop. Defang Li and Siqi Huang (Chap. 2) point out, for example, the still unexpressed potential of genetic improvement, and how *ad hoc* programs, together with ecophysiological studies (Danilo Scordia et al., Chap. 3) could lead to the selection of kenaf genotypes much more suited to European areas, even much sooner than foreseen. The use of environmental resources and the adoption of ideal agronomic techniques are also fundamental for the success of the crop. A great deal of more research is needed, but the results reported by Danilo Scordia et al. (Chap. 3), Efthimia Alexopoulou et al. (Chap. 4) and Ana Luisa Fernando (Chap. 5) show kenaf's considerable ability to use natural resources in a more efficient way than traditional crops, with consequent environmental advantages.

The most important progress achieved within the framework of the recent BIOKENAF project, coordinated in fact by one of the editors of this book, is brilliantly summarized in Chaps. 7 and 8 by Peter Soldatos et al. and Efthimia Alexopoulou et al., respectively. In these two chapters, readers will once again find confirmation of the considerable opportunities offered by this crop, not only from an environmental and social point of view, but also from an economic viewpoint, as described Peter Soldatos et al. in Chap. 7.

We express our gratitude by thanking all the authors for preparing the excellent contributions to this book, and the people who helped and encouraged us in the process of writing your book. To those whom we could not invite due to the size of the book, we offer our apologies.

Italy Andrea Monti
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# Contents

# Chapter 1
# Origin, Description, Importance, and Cultivation Area of Kenaf

**E. Alexopoulou, Y. Papatheohari, M. Christou and A. Monti**

**Abstract** This chapter discusses the origin and taxonomy of kenaf, the description of the plant parts (stems, leaves, flowers, seeds, and root), the importance of the crop worldwide, the cultivation area, as well as its importance. Kenaf (*Hibiscus cannabinus* L.) is an annual spring crop cultivated for long (4000 BC). It originated from Africa, disseminated in the 1900s in Asia (in India and then in China) and in the 1940s from Asia to northern and central USA. Kenaf belongs to the Malvaceae family and section Furcaria. It is closely related to cotton, okra, hollyhock, and roselle. Nowadays it is being cultivated in 20 countries worldwide and its total production (kenaf and allied crops) is 352,000 tons (2010/2011). Currently, China and Pakistan are the main producers. In the last part of the chapter the importance of the crop is discussed. Kenaf is an annual non-food fiber crop that used to be cultivated for numerous uses (paper pulp, fabrics, textiles, building materials, biocomposites, bedding material, oil absorbents, etc.). Recently, it is also considered as an important medicinal crop as its seed oil is recorded to cure certain health disorders and help in the control of blood pressure and cholesterol.

**Keywords** Kenaf • Origin • Genus • Crop importance • Cultivation area • Crop taxonomy • *Hibiscus cannabinus* L • Family Malvaceae • Furcaria section • Crop description • Stems • Flowers • Leaves • Seeds • Root • Multipurpose crop • BIOKENAF project • Annual crop • Fiber crop • Non-food crop • Energy uses • Fibers • Bark • Core • Spring crop

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## 1.1 Introduction

Kenaf is an annual spring crop cultivated for long (4000 BC) and its origin is from Africa. It belongs to the Malvaceae family and section Furcaria. Kenaf is closely related to cotton, okra, hollyhock, and roselle. It is a short day crop cultivated from 300 S to 450 N. Research on agronomics and end uses of the crop has been carried out worldwide during the last century. Many varieties are available worldwide (with short, intermediate, and long date habits).

It is considered an important bast fiber crop and used to be cultivated for its fibrous stem (contains long and short fibers in its stem fractions; bark and core, respectively) with numerous industrial applications (paper and pulp, fabrics, textiles, biocomposites, insulation mats, absorption materials, animal bedding, etc.). Recently, kenaf is being considered as an important medicinal crop. It was found that its oil has high contents of polyunsaturated fatty acids (PUFA). Its seed can cure many health disorders and diseases such as blood pressure, cholesterol balance, and some types of cancers. Thus, kenaf can be considered a dual non-food crop cultivated for its fiber and/or its oil production. This chapter describes in detail the crop origin and taxonomy, the plant parts, its cultivation area worldwide, and explains why kenaf is an important non-food crop with many alternative or complementary uses.

### *1.1.1 Origin of the Genus*

Kenaf (*Hibiscus cannabinus* L.) has been cultivated for long, probably as early as 4000 BC (Roseberg 1996). It originated in Africa, where diversified forms of the species are found growing widely as a component of the native vegetation of the countries of East Africa (Wilson and Menzel 1964; Wilson 1978; Dempsey 1975; Li 1990). The existence of semi-wild kenaf in Africa (Kenya and Tanzania) might be an indication of the origin of the cultivated kenaf from this continent (Chen et al. 2004). So far, the research on the origin of kenaf has been based on field surveys and investigations and no data on genetic studies have been collected to prove its origin.

At the beginning of the eighteenth century, kenaf was introduced into southern Asia and was first cultivated and commercially utilized in India (Dempsey 1975). The knowledge of how kenaf was introduced in India is limited but it is known that it came from Africa (Roxburgh 1795; Royle 1855; Hooker 1875; Howard and Howard 1911). The cultural interaction between ancient Egypt and the Indus may have played an important role for kenaf's dissemination from Africa to India, from where kenaf cultivation was expanded to other Asian countries. In the beginning of 1900, kenaf was disseminated into mainland China from Taiwan (Dempsey 1975; Charles 2002; Li 2002).

In 1902, Russia started to produce kenaf. Kenaf was cultivated commercially as a fiber crop in Asia and the USSR in the 1930s. During the Second World War, as foreign fiber supplies were interrupted, kenaf research and production was started in the U.S. to supply cordage material for the war effort (Wilson and Margaret 1967; Dempsey 1975). Accessions collected from Asia and central and North America were found to have close genetic relationships (Chen et al. 2004). More than 500 plant species were evaluated in the USA in the 1950s in order to cover the increasing future fiber demands in the USA. Kenaf was evaluated as an excellent cellulose fiber source for a large range of paper products (Nelson et al. 1962).

Currently, many countries pay more attention to kenaf research and cultivation because of its high biological efficiency and wide ecological adaptability. Kenaf is more commonly called “the future crop” (Mazumder 2000; Cheng 2001). Nowadays, kenaf is commercially cultivated in more than 20 countries, particularly in China, India, Thailand, and Vietnam (FAO 2003) but the knowledge of dissemination of the crop worldwide is still limited. Although kenaf originated from Africa, its production in Africa is very low. In 2010, the total production in Africa was just 3 % of the world production (FAO 2010).

Kenaf is connected with a long list of over 120 common names (Sellers and Reichert 1999) such as mesta, teal, ambari hemp, and rama that reflect the diversification and common uses of this crop. In English, the common name of kenaf in India is mesta, palungi, deccan hemp, and Bimli jute; in Taiwan it is ambari; in Egypt and Northern Africa it is til, teel, or teal; in Indonesia it is Java jute; in Brazil, it is papoula de Sao Francisco; in South Africa it is stokroos; and in West Africa it is dah, gambo, and rama (Taylor 1995).

### *1.1.2 Taxonomy of Kenaf*

Kenaf is a short day annual herbaceous plant that belongs to the Malvaceae, a family notable for both its economic and horticultural importance. The genus of *Hibiscus* is widespread, including some 400 species. Kenaf is closely related to cotton, okra, and hollyhocks. Next to cotton, it is the most widely cultivated fiber plant in the open country and can be found extending from Senegal to Nigeria. Kenaf, along with roselle, is classified taxonomically in the Furcaria section of Hibiscus.

The Furcaria section has about 40–50 species (Su et al. 2004) that were described throughout the tropics and they are closely related morphologically (Dempsey 1975). Kenaf is closely related to cotton (*Gossypium hirsutum* L.), okra (*Hibiscus esculentum* L.), and hollyhock (*Althaea rosea* L.). In some places, roselle (*Hibiscus sabdariffa* L.) is also called kenaf.

The chromosome number in the section Furcaria is a multiple of 18 in all the species, which have been counted. Natural species have been found with a chromosome number of 36 (kenaf and other species), 72, 108, 144, and 180. The diversity in numbers of chromosomes found in section Furcaria is not common in the plant kingdom. This chromosome diversity is reflected in the morphological and physiological diversity in the crop. This diversity represents a rich source of material potentially useful for kenaf breeding. A genome analysis had been carried out and it was found that kenaf and roselle share a common set of chromosomes (one genome) (Wilson 2000).

## 1.2 Description of the Crop

### *1.2.1 Stems*

Kenaf stems are generally round with thorns ranging from tiny to large such as on a blackberry bush depending on variety. The stem color varies from pure green to deep burgundy. Kenaf plants tend to grow as a single unbranded stem when planted at high production densities of 170,000–220,000 plants/ha with a height of 2.5–6 m. Kenaf stems have a thin bark over a woody core, surrounded by a leaf tuft (Kaldor 1989) (Fig. 1.1a). The stems contain two major fiber types, one with long fibers situated in the cortical layer, and the other with short fibers located in the ligneous zone.

The central area of the stem, corresponding to pith, consists of sponge-like tissues. The outer bark contains bast fibers of an average length of 2.5 mm and woody core fibers of an average of 0.6 mm. Kenaf fibers have three principal chemical constituents, which are the α-cellulose (58–63 %), hemicelluloses (21–24 %), and lignin (12–14 %). The minor constituents in kenaf stems are 0.4–0.8 % fats and waxes, 0.6–1.2 % inorganic matter, 0.8–1.5 % nitrogenous matter, and traces of pigments. In total, these minor constituents account for about 2 % (Stout 1981). The ash contained is higher in the bark (5.5–8.3 %) than in the core (2.9–4.2 %) while for the whole stem it is 2.1–6.5 %.

The core contains more lignin and less cellulose than the bark (Clark et al. 1971). The bast fiber compromises 35–40 % of the dry weight of the plant mature stem; and the core compromises the balance (Muchow 1983). The fiber content of the kenaf bark

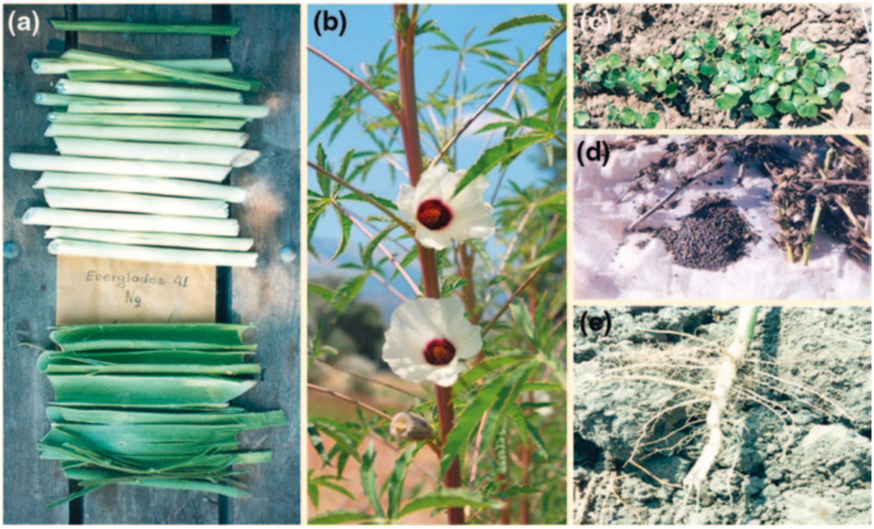

**Fig. 1.1** Kenaf parts (stem fractions, flowers, young seedlings, seeds and capsules, and root) (*source* BIOKENAF project)

content is about 50–55 %, increasing according to the plant population density, while the less valuable short fibers make up about 45–60 % of the inner core (Clark and Wolff 1969; Wood et al. 1983). Lower quality paper can be made from the short wood fibers of the core, while high quality paper can be made from the long fibers of the bark. Consequently, the core is more difficult to pulp than the bark, requiring more alkali and giving lower pulp yields; the resultant pulps are relatively slow draining with poor strength characteristics (Touzinsky et al. 1972; Bagby et al. 1975).

In a USDA study it was found that after maceration of green and field-dried kenaf, the average fiber length was 2.5 mm and the average width was 17 μm. The woody core fibers had an average length of 0.6 mm and an average width of 33 μm (White et al. 1970). The fiber length of softwoods is around 3.5 mm and of hardwoods, around 1 mm (Rydholm 1985). Hence, kenaf bast fibers are longer than hardwood fibers, but shorter than softwood fibers while the core fibers are shorter than hardwood fibers. Besides fibrous tissues, kenaf contains a non-fibrous tissue in the center of the stem, called pith.

### *1.2.2 Leaves*

The leaf shape varies and depends strongly on the variety. Kenaf varieties are divided into two categories; the (Everglades 71) varieties with deeply lobed leaves (usually called split or divided) and (Everglades 41) varieties with shallowly lobed leaves (usually called entire). The divided leaf shape can create a problem because it resembles marijuana (Fig. 1.1b). The entire leaf type has leaves that resemble those of its relatives such as okra and cotton (Baldwin 1994b). The leaves in the divided leaves varieties are deeply lobed with 3, 5, or 7 lobes per leaf.

The first few juvenile leaves of all kenaf seedlings have an entire shape (Fig. 1.1c). When the young plants start to develop, additional leaves are produced that start to differentiate. It can develop 3–10 entire juvenile leaves before the first divided leaf appears (Charles 2002). On the underside of the mid-vein of each leaf there is a nectar gland (Dempsey 1975). The seed capsule also has a nectar gland and both leaves and capsules are visited in large numbers by wasps.

When the plants are at an immature stage of growth (about 6 feet tall), the leaves contain 18–30 % crude protein on dry matter basis and for this reason it can be used as animal feed. The stems defoliate after the first killing frost and this drop returns significant qualities of nitrogen in the soil as well as calcium, magnesium, phosphate, and potassium. At the time of defoliation, the nitrogen content could be up by 4 % of the dry weight (Hollowell 1997).

### *1.2.3 Flowers*

The flowers of section Furcaria are characterized by having a calyx with prominent central rib and two prominent marginal ribs. These rigid structures apparently are used for supporting the fragile and delicate petals. Also, the flowers of all species have more or fewer narrow bracts, which are borne below the calyx. The tip of these bracts may be unforked as in kenaf or forked, according to the sectional name Furcaria. Kenaf flowers are typical of hibiscus genus, showing the characteristic fused statement column.

The flowers are large (7.5–10 cm), bell-shaped, and wide open with five petals. The flower color ranges from light cream to dark purple, with a number of shades between them, but apparently never in bright yellow, pink, or red tones. Many cultivars have flowers with a deep red or maroon center. They are borne on short stalks on the leaf axils on the upper portion of the stem and the main apical meristem retains its capacity for vegetative growth (Fig. 1.1b).

While the flowering per plant can last 3–4 weeks or more, each individual flower blooms for only one day. The flowers open early in the morning, begin to close about midday, and close in the mid-afternoon and never open again. The anthers release the pollen (which is bright orange or bronze color) about the time when the flower opens, and the style emerges shortly thereafter. The five-part stigma expands; the lobes become turgid, but do not touch the anthers. The corolla closes spirally so that the anthers are pressed in contact with the stigma and self-pollination can be done unless cross-pollination has already been recorded (Howard and Howard 1911).

Like its relative species such as cotton and okra, kenaf's flowers and nectaries attract a number of insects, which pollinate (and cross-pollinate) the flowers (McGregor 1976). Pate and Joyner (1958) stated that kenaf has been classified on several occasions as a self-pollinating crop, but more recently, it has been classified as a cross-pollinate crop. Because of the moderate level of cross-pollination, the seed obtained is frequently not true to type (Baldwin 1994a, 1996). The cross-pollination crop in kenaf can be varied from 2 to 24 %.

### *1.2.4 Seeds*

After pollination, seed capsules are formed that are 1.9–2.5 cm long and 1.3–1.9 cm wide. The seed develops in five-lobular capsules. Each capsule contains five segments with a total of 20–26 seeds/capsules (Dempsey 1975). The seed capsules are covered with small hairy structures that are irritating to the human skin. The capsules of the cultivated varieties are generally indehiscent and remain intact for several weeks after reaching maturity. From pollination, the seeds require 60–90 days in frost-free conditions to mature. According to Baldwin (1994), kenaf seeds take roughly 45 days to ripen. The seed is small (1.5–3.3 gr/100 seeds), black in color, and subreniform in shape (Fig. 1.1d). The seed retains viability for about 8 months under ordinary storage conditions. Kenaf seeds are grayish brown, approximately 6 mm long and 4 mm wide (35,000–40,000 seeds per kg).

The seeds contain 20 % and the oil has a similar fatty acid composition to cottonseed oil but does not contain gossypol, a polyphenolic compound in cottonseed which causes the oil to darken (Wood 1975). Kenaf oil is characterized by a high phospholipids content compared to most edible oils (Mohamed et al. 1995). The high oil content of kenaf seeds loses its viability when exposed to high temperature and increased humidity.

According to the chemical composition of kenaf seeds is 9.6 % moisture content, ash 6.4 %, fatty oils 20.4 %, nitrogenous matter 21.4 %, saccharifriable matter 16.7 %, crude fiber 12.9 %, and other matter 13.9 %. In the same study it is reported that the fatty oils correspond to five acids which are: palmitic oil 19.1 %, oleic acid 28 %, linoleic acid 44.9 %, stearic acid 6 %, and alpha-linolenic acid 0.5 %.

Previous studies reported that Kenaf seed contains 16–22 % oil and 30–33 % proteins and the Palmitic, oleic, and linoleic acids were reported as major fatty acids in kenaf oil (Hopkins and Chisholm 1959; Subbaram et al. 1964; Tolibave et al. 1986; Singh 1988). The minor fatty acid contents of kenaf seeds were the palmitoleic (1.6 %), linoleic (0.7 %), and the stearic (3.5 %) (Mohamed et al. 1995).

## *1.2.5 Root*

The plant has a long effective tap root system and relatively deep, wide-ranging lateral root system making the plant drought tolerant. Further to that, kenaf with its tap root system is considered to be an excellent user of residual nutrients from previous crops (Fig. 1.1e).

Kenaf root has deep root exploration that reaches to more than 1 m depth (Fig. 1.2). Kenaf roots are sensitive to plow-pan and maybe to other structural accidents or compactions.

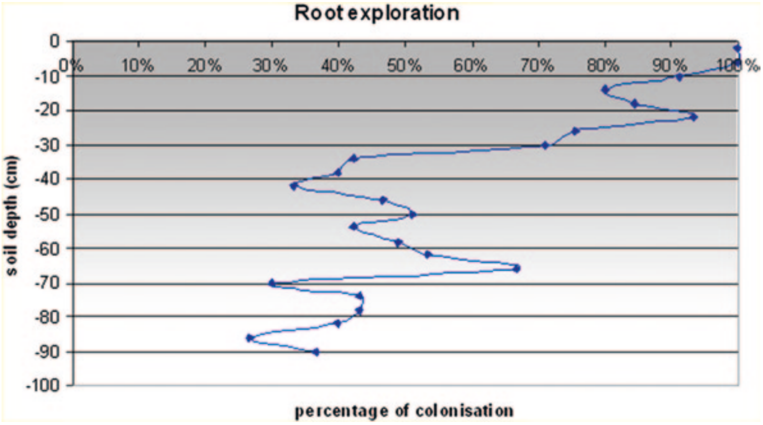

**Fig. 1.2** Kenaf root profile in a soil profile of 100 cm (*Source* INRA, BIOKENAF project)

## 1.3 Area of Cultivation

In 1985, the global kenaf production reached an all-time high of 2.8 million tons. After this time, kenaf production has shown to follow a declining trend. In 1995, the production of kenaf and allied fiber crops was 753,000 tons and continued to decline. Currently (2010/2011), kenaf is an important cash crop in many developing countries like, China, India, and Thailand. Nowadays, it is not easy to find any huge cultivation area of kenaf in the main producing countries of China and India and the crop is only planted on marginal lands with poor or no management. Japan consumes nearly all of the Asian kenaf production. The Japanese industry has set a short-term goal of 1 %, which would require about 300,000 tons of raw kenaf. In the longer term, the Japanese industry has set a goal of 10 % (Wood 1998).

An area of cultivation of 1,000 ha is reported in the USA (Kulger 1996). In 1999, an area of 2500 ha was planted in Texas, Mississippi, and Missouri for a number of fiber applications. In 2000, almost 10,000 ha of kenaf were cultivated in various parts of the United States. The four main areas of commercial kenaf activity in the USA are Georgia, Texas, Mississippi, and New Mexico. In Australia, there is no commercial production of kenaf and all the present fiber production is for experimental purposes.

In Europe, a cultivation area of 700 ha is reported in Bologna (Italy). The harvested material is being used from the company KEFI ITALIA, located close to Bologna, to produce insulation mats from the bark material (www.kenaf-fiber.com).

The production (in thousand tons) of kenaf and other allied crops (1995–2011) is presented in Fig. 1.3.

In 2010/2011, the total production of kenaf and allied crops recorded in the Far East was 82.5 %, in Latin America and the Caribbean countries it was 9 %, in Africa it was 4 %, in developed countries it was 2 %, and in the Near East it was 1 %. The production recorded in 2010/2011 was only 36 % of that recorded in 1994/1995.

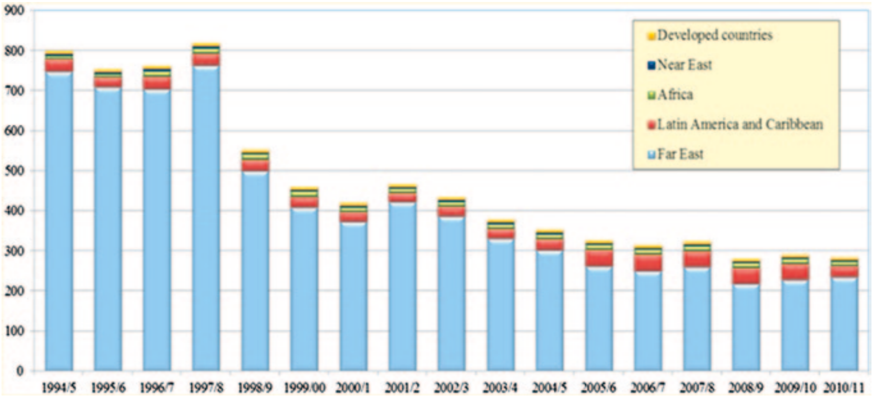

**Fig. 1.3** World production (thousand tons) for kenaf and other allied fiber crops (1994–2011)

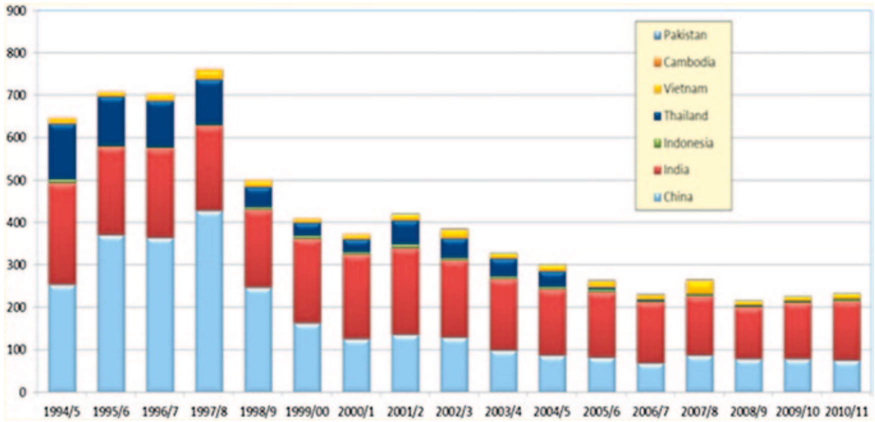

**Fig. 1.4** Kenaf and other allied crops production (thousand tons) in the main cultivation countries

In Fig. 1.3 is presented the production of kenaf and allied crops in the countries of the Far East. Almost 60 % of the kenaf production in the Far East countries (2010/2011) is in Pakistan (140 thousand tons), with China contributing 32 % of the total production, Pakistan 5 %, and Indonesia 1 %. The average overall production in 2010/2011 in countries of the Far East corresponds to 36 % of the production in 1994/1995. In Thailand, the kenaf production became much less in 2010/2011 corresponding to 1.4 % of the total production in 1994/1995 (Fig. 1.4).

## 1.4 Importance of the Crop

Kenaf is a traditional third world crop that is poised to be introduced as a new annually renewable source of industrial fiber in the so-called developed economies. The traditional uses of the crop were the fiber production from its stem (Dempsey 1975) as well as the food use. Kenaf in Africa had several non-fiber uses. People ate the scions and leaves either raw or cooked. The crude protein in the dry leaves is quite high (30 %) and in some countries was consumed as a vegetable. Due to its high crude protein it can be used as animal feed (Zhang 2003). Kenaf seeds are used for oil production and the various plant parts are used in medicines and in certain superstitious rites.

Kenaf, like all other important fiber crops (jute, roselle, hemp, flax, ramie, etc.), can be pulped to make a range of paper and pulps comparable in quality to those produced from wood. With forests dwindling and virgin wood becoming more expensive and the increasing demand for paper products, it can be understood why non-wood fiber crops such as kenaf are so important (Wood and de Jong 1997, Fried 1999). Kenaf in a period of 6 months can reach a plant height of 3–4 m and its production is two to three times higher (per ha and per year) than the southern pine forests (Fried 1999).

Although the importance of the crop is mainly with regard to paper pulp production, kenaf is being characterized as a multipurpose crop because it has a number of additional industrial applications. Thus, kenaf fibers (either derived from the bark or the core of the plant stem) can be an excellent source for several other uses such as for fabrics, building materials (particleboards, low-density panels, wall paper backing, furniture underlays etc.), bedding material, poultry and/or cat litter, oil absorbent, etc. (Kugler 1988; USDA 1988; Perry et al. 1993; Kulger 1996; Borazjani and Diehl 1994; Ramaswamy and Easter 1997; Kaldor et al. 1990). Additionally, the whole plant has high protein and good digestibility and may be pelletized.

Research work on kenaf is being carried out worldwide (USA, Australia, South America, Thailand, India, and Japan). Early research was started in the United States of America in the 1940s in order to use kenaf as a substitute for jute due to the supply distribution from the Far East during World War II (Roseburg 1996). In 1960, kenaf was selected by the United States Department of Agriculture from among 500 crop species (which included hemp) as the most promising non-wood fiber alternative for pulp and paper production. Since then, in the framework of national programs, a large amount of research work has been carried out resulting in a complementary mechanized approach, which has reduced labor requirements and environmental impacts. Nowadays, in USA more resources are asked for putting into work focusing on market development instead of the standard production research.

In Australia, the research on kenaf was initiated in 1972. The research was specifically directed toward growing the crop for production of paper and the field program was supported by studies on the paper making properties of the stem material. The research undertaken clearly confirmed the potential of kenaf as a feedstock for paper production and established the cultural practices necessary to cultivate the crop. The crop has not yet commercialized in Australia due to the fact that Australian pulp mills are mainly based on wood (Wood 1998).

Kenaf has been accepted by the European Community as a "non-food" crop with high production of biomass, composed primarily of cellulose-rich stalk (Venturi 1990; Webber 1993). It was designated for utilization in the production of industrial fiber. The research at the European level on kenaf started in the early 1990s and developments on the crop have been concentrated in the Mediterranean region with sub-tropical climates and have been focused mainly on the primary production in the framework of a European demonstration project aimed at testing kenaf as raw material for paper pulp production. In view of this project (EUROKENAF), demonstrative fields were carried out in all the Mediterranean countries to produce the raw material for its several uses.

The BIOKENAF project (www.cres.gr/biokenaf) offered an integrated approach for kenaf covering the whole production chain (production, harvesting, and storage) testing the suitability of the crop for industrial products (high added value) and energy. This integrated approach was carried out taking into consideration the environmental and economic aspects of the crop and through a market feasibility study was led to the production of industrial bioproducts and biofuels with respect to security of supply and sustainable land management.

In the BIOKENAF project (2003–2007), kenaf was considered an annual fiber crop of great interest for both the production of industrial raw materials and as bio-fuel under the pedoclimatic conditions of south Europe. The main reasons for considering kenaf as a high productivity multipurpose non-food of increasing importance for Europe are discussed below.

It is a multipurpose crop and can provide raw material for industrial and energy applications. The 30–40 % of the stem (bark) can be used for several high value fiber applications, while 60–70 % of the stem (core) among several industrial applications can be used for thermochemical process (combustion pyrolysis and gasification).

It has high biomass potential with relatively low inputs. Dry matter yields of up to 26 have been reported. Under semi-arid conditions, such as prevailing in Mediterranean areas, it requires 250–400 mm of water, which is much lower than in conventional land-use types (including maize, sugar beet, alfalfa, etc.) largely resembling cotton in its water requirements. On the other hand, considering the low N requirements (50–100 kg N/ha), this crop is believed to comprise an important alternative land use in lands with poor and moderate water availability.

It offers alternative land uses and can be used in crop rotation. Kenaf can be cultivated in rotation system. This is important in areas devoted to monocultures (cotton, cereals) and although are supplementary irrigated performing very low yields, which are unsustainable without the EU policies.

As an annual crop, it is similar to other conventional field crops with respect to cultivation and harvest. The production and management systems are being developed for agricultural annual non-food crops such as kenaf, thus bringing costs of delivery down to commercially accepted levels.

Recently, kenaf is considered as a valuable dual purpose crop (fiber and medicinal plant) native to India and Africa (Mohamed et al. 1995). Kenaf is composed of various bioactive components including tannins, saponins, polyphenolics, alkaloids, fatty acids, phospholipids, tocopherol, and phytosterols (Mohamed et al. 1995). This plant has been reported to be anodyne, aperitif, aphrodisiac, fattening, purgative, stomachic, and has long been used in traditional medicine to treat bilious conditions, bruises, and fever (Coetzee et al. 2008; Kobasy et al. 2001; Mohamed et al. 1995; Nyam et al. 2009).

A fairly new application is to use it as a food additive. Dry, powdered kenaf leaves when added to different kinds of foods showed improved contents of calcium and fiber, while the taste remained the same. It has been reported as an ideal food additive and its leaves can also be used as tea. Currently, it was also characterized as a dual crop; crop that can be cultivated for its fibers and/or for its seeds (oil production). From the seed oil and other parts of the crop, medicines can be produced.

The interest in natural fibers is also increasing lately due to new environmental legislation and concerns, resulting in a growing market for biodegradable and recyclable materials. The total worldwide demand for fiber (cellulosic, cotton, wool, man-made, others) is predicted to increase from approximately 50 million tons/year (1999 figure) to 130 million tons/year by 2050 (in line with the predicted growth of the world's population). Europe has already an established bioeconomy, with plants being the basis of European industries with an annual turnover of more than € 1 trillion (Plants for the Future Platform, 2005). But in order to rise to the challenges of a growing population, dwindling resources, and the environment, the new economy has to be knowledge based.

## 1.5 Conclusions

Kenaf is an annual spring crop originating from West Africa (4000 BC). In the eighteenth century it disseminated to Asia and from there went to North and Central America. It is known by more than 120 common names, worldwide. When it is cultivated in high populations it has an erect and unbranched stem. Its stem has two fractions; the bark with long fibers and the core with short fibers. In the middle of the core, the pith can be found that has great absorbing capacity. It is a self-pollinating crop and the cross-pollination varies from 2 to 24 %. Its seeds contain up to 22 % oil and have high content of polyunsaturated fatty acids. It has an effective tap root that makes it drought tolerant.

Currently, it is cultivated in more than 20 countries. Kenaf production was maximized in 1985 and thereafter started to decline. In 2010/2011, the total production of kenaf and other allied plants was 284,000 tons. It is mainly cultivated in Far East Countries; 60 % of the total kenaf production is derived from Pakistan, followed by China (26 %). In the area of its origin (Africa), kenaf production was only 4 % in 2010/2011.

Kenaf can be grown for numerous end uses. The traditional uses of the crop were to produce fiber and food. The fibers can be used to make cordage, rope, burlap cloth, and fish nets because of its rot and mildew resistance (Cook 1960). A range of new applications have been added to the traditional ones, for example: medicines, food additives, oil absorbents, medium for mushroom cultivation, natural fiber/plastic compounds, building materials, biocomposites, as well as for animal bedding and poultry litter.

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# Chapter 2
# Crop Physiology in Relation to Agronomic Management Practices

**Danilo Scordia, Giorgio Testa and Salvatore L. Cosentino**

**Abstract** This chapter describes the physiology of kenaf from seed germination and root development till the effects of water and nutrients stress on grown plants. Review on kenaf agro-physiology of experiments carried out worldwide are presented and discussed mainly at the canopy and whole-plant level with the aim to help producers to make decisions and planning of production. However, few literature reports experimental results on the physiology of this multipurpose crop especially in terms of assimilation rate and its relation with environmental and agronomic factors. Knowledge on gas exchange rate and stomatal conductance may be a key support in understanding the physiology of Kenaf in terms of water requirements, its ability of light conversion into carbonaceous molecules influencing crop production potential and, indirectly, the carbon sequestration activity. In kenaf seedling development takes place when temperatures are higher than 10 °C, supporting the idea that kenaf is a macrothermal plant and optimal sowing has to be carried out during spring-summer, depending on the area of cultivation. Kenaf is very sensitive to reduced soil water availability, however, under moderate water stress conditions the crop maintains root development while reducing final biomass yield. Recent studies from Greece and Italy showed that even though kenaf uses $CO_2$, solar radiation, water, and nitrogen less efficiently than $C_4$ crops its assimilation rates can reach 50–58 kg of $CO_2$ $ha^{-1}$ $h^{-1}$. However, great differences in terms of net photosynthesis have been reported by various authors, which may be related to the different environmental variables and agronomic managements during field and controlled experimental environments, such as air temperature, light intensity, water supply, nutrients availability, relative humidity, wind, cultivar, plant density, and soil type. Similar results were reported in the literature regarding stomatal conductance and transpiration rates. In experiments carried out during the night, stomatal conductance and transpiration rate determined

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water looses probably affecting the water requirement of the crop. Kenaf could be described as opportunistic in relation to water availability, with a high rate of stomatal conductance and transpiration when soil water is available but with markedly reduced leaf conductance and transpiration rate when water is limited. Extinction coefficient for light ($K_L$) and nitrogen ($K_N$), under water limited conditions, were found to be always smaller than under irrigated conditions, as a result of irregular adjustment of leaf orientation to incident radiation particularly during midday. Vertical Specific Leaf Nitrogen (SLN) distributions were found in canopies when leaf area index (LAI) was >1.5. It was observed a strong association between SLN and PAR distributions in irrigated kenaf canopies. Due to its tropical origin, kenaf behaves as a short-day plant remaining vegetative until daylength falls below 12.9 or 12.45 h. Flowering of late-maturity cultivars is under photoperiodic control; conversely, photoperiod does not influence the flowering of early maturity cultivars. Radiation use efficiency (RUE) in kenaf is positively associated with specific leaf nitrogen. RUE decreased under water deficit and nitrogen supply. Water use efficiency (WUE) decreased as the level of irrigation increased. It was higher than other $C_3$ crops, but lower as compared to $C_4$ crops tested in the same environments. Information on nutrient use efficiency (NUE) for kenaf is scarce and not well quantified to date. Higher NUE values were reported for micronutrients than for macronutrients. This last characteristic needs further investigation, since improvement of NUE is an essential and challenging prerequisite for the expansion of bioenergy crop productions into less fertile soils and marginal lands.

**Keywords** Kenaf • *Hibiscus cannabinus* L • Fiber crop • Non-food crop • P hysiology • Macrothermal plant • Photosensitive plant • $C_3$ plant • Seed germination • Root development • Gas exchange rate • Photosynthesis • μmol $CO_2$ $m^{-2}$ $s^{-1}$ • $CO_2$ gas • Photosynthetic active radiation • PAR • Light intensities • Transpiration • mmol $H_2O$ $m^{-2}$ $s^{-1}$ • Stomata • Stomatal conductance • Canopy • Leaf area index • LAI • Specific leaf area • SLA • Coefficients for light • $K_L$ • Coefficients for nitrogen • $K_N$ • Vertical specific leaf nitrogen • SLN • Daylength • Radiation use efficiency • RUE • Water use efficiency • WUE • Nutrient use efficiency • NUE • $^{15}N$ labeled

## 2.1 Introduction

Kenaf (*Hibiscus cannabinus* L.), is a "non-food" annual, herbaceous plant of the Malvaceae family, which has recently received great attention thanks to its high above-ground biomass yield and its chemical composition of the raw material (Alexopoulou et al. 2000; Amaducci et al. 2000). The high cellulose and hemicellulose and low lignin content makes kenaf an interesting crop for fiber, pulp, thermal insulation board, thermoplastic composite, energy, and biofuels (Amaducci et al. 2000; Alexopoulou et al. 2004; Baldwin and Graham, 2006; Ardente et al. 2008; Lips et al. 2009).

The species originated from tropical and sub-tropical regions. Many authors agree that kenaf originated in Africa, where several forms of the species are found as widespread (Siepe et al. 1997) and its domestication occurred around 4000 BC in the Sudan region (Dampsey 1975).

Basically, kenaf is a warm season photosensitive, $C_3$ photosynthetic pathway species with a high adaptability to a wide geographical range and soil types but very sensitive to frost and damaged by heavy rains and strong wind (BIOKENAF Booklet 2007). According to its sensitivity to daylength, kenaf is classified as a short-day plant, even though cultivars, either early or late-maturing, differ markedly in their response to daylength (Angelini et al. 1998). Patanè and Sortino (2010) reported that there is a strong daylength control on floral initiation of kenaf. In their study using cv. Tainung 2 under South Mediterranean climate they found that irrespective of sowing dates flowering took place in a very restricted period (from late September to early October).

The high assimilation capacity of this $C_3$ plant has also suggested to study the environmental performance of kenaf in terms of carbon storage potential and capacity to act as carbon dioxide sink (Pervaiz and Sain 2003).

However, few literature reports experimental results on the physiology of this multipurpose crop especially in terms of assimilation rate and its relation with environmental and agronomic factors. Knowledge on gas exchange rate and stomatal conductance may be a key support in understanding the physiology of Kenaf in terms of water requirements, its ability of light conversion in carbonaceous molecules influencing crop production potential and, indirectly, the carbon sequestration activity.

This chapter describes the physiology of kenaf from seed germination and root development till the effects of water and nutrients stress on grown plants. Review on kenaf agro-physiology of experiments carried out worldwide are presented and discussed mainly at the canopy and whole-plant level with the aim to help producers to make decisions and planning of production.

## 2.2 Seed Germination and Root Development

### *2.2.1 Seed Germination*

After reaching maturity, the small, black, subreniform seeds of kenaf (approximately 1.5–3.3 g/100 seeds), retain viability for about 8 months under ordinary storage conditions (Baldwin 1994). Seeds stored at 8 % moisture content remain viable for up to 5.5 years when stored at 0 °C, while seeds stored above 10 °C and 12 % moisture show significant decrease in seed viability (Toole et al. 1960). Meints and Smith (2003), confirmed that germination under ideal conditions remained high in seeds stored up to 4 years at 10 °C and did not show appreciable differences in field emergence or performance through the growing season. Based on their results, kenaf seeds will continue to perform well in field production when stored up to 5 years at 10 °C.

Germination and seedling development in kenaf are, however, critical phases and the duration of these phases is a function of only temperature (Angelini et al. 1998), if water is not a limiting factor (Mosley and Baldwin 1999).

Seedling establishment comprises the germination and emergence phase, and the root development phase. In kenaf seedling development from sowing to emergence can be described in terms of three phases: (i) sowing to germination (ii) a lag phase in hypocotyl elongation and (iii) linear hypocotyl elongation. Seedlings emerge when the length of the hypocotyl equals sowing depth (Carberry and Abrecht 1990), with a simultaneous initial development of roots which enables seedlings to acquire the necessary water and nutrients for growth.

Angus et al. (1981) have calculated that the thermal time for approximately 50 % emergence of kenaf seedlings from a depth of about 30 mm was 44.1 °Cd above a base temperature of 9.2 °C. However, this requirement usually changes for different sowing depths, cultivar, and climatic conditions of a specific region or area of cultivation (Abrecht 1989).

Carberry and Abrecht (1990) conducted a study to examine seed germination and the elongation of the hypocotyl and radicle of kenaf cv. Guatemala-4 under eight constant temperature conditions (from 15 to 45 °C). Final germination percentage was unaffected by temperatures in the range of 15–35 °C, but declined sharply at the higher temperatures. The minimum, optimum, and maximum temperatures for rate of seed germination, were found to be 9.7, 35, and 45 °C, respectively.

Values of optimum and maximum temperatures for the lag and linear phases of hypocotyl elongation were about 31 and 43 °C, respectively; similar values of optimum and maximum temperatures for elongation of the radicle were found. A simulation model of seed germination was developed by the same authors, who showed that under a standard base temperature of 10 °C, the thermal-time requirements for seed germination and the lag and linear phases of hypocotyl elongation of kenaf were 8.2, 17.0, and 0.45 °Cd mm$^{-1}$, respectively. Base, optimum, and maximum temperature values for hypocotyl elongation of 10, 31, and 43 °C, respectively, were proposed as estimates for post-emergent development of kenaf.

Following Carberry and Abrecht (1990) findings, a study on kenaf germination was carried out in central Italy with the aim to assess cultivars suitable to early sowings and resistant to cold in the early stages of growth (Angelini et al. 1998). Fifteen kenaf lines and cultivars selected for tolerance to low temperatures were compared to cv. Tainung 2, this latter known to have great sensitivity to low temperatures. Mean germination percentage and mean germination time were lower in all lines at 8 °C compared to 10 °C (74.6 vs. 84.1 % and 13.9 vs. 8.8 days, respectively). In cv. Tainung 2, both parameters resulted to be considerably lower compared to the mean of all lines. At alternating temperatures of 20/30 °C differences between most lines and cv. Tainung 2 were not found (Angelini et al. 1998). According to Angus et al. (1981) and Carberry and Abrecht (1990), Angelini et al. (1998) stated that seedling development takes place when temperatures are higher than 10 °C, supporting the idea that kenaf is a macrothermal plant, and optimal sowing has to be carried out during spring-summer, depending on the area of cultivation.

### 2.2.2 Root Development

Roots play an important role in supplying water to plant tissue. The root development is critical for the growth and productivity of crops (Seiler, 1998). Root development and distribution on soils are important information for root-water studies in soil–plant systems (Asseng et al. 1997). Estimates of the amount of roots per unit volume of soil are required in studies for water uptake by plants.

Patanè et al. (2009) using kenaf cv. Tainung 2 and four water conditions (100, 50, 25 % of Etm restoration during the whole crop cycle and irrigated only at sowing, respectively $I_{100}$, $I_{50}$, $I_{25}$ and $I_0$) under south Mediterranean climate, have shown that kenaf under different moderate water stress conditions maintains root development while reducing final biomass yield. In their study root length density, according to the method of Newman (1966), was calculated following the formula:

$$\text{Root length density } (L) = \pi\, N\, A\, \rho s\, /2HM$$

where $L$ is the root length density (cm cm$^{-3}$), $\pi = 3.14$, $N$ is the total number of root distribution crossing the gridlines, $A$ is the area of root distribution (132.66 cm$^2$), $\rho s$ is the apparent soil gravimetric mass (g cm$^{-3}$), $H$ is the total length of the gridlines (80 cm), and $M$ is the soil sample mass (g).

In their results, the amount of water distributed affected $L$ in the most superficial layer of soil (0–20 cm), where the bulk of roots developed. In particular, under good soil water availability ($I_{100}$), root apparatus more developed as compared to that of other experimental conditions. In the dry control ($I_0$), $L$ was about 50 % shorter than what measured at the fully irrigated treatment, due to strong soil water deficit in the most superficial soil layers. At the same soil depth (0–20 cm), intermediate water regimes ($I_{25}$ and $I_{50}$, respectively) determined similar $L$ (5.38 and 5.57 cm cm$^{-3}$, respectively), both different to those measured at the extreme water regimes ($I_0$ and $I_{100}$, respectively).

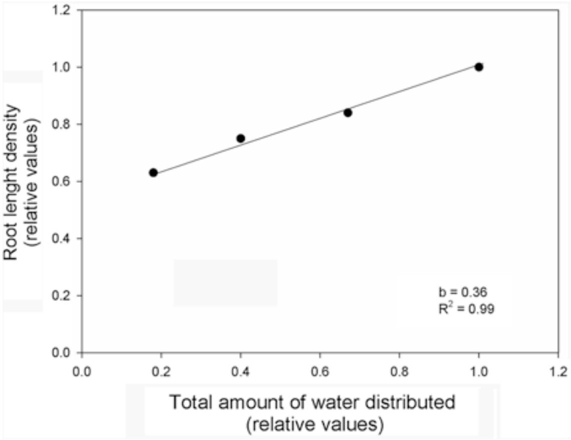


**Fig. 2.1** Relationship between relative values of root length density versus relative values of total water distributed in each irrigation treatment (from Patanè et al. 2009)

At deeper soil layers (20–40 cm), the differences among water treatments were less evident, in particular those between extreme water regimes. These differences further decreased in the deepest soil layers (60–80 cm) where water treatments did not vary in $L$; this last, however, at these soil depths was quite negligible (0.61 cm $\text{cm}^{-3}$, on the average of water treatment). A relationship between root length density ($L$) and total amount of water distributed was developed (Fig. 2.1). In kenaf, root growth seems to have a low sensitivity to water stress declining at low rates when soil water availability decreases ($b = 0.36$).

## 2.3 Kenaf Physiology

After seedling emergence and root development, kenaf starts growing driven by photosynthetic activity. All plants use the Photosynthetic Carbon Reduction (PCR or Calvin-Benson) cycle for $CO_2$ fixation in which Ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) catalyzes the first step producing a three-carbon compound, phosphoglycerate (3-PGA). The plants using this process are known as $C_3$ (Lara and Andreo 2011). A major problem with $C_3$ species is that Rubisco catalyzes two reactions, carboxylation and oxygenation; these two reactions, however, compete each other (Portis and Perry 2007). Environmental variables, such as high temperature and drought can result in an increase in oxygenation leading the flow of carbon through the photorespiratory pathway, resulting in 25–30 % losses in carbon fixation (Lara and Andreo 2011). To overcome the limitation of photorespiration, some plants (only 3 % of the vascular plants), mainly native from tropics and warm temperate zones adapted to high temperature and high light intensity, have developed the so-called $C_4$ pathway. In these plants, photorespiration is suppressed by great elevation of the $CO_2$ concentration at the site of Rubisco, suppressing the oxygenase activity and increasing growth rates, carbon, water, and nitrogen uses (Lara and Andreo 2011). Knowledge on gas exchange rate and transpiration can hold the better perceptive of kenaf physiology which finally affects its growth and biomass productivity.

### *2.3.1 Photosynthesis of Kenaf*

Although kenaf is a $C_3$ species originated from tropical and sub-tropical regions, the high assimilation capacity of this $C_3$ plant has suggested to study the environmental performance of kenaf in terms of carbon storage potential and capacity to act as carbon dioxide sink (Pervaiz and Sain 2003). However, few literature reports experimental results on the physiology of this multipurpose crop especially in terms of assimilation rate and its relation with environmental and agronomic factors. Recent studies from Greece and Italy showed that even though kenaf uses $CO_2$, solar radiation, water, and nitrogen less efficiently than $C_4$ crops its assimilation rates can reach 50–58 kg of $CO_2$ $ha^{-1}$ $h^{-1}$ (32–37 μmol $CO_2$ $m^{-2}$ $s^{-1}$) (Danalatos and Archontoulis 2005; Cosentino et al. 2004).

A study on carbon dioxide assimilation capacity in relation to soil water conditions in internal hilly areas of Sicily, Italy, has been recently conducted by Cosentino et al. (2004). Gas exchange at leaf level has been measured at noon on five dates (August 6th, 12th, 21st and 28th, and September 6th) during vegetative phase on the last fully expanded leaf of kenaf cv. Tainung 2 under four different soil water contents (100, 50, 25 % of Etm restoration during the whole crop cycle and irrigated only at sowing, respectively $I_3$, $I_2$, $I_{1,}$ and $I_0$).

In the best water conditions ($I_3$) the crop maintained the highest net photosynthesis level (28.4 μmol $CO_2$ $m^{-2}$ $s^{-1}$, in the average of the five measurements), compared to $I_2$ (21.3 μmol $CO_2$ $m^{-2}$ $s^{-1}$), $I_1$ (17.8 μmol $CO_2$ $m^{-2}$ $s^{-1}$), and $I_0$ (15.5 μmol $CO_2$ $m^{-2}$ $s^{-1}$).

From the first measurement onward, a slight reduction in net assimilation activity was observed in all water treatments. The last field measurement occurred just few hours after a rainfall, which determined a relevant increase in net photosynthesis, irrespective of the water regime.

Kenaf is a $C_3$ crop but the observed net assimilation rate resulted quite high; this contribute to explain the high growth rate, which makes this crop very interesting in terms of biomass production and carbon sequestration.

Archontoulis et al. (2005) conducted a similar study on similar environments (south Mediterranean), in which different light intensities (in the range of 0–2,000 μmol PAR $m^{-2}$ $s^{-1}$) and temperatures (in the range of 10–40 ºC) on leaf photosynthesis of kenaf cv. Everglades 41 was carried out. It was concluded that kenaf is characterized by a high photosynthetic capacity. Maximum rates of about 50 kg $CO_2$ $ha^{-1}$ $h^{-1}$ were achieved at early crop development stages, when the maintenance respiration was still at a low level. The optimum temperature for maximum assimilation increased with an increase in light intensity; the optimum temperature for kenaf was in the range of 25–29 ºC.

More recently, a comparative photosynthesis of three variety of Kenaf, namely Guantemala 4 (G4), V36, and kohn kaen 6 (KK60) was measured within four regular intervals of 30 days under glasshouse with temperature of approximately 25 °C during the day and 20 °C during the night.

Although the varieties showed different gas exchange pattern in each stage of their growth, results of the study showed that there was no significant difference between these three varieties in terms of their net photosynthesis. It was reported that net assimilation rate tended to increase gradually from 2.8 μmol $CO_2$ $m^{-2}$ $s^{-1}$ at first month to a peak of 6.5 μmol $CO_2$ $m^{-2}$ $s^{-1}$ on second month and then decrease to 3.0 and 1.5 μmol $CO_2$ $m^{-2}$ $s^{-1}$ at third and forth growth month, respectively (Tahery et al. 2011).

Abdul-Hamid et al. (2009) conducted experiments throughout Malaysia on the utilization of less fertile soils, such as “Beach Ridges Interspersed with Swales Soil” (BRIS soil). Different level of fertilizer applications were supplied with the objective of studying the effects on growth and physiology of Kenaf variety V36 planted on BRIS soil. All measurements were taken at 08.00–11.00 am to avoid the midday depression in photosynthesis. The analysis of variance revealed that photosynthesis rate was significantly influenced by the level of fertilization in the dry season; net photosynthesis was in the range of 11.34–17.07 μmol $CO_2$ $m^{-2}$ $s^{-1}$ in the low and high fertilization, respectively. Contrasting results were, instead, found in the wet season, probably due to the humidity in the air which might affect stomatal conductance that reduced water through vapor to balance physiological plants and at the same time photosynthesis rate was reduced.

Hossain et al. (2010) studied the net photosynthesis under different levels of nitrogen (0, 50, 100, 200, and 400 mg $l^{-1}$), phosphorus, and potassium (0, 25, 50, 100, and 200 mg $l^{-1}$) of kenaf cv. V36. Photosynthesis was significantly increased with the increase of nutrient concentration up to 200N, 100P, and 100K and afterwards, decreased. Photosynthesis of 200N, 100P, and 100K were 14.45, 12.56, and 12.83 μmol $CO_2$ $m^{-2}$ $s^{-1}$, respectively, when averaged across the measuring times. The lowest photosynthesis was observed in 0 N, 0 P, and 0 K treatments (2.5–4.0 μmol $m^{-2}s^{-1}$). Some reports suggest that N deficiency affects more strongly the leaf development than photosynthesis (Watson 1952; Wong 1979; Radin and Boyer 1982; Reddy et al. 1997). Field and Mooney (1986) and Gerik et al. (1998) described the effects of low N, P, and K nutrition on plants causing slower leaf expansion and consequently lower photosynthetic rates. In this respect, Muchow (2009) found that photosynthetic capacity of kenaf increased with specific leaf nitrogen (SLN) from 0 to 24 g N $m^{-2}$. It was also confirmed by Archontoulis et al. (2012) who showed increasing the leaf nitrogen per unit area increases the net assimilation rate as well.

The decline in net photosynthesis at low N, P, and K levels might be explained by both greater stomatal resistance and the less biochemical efficiency of chloroplasts (Chapin, 1980; Reddy et al. 1996).

The great differences in the value of net photosynthesis reported by various authors may be related to the different environmental variables and agronomic managements during field and controlled experimental environments, such as air temperature, light intensity, water supply, nutrients availability, relative humidity, wind, cultivar, plant density, type of soil (Table 2.1).

Among others, the level of irradiance is an important ecological factor which determines the assimilation rate. Under high or low light intensities, the diffusion rate of $CO_2$ from the air to the stomata is the major factor limiting $CO_2$ assimilation. For instance, the photosynthetically active radiation (PAR) during the growing period was 500–700 μmol $m^{-2}$ $s^{-1}$ in the experiments of Hossain et al. (2010), while it was in the range of 280 and 2,000 μmol $m^{-2}$ $s^{-1}$, as typical of spring-summer period in the South Mediterranean environments, as reported in both Archontoulis et al. (2005) and Cosentino et al. (2004). This difference in PAR may explain the difference in $CO_2$ assimilation rate of kenaf studies, as have been also reported by Riggi et al. (2004). They found linear regression curves when plotted photosynthetic rate and PAR levels under artificial light conditions and two soil water treatments (full irrigated and irrigated only at sowing, respectively $I_{100}$ and $I_0$) of kenaf cv. Tainung 2. Accordingly, Cosentino et al. (2004) and Archontoulis et al. (2005) stated that the higher the PAR, the higher the net photosynthesis in kenaf.

**Table 2.1** Photosynthesis of different cultivars of kenaf according to the treatment, experimental environment, latitude and longitude of the site, photosynthetic active radiation (PAR), and soil type

| Cultivar | Treatment | Environment | Latitude/ longitude | Country | PAR (μmol $CO_2$ $m^{-2}$ $s^{-1}$) | Soil type | Net photosynthesis (μmol $CO_2$ $m^{-2}$ $s^{-1}$) |
|---|---|---|---|---|---|---|---|
| Tainung 2[a] | Water stress | Field | 37°23′N, 14°21′E | Italy | ±1750 | Xerofluvent | 15.5–28.4 |
| Everglades 41[b] | Light intensity/leaf temperature | Field | 39°25′N, 22°05′E | Greece | 0–1675 | Acquic Xerofluvent | 3.2–31.5 |
| Guantemala 4[c] | Cultivar | Greenhouse | 02°59 N, 101°43′E | Malaysia | – | Sand/clay/peat (2:1:1) | 2.8–6.5 |
| V36[c] | Cultivar | Greenhouse | 02°59′N, 101°43′E | Malaysia | – | Sand/clay/peat (2:1:1) | 2.3–6.0 |
| Kohn kaen 6[c] | Cultivar | Greenhouse | 02°59′N, 101°43′E | Malaysia | – | Sand/clay/peat (2:1:1) | 4.6–6.8 |
| Kenaf (not specified)[d] | Flooding | Pot | 33°35′N, 130°23′E | Japan | 1000 | Sandy | 17.2–19.8 |
| V36[e] | Fertilizer level | Field | 05°36′N, 102°44′E | Malaysia | – | BRIS | 11.3–17.1 |
| V36[f] | Fertilizer level | Shadehouse | 02°59′N, 101°42′E | Malaysia | 500–700 | Hoagland solution | 2.5–14.5 |
| Everglades 41[g] | Leaf nitrogen content | Field | 39°25′N, 22°05′E | Greece | 0–2000 | Acquic Xerofluvent | 9.5–35.5 |

*Source* [a]Cosentino et al. (2004), [b]Archontoulis et al. (2005), [c]Tahery et al. (2011), [d]Mai and Kubota (2009), [e]Abdul-Hamid et al. (2009), [f]Hossain et al. (2010), [g]Archontoulis et al. (2012)

### *2.3.2 Transpiration and Stomatal Conductance of Kenaf*

Plant transpiration is a part of the water cycle, and it is a process similar to evaporation. It consists of the loss of water vapor from parts of plants, especially in leaves but also in stems, flowers, and roots (Benjamin 2007). Leaf transpiration occurs through stomata, and can be thought of as a necessary "cost" associated with the opening of the stomata to allow the diffusion of $CO_2$ gas from the air for photosynthesis.

Most of the water taking part in the transpiration process is used for cooling purposes, i.e., to maintain certain temperature equilibrium in the plant (Archontoulis et al. 2005) and also in changing cell's osmotic pressure, and enables mass flow of mineral nutrients and water from roots to shoots.

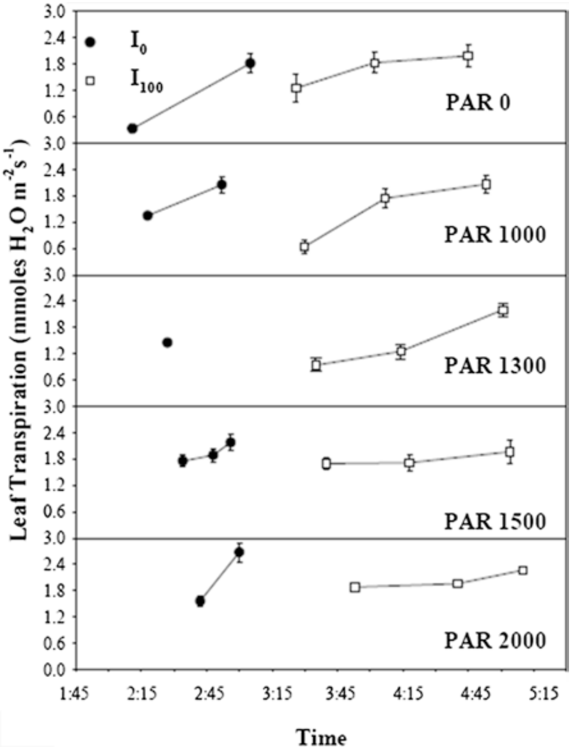
The rate of transpiration is directly related to the degree of stomatal opening, and to the evaporative demand of the atmosphere surrounding the leaf. The amount of water lost by a plant depends on its size, along with surrounding light intensity (Debbie and Michael 2010) temperature, humidity, and wind speed (all of which influence evaporative demand) (Jarvis and Davies 1998; Jones 1998).

In kenaf cv Guatemala 4 (G4), V36, and kohn kaen 6 (KK60), Tahery et al. (2011), who measured at four regular intervals of 30 days under glasshouse with temperature of approximately 25 °C during the day and 20 °C during the night, found that except the first measurement in which all varieties showed identical transpiration rate (1.3–1.6 mmol $H_2O$ $m^{-2}$ $s^{-1}$), at other stages of growth, there were differences in the transpiration rate. G4 had highest at 60 days (3.6 mmol $H_2O$ $m^{-2}$ $s^{-1}$) and KK60 had the lowest rates of transpiration at day 120 (0.53 mmol $H_2O$ $m^{-2}$ $s^{-1}$).

In the mean of all measurements, G4 was assigned to have the highest transpiration rate (2.09 mmol $H_2O$ $m^{-2}$ $s^{-1}$), while the lowest transpiration rate belonged to both of V36 and KK60 (1.71 mmol $H_2O$ $m^{-2}$ $s^{-1}$).

Some authors carried out field experiments observing stomatal opening during the night that, in turn, may affect water requirement and leaf transpiration (Muchow et al. 1980). In this respect, Riggi et al. (2004) conducted night measurement, in South Mediterranean environment, with the aim to study stomatal conductance and leaf transpiration in relation to different soil water content treatments (full irrigated and irrigated only at sowing, $I_{100}$ and $I_0$ respectively) in vegetative stage of kenaf cv. Tainung 2. Measurements have been carried out from 2:00 am up to 5.15 am imposing different Photosynthetic Photon Flux Density (PPFD) levels (0, 1,000, 1,300, 1,500, and 2,000 μmol $m^{-2}s^{-1}$ of PAR). Within each soil water content treatment, transpiration rate increased during the night and the highest values have been registered on the last measurement interval (5.15 am), as shown in Fig. 2.2. In natural condition, at 0 μmol $m^{-2}$ $s^{-1}$ PPFD level, the first value registered for $I_0$ treatment at 2:00 am resulted very low (0.33 mmol $H_2O$ $m^{-2}s^{-1}$) due to the stomatal closure observed. However, on the measurement reported one hour later (3:00 am), the transpiration rate increased up to 1.82 mmol $H_2O$ $m^{-2}s^{-1}$. A slighter increment has been observed for irrigated treatment as well, moving from 1.25 mmol $H_2O$ $m^{-2}s^{-1}$ reported at 3:20 am to 1.99 mmol

**Fig. 2.2** Leaf transpiration in response to different artificial light intensity during night measurements for the unirrigated (•) and irrigated (□) treatment (from Riggi et al. 2004)



$H_2O$ $m^{-2}s^{-1}$ registered at 4:45am. Under all the artificial light levels studied, unexpected high leaf transpiration rates was observed in the rainfed treatment, and for the latest data collected within each treatment (irrigation treatment and PAR levels) no statistical differences was reported.

Stomatal conductance increased during the night for all the adopted light intensity levels and for both studied treatments (Fig. 2.3). First measurements have been conducted on unirrigated treatment at 0 PPFD level at 2:00 am and substantially no stomatal conductance has been observed (0.02 mol $m^{-2}s^{-1}$). However, data registered at 3:00 am with no artificial light, shown an increase of stomatal opening and stomatal conductance equal to 0.24 mol $m^{-2}s^{-1}$.

For the irrigated treatment, in relation to the wider observation interval (ranging from 3:20 to 5:15 am) a relevant increase in stomatal conductance and so in stomatal opening has been observed especially for the lower PPFD levels. Respectively at 0, 1,000, and 1,300 μmol $m^{-2}s^{-1}$ of PAR, increments equal to 300, 800, and 600 % have been registered, while less evident increase in stomatal conductance have been observed for the highest PAR levels (respectively 140 and 160 % for 1,500 and 2,000 μmol $m^{-2}s^{-1}$ of PAR).

In order to study separately the influence of light intensity and night time on stomatal behavior, stomatal conductance measured in the full irrigated ($I_{100}$) was split in three different 30 minutes intervals respectively ranging from 3:20 to 3:50

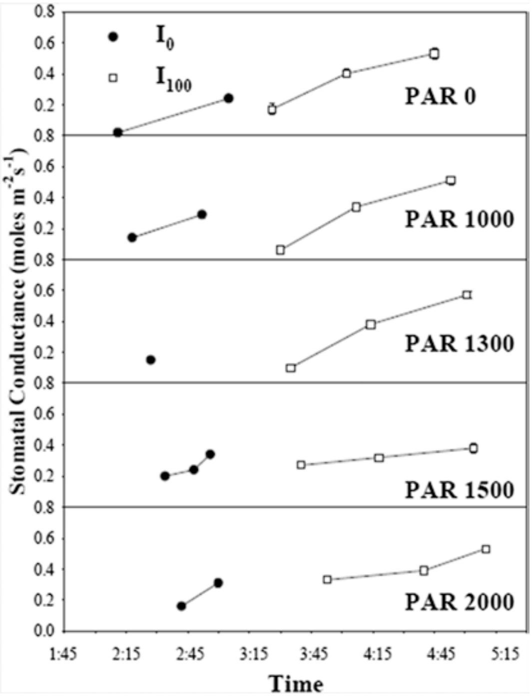


**Fig. 2.3** Stomatal conductance in response to different artificial light intensity during night measurements for the unirrigated (•) and irrigated (□) treatment (from Riggi et al. 2004)

am, from 4:00 to 4:30 am, and from 4:45 to 5:15 am and plotted against light intensity (Fig. 2.4). In this way, it was possible to emphasize evident positive relation between PPFD and stomatal conductance only in the earlier interval, while after 4:00 am no response was observed to light intensity; at 4:00–4:30 am interval stomatal conductance at all light intensity ranged between 0.3 and 0.4 mol $m^{-2}$ $s^{-1}$ while in the last interval it ranged between 0.48 and 0.59 mol $m^{-2}$ $s^{-1}$. Accordingly with Muchow et al. (1980) results, the reported data suggest night stomatal opening incrementing during the nyctoperiod. It was concluded that the observed nocturnal stomatal conductance and transpiration rate determine water losses also during the night probably affecting the water requirement of the crop. The observed relation between night time and stomatal opening for both soil water content treatments, not influenced by artificial light intensity, seems to suggest an endogenous control of stomatal behavior. However, more data are needed aiming at verifying the real nature of the observed phenomena.

Archontoulis et al. (2005) carried out a study in which different light intensities (in the range of 0–2,000 μmol PAR $m^{-2}$ $s^{-1}$) and temperatures (in the range of 10–40 ºC) on leaf transpiration of kenaf cv. Everglades 41 was attempted. An exponential relationship, independent of radiation, between leaf temperature and transpiration rate was found: $Y = 0.1246e^{0.1457*\text{temp}}$.

It was concluded that transpiration rates increased exponentially with increasing leaf temperature at all light levels. At temperatures above 35 ºC, a single leaf may transpire the equivalent of 30 mm per day at full canopy.

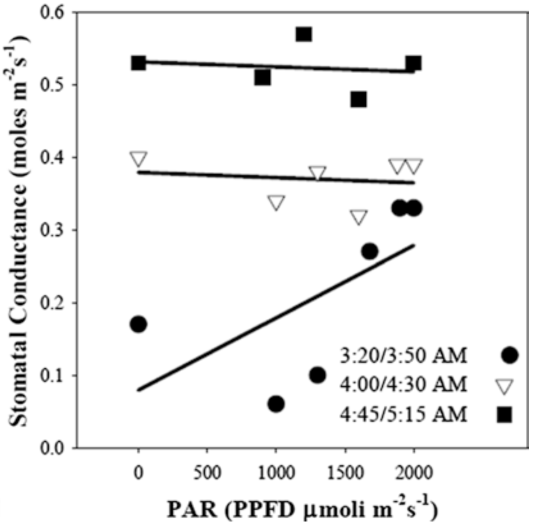


**Fig. 2.4** Stomatal conductance during different night periods under increasing light intensities (from Riggi et al. 2004)

The effects of water stress (three watering regimes representing well-watered control, moderate stress, and severe stress) of Kenaf cv. Cuba 108, grown on a loose-textured sandy soil in the greenhouse, have also been studied (Ogbonnaya et al. 1998). It was found that all the levels of stress brought stomatal conductance and transpiration to zero. Transpiration rate started declining steeply below -0.5 MPa leaf water potential, and eventually ceased below -1.0 MPa. Moreover, stomatal conductance and transpiration rate progressively declined with age in the adequately watered control. Kenaf could therefore be described as opportunistic in relation to water availability, with a high rate of stomatal conductance and transpiration when soil water is available but with markedly reduced leaf conductance and transpiration rate when water is limited. This contrasts with wheat, which utilizes water sparingly when it is available but has only a gradual decrease in photosynthesis as water deficits develop (Henson et al. 1989).

Kenaf was also observed to roll its leaves during drought. These two mechanisms could be described as drought tolerance by dehydration postponement (Kramer 1983), equivalent to drought avoidance by Levitt (1980).

### *2.3.3 Vertical Distributions of Light in Kenaf Canopy*

Organization and spatial distribution of leaves within the canopy directly affect the amount of light absorbed by this integrated system. Photosynthetic capacity at canopy level depends not only on factors affecting leaf level photosynthesis but also on factors influencing properties of canopy microclimate, particularly its light distribution profile (Matloobi 2012).

Plants, living in a changing light environment have the capacity to adjust their morphology and physiology to a particular set of light conditions by acclimatation or phenotypic plasticity (Oguchi et al. 2005). For instance, plants are able to adjust leaf area per unit biomass invested in leaves (i.e., specific leaf area) by altering leaf thickness (leaf weight to leaf area) or by adjusting leaf weight to plant weight (Niinemets 1999).

Leaf area development is an important determinant of the proportion of the incident radiation intercepted and consequently of stem yields. Carberry and Muchow (1992), who conducted a study on leaf area development of kenaf cv. Guatemala 4 grown under irrigation at a range of plant population densities at three sites in tropical Australia, found that Kenaf produced nodes, and therefore leaves, at a constant rate until the onset of flowering, after which vegetative development generally ceased. The thermal time required for production of new nodes remained constant from sowing to flowering at 36.3 °C days node$^{-1}$ at a population of 50 plants m$^{-2}$. Leaf area per node was described quantitatively in terms of three phases where, as node number increased, leaf area per node at first increased linearly, reached a plateau, and finally declined linearly. The rate at which the leaf area at old nodes was senesced was found to be equivalent to the rate of production of new nodes.

The projected leaf area per unit leaf dry mass, specific leaf area (SLA) and the leaf area over surface area, leaf area index (LAI), are of great importance in understanding the processes of plant growth and photosynthesis. SLA and LAI influence the leaf area ratio and thus the relative growth rate of the crop. The higher SLA and LAI, the higher the growth rate (more light intercepted, higher net assimilation rate) and thus the higher the biomass production (Archontoulis et al. 2005).

Among factors influencing canopy architecture and vertical distribution of light, water and nitrogen availability play a key role. Without water stress, the Beer's law has long been used by many authors to describe vertical distribution of light and nitrogen in plant canopy by assuming an exponential decline over canopy depth (Hirose and Werger 1987; Monsi and Saeki 2005, Archontoulis et al. 2011). Vertical distributions of light and nitrogen in a crop canopy are generally quantified by the so-called extinction coefficients for light ($K_L$) and for nitrogen ($K_N$). In most studies, extinction coefficient for nitrogen ($K_N$) has been shown to be closely related to extinction coefficients for light ($K_L$), indicating that nitrogen allocation is driven to some extent, either directly or indirectly, by light distribution (Evans 1993; Anten et al. 1995; Milroy et al. 2001; Pons et al. 2001; Bertheloot et al. 2008; Archontoulis et al. 2011). Under water stress, the light and nitrogen distributions over canopy depth are more complicated because water stress affects not only appearance and elongation of leaves and uptake and partitioning of nitrogen, but also morphological aspects of leaf positioning, leaf angle, and azimuth angle (Archontoulis et al. 2011).

Recently, vertical distributions of light and nitrogen in canopies of kenaf grown with and without water stress have been quantified by Archontoulis et al. (2011). Under water limited conditions $K_L$ values were found to be always smaller than under irrigated conditions, as a result of irregular adjustment of leaf orientation to incident radiation particularly during midday. Both $K_L$ and $K_N$ did not change significantly in all irrigated crops, except between years (0.62 and 0.71, respectively at first and second year experiment). Earlier studies from Muchow (1992), Manzanares et al. (1993), and Losavio et al. (1999a) including different genotypes and management practices of kenaf indicated constant $K_L$ values per experimental season ($K_L$ of 0.56, 0.72, and 0.35, respectively).

Vertical Specific Leaf Nitrogen (SLN) distributions were found in canopies when LAI was >1.5, while when LAI was ≤1.5, i.e., at early or late growth stages or in water-stressed canopies, there were no obvious SLN gradients. SLN values at the canopy bottom were around 1.0 g N $m^{-2}$ when LAI was ≥3 and 2.2–3.8 g N $m^{-2}$ at the top leaves in irrigated treatments. It has been previously reported that maximum net assimilation rates were saturated at SLN >2.0 (Muchow 1990). Archontoulis et al. (2011) also observed strong associations between SLN and PAR distributions in irrigated kenaf canopies. Crops responded to irrigation by increasing their LAI or maintaining high LAI values for a longer period rather than changing the pattern of SLN distribution.

This strong effect of water regime on LAI was also confirmed by Patanè et al. 2009. In their study on kenaf cv. Tainung 2 and four water regimes (100, 50, 25 % of Etm restoration during the whole crop cycle and irrigated only at sowing, respectively $I_{100}$, $I_{50}$, $I_{25,}$ and $I_0$) in south Mediterranean environment a maximum value of LAI was attained when crops received the full irrigation volume (3.24). Water stress in $I_{25}$ and $I_0$ exerted a detrimental effect upon LAI which never exceeded a value of 1.

Archontoulis et al. (2011) study has shown that SLN distributions in irrigated kenaf canopies appeared to be largely associated with the light environment.

Such associations between light and nitrogen gradients have been found in many crops (Sadras et al. 1993; Anten et al. 1995; Del Pozo and Dennett 1999; Milroy et al. 2001; Lötscher et al. 2003), and are explained either from an adaptive response to irradiance gradient in order to maximize canopy photosynthesis (Hirose and Werger, 1987) or as a consequence of the mediation by cytokinins in the transpiration stream on the response to light (Pons et al. 2001).

### 2.3.4 *Sensitivity of Kenaf to Daylength*

Vegetative development of Kenaf generally declines rapidly following the onset of flowering. Due to its tropical origin, kenaf behaves as a short-day plant remaining vegetative until daylength falls below 12.9 h (Carberry et al. 1992) or 12.45 h (Alexopoulou et al. 2000). Flowering of late-maturity cultivars is under photoperiodic control; conversely, photoperiod does not influence the flowering of early maturity cultivars (Alexopoulou et al. 2000), which, however, due to a shorter period of vegetative growth are less productive in terms of final biomass yield (Foti et al. 1998; Alexopoulou et al. 2000).

The high sensitivity of this species to daylength makes quite difficult to produce seed in Europe, and limits its cultivation to this purpose to semi-arid environments of Southern Europe, where light and temperature conditions are the most favorable for seed maturation (Liu and Labuschagne 2009). In fact, in Northern Europe, late floral initiation makes difficult to produce mature seed prior to a killing frost, as have been also reported for the United States, where seed production of late-maturity cultivars is limited only to Southern Countries (Meints and Smith 2003).

Therefore, seed production is always feasible for the early varieties, while for the late ones seed production depends on the prevailing climatic conditions during autumn (Alexopoulou et al. 2000). This effect, therefore, affects the choice of the most suitable cultivar and sowing time and, as a consequence, harvests time.

The relation between climatic factors and the "sowing—flowering" interval in kenaf has been extensively studied by Carberry et al. (1992) and by Williams (1994), who described a qualitative response of floral induction to photoperiod.

Patanè and Sortino (2010) reported that there is a strong daylength control on floral initiation of kenaf. In their study using cv. Tainung 2 under South Mediterranean climate they found that irrespective of sowing dates (late May to early July) flowering took place in a very restricted period (from late September to early October).

The synchronous occurrence of flowering shortened the "emergence—flowering" interval while postponing sowing time, from 109 days to 85–92 days. The length of the following interval "flowering - pod ripening" was, instead, quite constant (Fig. 2.5).

In their experiment, thermal time from "sowing—emergence" resulted 76.2 °Cd with a base temperature of 12 °C and a threshold temperature of 23 °C; thermal time of "emergence—flowering" interval, with a base temperature of 10 °C and a threshold temperature of 31 °C, ranged from 2090 °Cd (sowing of 24 May, 2001) to 1718 °Cd (sowing of 30 June 2000). It was observed that thermal time decreased from the first to the last sowing date in both year experiments, and this fact could be explained as a photoperiod effect (Fig. 2.6).

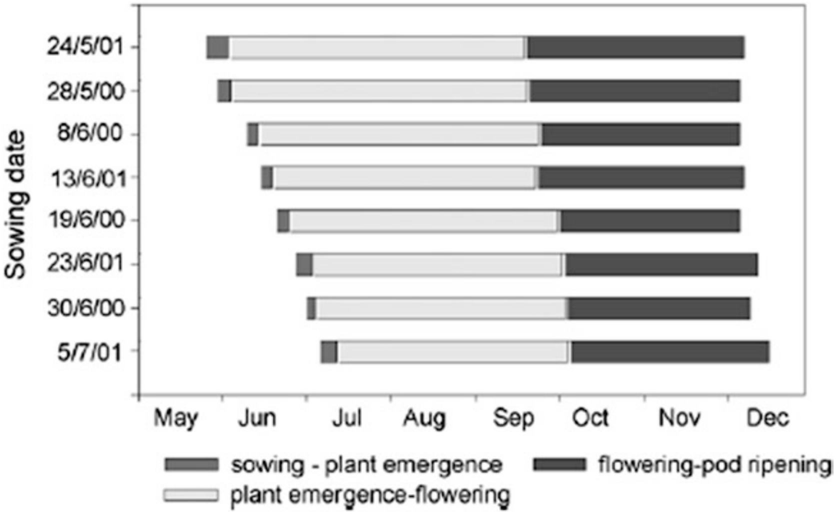


**Fig. 2.5** Length of main phonological stages of crop growing season in relation to sowing dates (from Patanè and Sortino 2010)

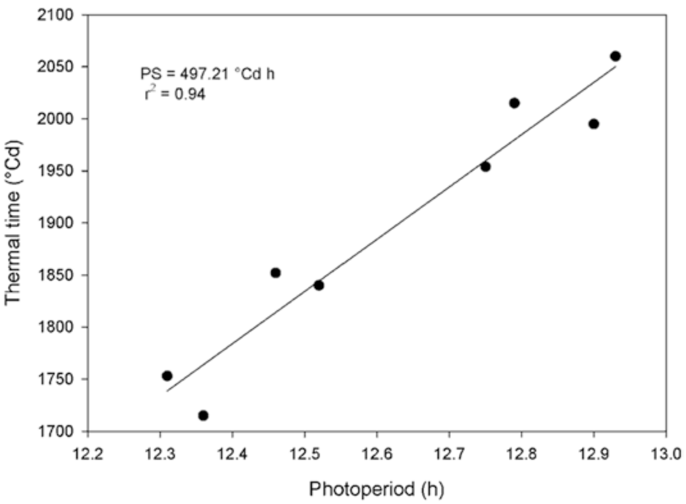


**Fig. 2.6** Relationship between thermal time calculated for the plant "emergence—flowering" interval and photoperiod at flowering for each sowing time (from Patanè and Sortino 2010)

The photoperiodic sensitivity (calculated regressing thermal time of the interval 'emergence—flowering' against photoperiod at flowering time) resulted equal to 497.21 °Cd h, and can be considered as thermal time to flowering controlled by photoperiod, as reported by Williams (1994). An average value of base vegetative phase (subtracting the photoperiodic sensitivity from thermal time to flowering) of 1563.0 °Cd was obtained.

At a thermal time value of 1563 °Cd corresponded a photoperiod of 13.83 h for the first sowing date and 14.06 h for the second one. The authors stated that the average of these two values (13.94 h) can be considered as critical photoperiod for cv. Tainung 2. This value is quite close to those obtained by Williams (1994) for other cultivars of kenaf.

The photoperiod inductive phase values (calculated for each sowing date) varied between 497.2 and 182.2 °Cd h. It was concluded that a positive trend in seed yield in response to lengthening of 'emergence—flowering' interval was found. With early sowings the crop is able to assimilate a higher total dry matter before flowering, useful for sustaining a higher stem, pod, and seed production (Patanè and Sortino 2010).

## 2.4 Resource Use Efficiency

### *2.4.1 Radiation Use Efficiency*

Radiation use efficiency (RUE) is a crop-specific parameter and can be defined as the relationship between biomass production per unit light intercepted or adsorbed by the crop. It is widely used to measure the growth efficiency of plant productivity across different crops and management practices. The value of the RUE is expressed in grams of aerial dry matter or total dry matter per megajoule of radiation (g $MJ^{-1}$); it varies depending on whether radiation is measured as total solar radiation or as PAR (Justes et al. 2000; Lindquist et al. 2005). The radiation intercepted by a crop is different from that absorbed by it and, therefore, introduces variation in RUE calculations. Some authors suggest that conversion of RUE based on solar radiation, with respect to that based on PAR, is achieved simply by multiplying the fraction of total solar radiation that is photosynthetically active (usually 0.5, Sinclair and Muchow 1999), while Bonhomme (2000) pointed out that the appropriate multiplication factor depends on canopy LAI. When canopy LAI is large it has been assumed that 85 % of intercepted PAR (IPAR) is absorbed by the leaf canopy, while smaller values have to be used when canopies are less dense (Sinclair and Muchow 1999; Bonhomme 2000).

However, variation in estimates of RUE can be substantially reduced by measuring both intercepted and absorbed radiation continuously during a sampling period (Lindquist et al. 2005).

A number of factors contribute to the variation in estimates of RUE, which includes physical factors of the environment or intrinsic crop characteristics, such as extreme temperatures, either very low or very high, developmental stage, sowing period, plant density, water stress, or nitrogen deficiency (Sinclair and Muchow 1999).

Cultivars with better nitrogen uptake and the ability to partition more of the nitrogen uptake to leaf would be expected to have higher RUE. Higher RUE, however, also results in higher rates of water use and as water use is linked to biomass production, greater risk of soil water deficit under low rainfall conditions may be expected (Muchow and Carberry 1993).

Muchow (1990) stated that RUE is positively associated with specific leaf nitrogen in kenaf. In a field study carried out in semi-arid tropical Australia with the aim to determine the effect of water and nitrogen supply on kenaf cv. Guatemala 4, a baseline RUE of 1.2 g $MJ^{-1}$ was observed (Muchow 1992). Lower values were obtained under water deficit and nitrogen supply (Muchow 1992). The baseline RUE was similar to the maximum RUE reported for sorghum at the same location, but lower than that for maize (both $C_4$ species).

This high sensitivity of RUE to nitrogen deficiency was also observed by Muchow and Davis (1988) and Sinclair and Horie (1989) for maize, sorghum, rice, and soybean.

Higher RUE (2.4 g $MJ^{-1}$) compared to that showed by Muchow (1992) was reported in experiments carried out in Mediterranean environments using kenaf cv. Tainung 2 and 100 % of maximum evapotranspiration restitution (Perniola et al. 1997). However, in the treatment where only water was supplied at sowing a RUE of 1.1 g $MJ^{-1}$ was achieved, while increasing the water at 50 % of maximum evapotranspiration restitution or irrigation when only soil water content reached -1.5 MPa resulted in a RUE of 1.6 g $MJ^{-1}$. Lower RUE lead also to decreased crop growth rate (CGR) of 36 % in the limited water supplies and 83 % in the irrigation only at sowing compared to the fully irrigated treatment (Perniola et al. 1997).

### 2.4.2 Water Use Efficiency

Water use efficiency (WUE) at leaf level is generally expressed as net assimilation of $CO_2$ per unit of water transpired (μmol $CO_2$ mmol $H_2O^{-1}$). The most important effects of genotype and environment on WUE at leaf level are described by the equation of Fisher and Turner (1978), who have taken into account the differences in concentration of $CO_2$ and $H_2O$ between air and leaf, the diffusivity of $CO_2$ and water vapor, and the diffusion resistance of the boundary layer of stomata and mesophyll (Rivelli et al. 1998).

At field level WUE is defined as biomass yield divided by the total amount of water applied.

Kenaf is described as opportunistic in relation to water availability, with a high rate of stomatal conductance and transpiration rate when water is not limited, and a markedly reduced stomatal conductance and transpiration rate when water availability is restricted (BIOKENAF Booklet 2007).

In a field experiment carried out in Mediterranean environment, using kenaf cv. Tainung 2 and four water regimes, an average WUE value of 1.4 μmol $CO_2$ mmol $H_2O^{-1}$ has been reported. WUE ranged between 1.9 μmol $CO_2$ mmol $H_2O^{-1}$ (50 % of ETc) and 1.1 μmol $CO_2$ mmol $H_2O^{-1}$ (100 % of ETc) (Rivelli et al. 1998). However, when WUE was normalized with respect to the vapor pressure deficit (VPD) measured at leaf level values of 6.6 and 3.6 μmol $CO_2$ mmol $H_2O^{-1}$ kPa were achieved at 50 and 100 % of ETc, respectively (Rivelli et al. 1998). Similarly, the relationship between kenaf water use and crop dry matter production were conducted under typical Mediterranean climate in Southern Italy. It was reported that kenaf was able to reach a WUE of 2.3 kg $m^{-3}$ of water even though elevated irrigation regimes are necessary in order to obtain high productive levels from kenaf (Losavio et al. 1999b).

Higher WUE were obtained in a field study on kenaf at five different levels of irrigation in central California. WUE ranged between 1.52 kg $m^{-3}$ in the irrigation level of 150 % ETc to 4.36 kg $m^{-3}$ in the irrigation level of 50 % ETc. WUE decreased as the level of irrigation was increased from 25 to 150 % ETc. This trend is common for many species, including cotton and corn (Howell 2000) and is partially due to increased evaporation and deep percolation losses at the higher irrigation levels (Bañuelos et al. 2002).

Similar results were achieved by Patanè et al. 2007 using kenaf cv. Tainung 2 and four water regimes (100, 50, 25 % of Etm restoration during the whole crop cycle and irrigated only at sowing, respectively $I_{100}$, $I_{50}$, $I_{25}$, and $I_0$) in South Mediterranean environment. WUE was in the range of 3.75 and 4.22 g dry matter $l^{-1}$ for full irrigation ($I_{100}$) and irrigation only at sowing ($I_0$), respectively. In their study the irrigation water use efficiency (IWUE) was also calculated, giving a more accurate tool to evaluate the efficiency of water transformation into biomass in relation to the different water treatments. Table 2.2 shows the water utilized by the crop according to the different water treatments and both WUE and IWUE of kenaf cv. Tainung 2 (Patenè et al. 2007).

A linear relationship between water supplied and the dry biomass produced demonstrates how kenaf is particularly reactive to the amount of irrigation water, keeping reduced levels of yield with limited amount of water while increasing the IWUE in these conditions (Fig. 2.7).

**Table 2.2** Water utilized by the crop according to the different water treatment and the WUE and IWUE of kenaf cv Tainung 2[a]

| Water treatment | Irrigation water supplied (mm) | Rainfall (mm) | Total (mm) | WUE (g DM $l^{-1}$) | IWUE (g DM $l^{-1}$) |
|---|---|---|---|---|---|
| $I_0$ | 92.6 | 130 | 222.6 | 4.22 | 7.72 |
| $I_{25}$ | 210.3 | 130 | 340.3 | 4.08 | 5.57 |
| $I_{50}$ | 327.9 | 130 | 457.9 | 3.82 | 4.71 |
| $I_{100}$ | 563.3 | 130 | 693.3 | 3.75 | 4.27 |

*Source* [a]Patenè et al. (2007)

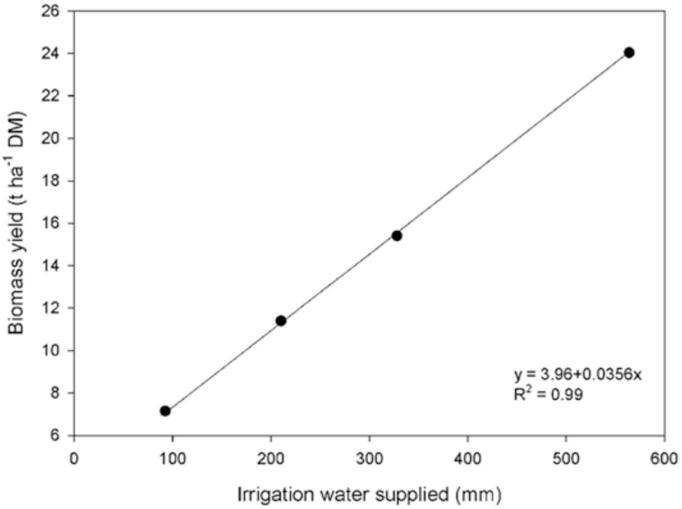


**Fig. 2.7** Relationship between irrigation water supplied and biomass yield of kenaf cv Tainung 2 (from Patanè et al. 2007)

### 2.4.3 Nutrient Use Efficiency

Nutrient use efficiency (NUE) is dependent on many factors including soil nutrient availability, uptake, transport, storage, mobilization, usage within the plant, and may be generally defined as biomass yield per unit input applied. Mosier et al.

(2004) described four agronomic indices to explain NUE: partial factor productivity (PFP, kg crop yield per kg nutrient applied); agronomic efficiency (AE, kg crop yield increase per kg nutrient applied); apparent recovery efficiency (RE, kg nutrient taken up per kg nutrient applied); and physiological efficiency (PE, kg yield increase per kg nutrient taken up). Crop removal efficiency (removal of nutrient in harvested crop as % of nutrient applied) is also commonly used to explain nutrient efficiency (Roberts 2008). The most commonly limiting nutrients for plant growth, especially for annual crops, are N, P, K, and S.

Information on NUE for bioenergy crops, including kenaf, are scarce and not well quantified to date. Hossain et al. (2011), studied five kenaf varieties (V36, G4, KK60, HC2, and HC95) grown in pots under shade house condition and sandy BRIS soil. They reported that most of the kenaf varieties showed variation in NUE (g dry matter $mg^{-1}$ nutrient). Values of <1.0 g DM $mg^{-1}$ nutrient were observed for macronutrients, whereas higher NUE values were obtained for micronutrients.

Among macronutrients (N, P, and K), phosphorous use efficiency (PUE) was greater than potassium use efficiency (KUE) and nitrogen use efficiency (NUE). The most efficient cultivar was HC95 with 0.35, 0.09, and 0.07 g DM $mg^{-1}$ nutrient, respectively for PUE, KUE, and NUE, while lowest values were reported for cultivar V36 (in the same order of 0.24, 0.08, and 0.05 g DM $mg^{-1}$ nutrient). According to the micronutrient use efficiency, higher values were observed for Cu (293.34 g DM $mg^{-1}$ nutrient), followed by Mn (67.84 g DM $mg^{-1}$ nutrient), Zn (45.66 g DM $mg^{-1}$ nutrient), and Fe (14.41 g DM $mg^{-1}$ nutrient) in cultivar HC95.

From the agronomic and environmental point of view, improvement of NUE is an essential and challenging prerequisite for the expansion of bioenergy crop productions into less fertile soils and marginal lands with low nutrient availability and to avoid risk of losses when fertilizers are applied at rates above agronomic need.

In order to determine the correct crop fertilization, a clearer understanding of the uptake of the applied nutrients and the storage in various plant organs is necessary. In this respect, Mantineo et al. (2008) carried out a study on the destiny of the nitrogen from mineral fertilizer on kenaf under water levels (100, 50, and 25 % of Etm restoration during the whole crop cycle, respectively $I_{100}$, $I_{50}$, and $I_{25}$) and nitrogen doses ($N_{75}$ and $N_{150}$, respectively 75 and 150 kg $ha^{-1}$ of N) by means of $^{15}N$ labeled nitrogen application. Isotopically labeled nitrogen was distributed in the top dressing fertilization as $(^{15}NH_4)SO_2$ and at harvest leaves, stems, flowers, and roots were analyzed for N labeled. Nitrogen derived from fertilizer index (Ndiff) was determined according to Recous et al. (1988) method:

$$\text{Ndiff\%} = 100\,(c - b)\ /\ (a - b)$$

where $a$ is the atom% $^{15}N$ abundance of fertilizer, $b$ is the atom% $^{15}N$ abundance of control plants that did not receive labeled fertilizer, $c$ is the atom% $^{15}N$ abundance of labeled plant sample. Nitrogen recovered from labeled fertilizer (%Nrec.) was calculated according to Hauck and Bremner (1976) as:

$$\text{\%Nrec.} = 100P\,(c - b)\ /f\ (a - b)$$

where $P$ is meq of $N$ in the sample and $f$ is meq of $N$ in the fertilizer.

**Table 2.3** Percentage of N derived from the fertilizer (Ndiff%) out of the total plant N and percentage of N in the plant recovered from the fertilizer (%N rec.) out to the dosage of applied fertilizer[a]

| | Stem | | Leaves | | Flowers | | Roots | | Plant | |
|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | Ndiff% | Nrec.% | Ndiff% | Nrec.% | Ndiff% | Nrec.% | Ndiff% | Nrec.% | Ndiff% | Nrec.% |
| $I_{25}$ $N_{75}$ | 14.36 | 9.42 | 18.36 | 27.18 | 18.78 | 3.03 | 27.65 | 2.39 | 17.65 | 42.02 |
| (St. Error) | (2.1) | (3.8) | (4.7) | (6.6) | (2.3) | (0.7) | (0.8) | (0.1) | (2.5) | (9.9) |
| $I_{25}N_{150}$ | 22.41 | 10.72 | 26.90 | 20.92 | 26.59 | 2.07 | 31.55 | 1.71 | 24.88 | 35.47 |
| (St. Error) | (3.3) | (2.3) | (2.0) | (0.6) | (3.1) | (1.0) | (1.7) | (0.1) | (2.5) | (2.6) |
| Average$I_{25}$ | 18.39 | 10.09 | 22.77 | 24.05 | 22.68 | 2.55 | 29.60 | 2.05 | 21.27 | 38.74 |
| $I_{50}$ $N_{75}$ | 11.91 | 20.08 | 12.66 | 27.17 | 13.02 | 3.17 | 25.05 | 3.93 | 13.51 | 54.35 |
| (St. Error) | (2.8) | (1.7) | (5.2) | (10.7) | (3.5) | (0.1) | (1.8) | (0.9) | (3.3) | (11.5) |
| $I_{50}N_{150}$ | 21.67 | 17.50 | 24.27 | 33.00 | 24.69 | 2.95 | 32.50 | 2.33 | 23.51 | 55.77 |
| (St. Error) | (5.8) | (3.3) | (9.7) | (14.1) | (8.3) | (0.9) | (1.9) | (0.1) | (6.4) | (18.1) |
| Average$I_{50}$ | 16.79 | 18.79 | 18.46 | 30.08 | 18.85 | 3.06 | 28.76 | 3.13 | 18.51 | 55.06 |
| $I_{100}$ $N_{75}$ | 30.48 | 45.48 | 12.29 | 29.29 | 13.78 | 4.20 | 28.60 | 3.50 | 25.29 | 82.47 |
| (St. Error) | (7.0) | (12.2) | (3.1) | (4.6) | (2.9) | (1.4) | (0.4) | (1.1) | (5.2) | (18.0) |
| $I_{100}N_{150}$ | 39.48 | 30.16 | 26.51 | 24.57 | 25.09 | 3.10 | 36.90 | 3.86 | 36.65 | 61.69 |
| (St. Error) | (3.5) | (1.2) | (0.1) | (4.5) | (2.3) | (0.8) | (1.5) | (0.9) | (1.9) | (3.1) |
| Average$I_{100}$ | 34.98 | 37.82 | 19.40 | 26.93 | 19.43 | 3.10 | 32.73 | 3.68 | 30.97 | 72.08 |
| Average$N_{75}$ | 18.92 | 24.99 | 14.53 | 27.88 | 15.19 | 3.47 | 27.11 | 3.27 | 15.08 | 59.61 |
| Average$N_{150}$ | 27.85 | 19.47 | 25.89 | 26.16 | 25.45 | 2.71 | 33.64 | 2.62 | 27.78 | 50.98 |
| Average | 23.38 | 22.23 | 20.21 | 27.02 | 20.32 | 3.09 | 30.38 | 2.95 | 21.43 | 55.29 |

*Source* [a]Mantineo et al. (2008)

On the average of the studied factors, nitrogen derived from the fertilizer in the plant (Ndiff%) and the nitrogen recovered in the plant from labeled fertilizer (%Nrec.) resulted equal to 21.4 and 55.29 %, respectively (Table 2.3). The percentage of *N* derived from fertilizer (Ndiff%), in the average of the studied treatments, found in the roots (30.38 %) resulted higher compared to the stems, leaves, and flowers (23.38, 20.21, 20.32 %, respectively). The percentage of N derived from fertilizer in the plant (Ndiff%) increased with the N fertilization levels (15.08 % against 27.78 % in $N_{75}$ and $N_{150}$, respectively). With low availability of water in the soil, Ndiff% was equal to 21.27 % (25 % ETc) and 18.51 % (50 % ETc), whereas with good water condition Ndiff% attained 30.97 %. Irrigation levels from 25 to 100 %, ETc, increased the N recovered from labeled fertilizer (%Nrec.) from 38.74 to 72.08 %, while the level of N application determined slight differences of N recovery (59.61 to 50.98 %, respectively for $N_{75}$ and $N_{150}$). It was concluded that the percentage of N derived from fertilizer (Ndiff%) is almost 24 %, while the other N derives from organic matter in the soil, N in irrigation water and dry deposition. The plant has uptaken almost 55 % of the fertilizer applied. The remaining part of fertilizer was probably immobilized by microorganism and, partially, was lost by volatilization or leaching.

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# Chapter 3
# The Breeding of Kenaf

**Defang Li and Siqi Huang**

**Abstract** The main purpose of breeding new kenaf is developing new varieties that are higher yielding, resistant to pests and diseases, drought-resistant or regionally adapted to different environments and growing conditions. Kenaf breeding can be accomplished through many different techniques ranging from simply selecting plants with desirable characteristics for propagation, to more complex molecular techniques. Classical kenaf breeding uses crossing of closely or distantly related individuals to produce new kenaf varieties or lines with desirable properties. Plants are crossbred to introduce traits/genes from one variety or line into a new genetic background. Modern plant breeding may use techniques of molecular biology to select, or in the case of genetic modification, to insert, desirable traits into kenaf. The main methods which have been used in kenaf are introduction and breeding, system selection, crossbreeding, mutation breeding, transgenic breeding, and so on.

## 3.1 Introduction

The Kenaf is a 4,000-year-old new crop with its roots in ancient Africa. As a member of the hibiscus family (*Hibiscus cannabinus* L), it is related to cotton and okra, and grows well in many parts of the world. It offers a way to make paper without cutting trees. Kenaf grows quickly, rising to heights of 3–5 m in as little as 4–5 months (Li 2010). There are many different varieties of kenaf, and certain varieties will perform better in certain locations, or under certain conditions than other varieties. Breeding selection of new cultivars is the most effective measure to increase production per unit area and improve fiber quality. There are many methods of breeding, such as pedigree selection, inter-varietal cross breeding, multiploid

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breeding, and high photo-efficiency breeding, etc. Breeding selection of kenaf mostly start from introduction of new varieties and pedigree selection. As demands grow later for more varieties to expand production, inter-varietal cross breeding has become the chief form of breeding selection. Gradually, consideration is being given to new technologies such as the use of distant hybridization and radiation breeding.

## 3.2 Methods of Kenaf Breeding

Hybridization consists of simple cross, complex crosses, and back crosses. A simple cross is also called a positive cross. In the case of A × B, it is called positive cross. In the case of B × A, it is called negative cross. In a complex cross, the hybrid progeny will be used for further crossing. For example, $(A \times B)F_1 \times C$ is called a 3-varietal cross. $(A \times B)F_1 \times (C \times D)F_1$ is called 4-varietal cross. Hybrid progeny can be further improved in this way. As a result, one hybrid cultivar can possess numerous advantages of several varieties. In a back cross, the hybrid progeny of a simple cross are used to hybridize with a parent plant. For example, $(A \times B)F_1 \times A$ or $(A \times B)F_1 \times B$. Back cross can be carried out several times. For example, $(A \times B)F_1 \times A\text{-} > B_1F_1Xa\text{-} > B_2F_1Xa\text{-} > B_3F_2$. The most commonly used method is the positive cross.

Hybrid breeding is a complicated and demanding job. In practice, a fairly large population is needed to meet the requirement for selection. When the population is too large, there would be too much work to do. How do we do it in a reasonable way? Let us take an example to specify the method for breeding selection and points for attention concerning the development of a variety called “China kenaf NO.13” (Li et al. 2009; Chen et al. 2011b).

## 3.3 Breeding Target

The breeding target is a question of top priority that the breeder must consider first before any breeding plan can be made and it depends on the need for production. Generally, aspects to be considered are high yield, superiority, and resistance. Consideration is also given to local natural conditions, cropping systems, and the possibility of carrying out mechanical operation.

As different regions have different natural conditions and cropping systems, breeding targets will vary accordingly. The criteria of determination of breeding target for kenaf have been “disease-resistant, high yielding, early sowing but not early flowering”, “disease-resistant, high yielding, salt tolerant”, “disease-resistant, high yielding, late maturing”, and so on. We are trying to breed a new variety that can be high yielding (10 % higher than current varieties), resistant to disease (disease index to be decreased by 20 %), and medium to late maturing, suitable for growing in South China.

## 3.4 Parent Plants and Their Combinations

Selection of parent plants depends on the breeding target. Accurate selection is the key to the success of hybrid breeding. Selection can be made according to the following principles: The characters of both parent plants should be consistent with the breeding target so that they can complement each other; Selection of geographically distant varieties for hybridization can enrich genetic constitution and help breed new cultivars that accord with the breeding target; Selection of one of the varieties is used for large-scale production as one of the parent plant.

In selecting a high-yielding variety, consideration should be given to different yield characters. High yield is a comprehensive character which is affected by many factors. Attention should be paid to height of plant, thickness of stem, height of branches, and fiber percentage/plant of high yielding varieties.

According to the selection principles for parent plant, the parent plants consist of 8 varieties, including Zhonghongma No.1, Qinpin 3, Meifeng No.4, YA1A, China kenaf No.1, Fuma 882, Qiongshan, and Zhongzahong 316.

Combinations: the above varieties are used to make 20 hybrid combinations such as Zhonghongma No.1 × Qinpin 3, Qinpin 3 × Meifeng No.4, China kenaf No.1 × Fuma 882. The total number of hybrid capsules obtained is 236. Each combination has 15–20 capsules.

## 3.5 Regulation of the Flowering Stage

After having selected the right parent plants in accordance with the breeding target, we first try to know the flowering stage of parent plants. Hybrid breeding can be made only when the flowering stage of the two parent plants have to be regulated. Normally, this could be regulated by sowing at different times. In case the flowering stages of the two parents vary greatly, short day treatment should be carried out to help the late maturing parent plants to flower in advance. The stepwise procedure for hybridization is: selection of plant-selection of flower bud- emasculation-pollination-seed harvest.

## 3.6 Selection and Cultivation of Hybrid Progeny

Ways of selecting hybrid progeny consist of pedigree selection, modified pedigree selection, and mass selection.

In the first year (F1), seeds are sown according to the hybrid combination from single capsules. Generally, there is no need for selection. The only reason for this is to remove false hybrids and inferior individual plants. The population should be larger and the selection rules should be stricter. Seeds are respectively harvested from the selected single plant. The methods for F3 up to F5 are basically the same as those for F2. The aim is to select superior single plants from the stabilized superior lines, in which case comparison of stains and varieties can breed superior varieties.

### 3.6.1 Breeding Selection of Hybrid

In the same winter when hybrid capsules are obtained the F1 is grown in the southernmost China of Hainan Province (18 North Latitude). The purpose of growing material is to accelerating the process of breeding. Sowing is usually carried out in October. In the next March to April, seeds can be harvested. From the start of emergence of seedlings, "false" hybrids are removed in accordance with the law of dominance and excessiveness. For example, an F1 between a variety with an auxiliary bud and the one without will have an axillary bud. F1 between a green variety and a red variety is red. F1 between a variety with unlobed leaves and one with lobed has lobed leaves. Apart from removal of false hybrids, some seeds will also be lost due to natural and mechanical causes. Seed of 254 hybrid capsules are harvested from 20 combinations for F1. The total number of plants is 886.

For F2, seeds from the respective single plants are sown. Each line has a sowing area of 3 $m^2$ (the number of seedling is fixed between 80 and 100). F2 has a population of 886 lines. The total number of seedlings is between 80,000 and 90,000. Parent plants are used to make comparison with the F2 progeny in order to characterize their morphological characters (leaf shape, pigmentation of stem and axillary bud, height of plant), resistance to disease and growth period. After the characterization, let us say that two inferior combinations are removed and 620 superior single plants are selected from 18 hybrid combinations (each combination has about 100 plants). Selection of F2 should be strict; otherwise more work will be involved for the progeny.

*Criteria of selection*. Plant height should be the same as that of the high-yielding parent plant. Resistance to the disease should be the same as that of the highly resistant parent plant. Growth period should be the same as that of the breeding target.

For F3, the sowing area of each line is slightly smaller than that of F2, that is about 2 $m^2$. But the population is still the same as that of F2. Methods for characterization and selection are the same as those of F2. 1034 superior single plants are selected from 12 combinations.

The method for F4 is identical to that for F3, but the check varieties should be those used for eventual production in the large area. Emphasis of characterization is laid on whether the morphological characters and growth period are stable, production and resistance to disease can reach the breeding target with reference to height of plant, thickness of bark and height of branches. 642 superior single plants are selected from 12 combinations.

For F5 generation, the chief work to be done is to check the stability of the population. Selection is carried out in accordance with the breeding target. Results of characterization in our example show that 37 single plants from six combinations can meet the requirement. Seeds of those selected materials are mixed harvested in order to make strain comparisons.

### *3.6.2 Strain Comparison*

The plot area is 6 $m^2$ and there are three replications, the sequence of which is arranged in order. Commercial varieties are used for comparison. One area is used to characterize resistance to disease. Artificial inoculation of anthracnose is also characterized. From this, four strains are selected from 37 strains for making experiments on cultivar compassion. They are numbered 71-10, 71-22, 71-28, and 71-36, respectively.

### *3.6.3 Experiment on Cultivar Comparison*

The plot area is 8 $m^2$ and there are five replications, the sequence of which is arranged at random; four of them are carried out to test the yield and one of them is carried out to make investigations and get samples. The experiment will last 3 years. From the second year onwards demonstrative experiments on new cultivars will be simultaneously carried out in kenaf production regions in the south of China. The result of experiments shows that "China kenaf No.13" performs very well. Its results of 3 years experiments and demonstrative trail data for production are documented and submitted to the Varieties Examination Committee. It is recognized as a superior of kenaf after being jointly examined by the specialists. It is now widely grown in kenaf production regions. It has been selected from the combination between "Zhonghongma No.1" and "Qinpin 3". Its stem and leaf stalks are red, without axillary buds; the leaf blade is quite thick; it grows quite fast in early stage; the stem is strong and thick; the thickness of the upper and lower stems is fairly regular; its height is 510 cm; its growth period in Hunan province is between 150 and 190 days, belonging to the medium and late maturing type; yield per ha is 6,750 kg.

## 3.7 Items and Contents of Characterization

Items and contents of characterization vary with different breeding targets. Take for example the breeding selection of the new cultivar of kenaf, "China kenaf No.13", which is aimed at increasing resistance to anthracnose as its first objective. From F2 to F4, artificial inoculum is applied continuously for breeding selection. A large number of susceptible varieties are eliminated. Resistant and high-yielding superior strains are selected from F4 after breeding selection through cultivar comparison experiments.

## 3.8 Methods and Procedure for Selection

### *3.8.1 Rough Selection*

It is carried out in the late stage of the vigorous growth period. Its purpose is to eliminate sick, inferior, and early flowering plants. The total number of eliminated plants must be discarded.

### *3.8.2 Preliminary Selection*

It is carried out in the flowering stage. Tall healthy and vigorous plants are selected. The selected plants should be marked.

### *3.8.3 Re-selection*

It is carried out in the late of flowering stage. Check cultivars are used for comparison in order to make better selection. Inferior combinations and lines are eliminated. Superior single plants are selected from those lines which performed very well. The selected plants are investigated, recorded (concerning their morphological characters, resistance to disease and economic characters), numbered, and tagged. To enable the selected plants to display fully their respective characters, the inferior materials must be discarded.

### *3.8.4 Final Selection*

It is carried out in the seed harvest period. According to investigation and their field performance, the materials to be selected are finally examined. Every selected single plant is harvested and seeds are collected and conserved. Seeds of the stabilized superior lines discovered from F4 and F5 are mixed harvested. Their yield should be tested for making strain comparison in the next year.

### *3.8.5 Fundamentals of Selection*

Breeders must fully understand the genetic variation in kenaf and make use of it. Characterization of "false" and genuine $F_1$ progeny is based on the laws of

**Table 3.1** The main characters of kenaf

| Parameters | Characters of parent plants | Performance of F1 |
|---|---|---|
| Leaf | Unlobed leaf × Lobed leaf | Lobed leaf |
| Pigmentation of stem | Green × Red | Light red |
| | Green × Green | Green |
| Growing period | Early maturing × Late maturing | Medium to slightly late maturing |
| Height of plant | Medium × Tall | Fairly tall |

dominance. The main characters of $F_{1,}$ which include the leaf shape, growing period, height, pigmentation of stem and flower, may be used for characterization. Qualitative traits should be selected from $F_2$ to $F_4$ with reference to the laws of genetic variation, while quantitative traits should be selected with reference to their respective selection which can be made from the early progeny, while for those with low heritability, selection should be made from the late progeny. For example, growing period, height of plant and disease resistance has high heritability. Such traits can be extensively selected in $F_2$ and $F_3$. Traits with slightly lower heritability such as thickness of fresh bark and fiber percentage/plant should be selected in $F_3$ and $F_4$ (Table 3.1).

## 3.9 Acceleration of the Process of Breeding

It takes about 8 or 9 years to breed a new cultivar. This is because hybrid progeny will not stabilize until after several generations. The duration can be shortened by 2–3 years in the following ways:

1. Sowing of F1 and F3 in non-growing period.
2. Use of right means of characterization. From F2 to F3, eliminate inferior materials as much as possible. In this way, superior materials may be obtained more quickly in F4.
3. In case special superior materials are found, increase the number of seed and expand the experiments of these special types.

In order to breed a new superior cultivar, first of all, select good parent plants and at the same time, use correct methods of selecting. Sometimes, the success of this work depends on the skilfulness of the breeders. The key to the settlement of this question lies in repeated experiments in order to make sure that the selection is correct.

Finally, we succeed to breed the Kenaf new variety, china Kenaf No.13 (original name: Lc0301), which was bred from progeny of “Zhonghongma No1 × Qinpin 3”, is a textile and multipurpose new Kenaf Variety with high yield, disease-resistance, lodging resistances, high quality, and wide adaptability. Meanwhile, it is decomposite leaf, red stem, and no early flowering. In China national kenaf regional trial, the average fiber yield of china Kenaf 13 was 4251.31 kg/h2, 16.37 % higher than that of CK “china Kenaf 12” from 2004 to

2006. Average fiber and stem yields ranked the second place among the conventional varieties. The main symbols of China Kenaf 13 are high plant, thick bark, high percent of effective plants, bast fiber percentage, disease-resistance, and fiber quality. Its average fiber strength was 316 N, fineness was 267. All of the traits were better than that of CK. Disease index was 12.1 and rotten head rate was 0.8 % showed that it was high resistant to the anthracnose disease.

## 3.10 Method of Breeding for Disease Resistance

The methods used for disease resistance breeding in China are introduction, selection, and hybridization.

*Introduction*. If the source of resistance is available for an on-going breeding programme, introduction would become the most essential and effective step. For example, the introduction of anthracnose-resistant kenaf variety “Qingpin No.3” which comes from Vietnam effectively controlled the great damage caused by C. *hibisci* in China.

*Pure line selection*. Straight selection of resistant among heterogeneous varieties in heavily diseased field or artificially in calculated population offers the cheapest and quickest method of developing a resistant variety. The selected individuals are subjected to a progeny test under artificial inoculation. The resistant and agronomically superior plants are selected and released for commercial production. Such examples are numerous. The anthracnose-resistant kenaf variety “722” and “Xioanghong No.1” were selected from a heterogeneous population of an introduced variety “African Divided Leaf”. The anthracnose-resistant kenaf variety “Yueyuan No.2” was selected from “New kenaf” in a heavily diseased field.

*Intervarietal hybridization*. This is currently the most commonly used method. It serves the following two chief purposes:

1. Through the pedigree method to combine disease resistance and some other desirable characters of one variety with the superior characters of another; for example, the high-yielding, anthracnose-resistant kenaf variety “7804” was derived from a cross of “714” × “Leiyang Keanf”. 714 is highly resistant to anthracnose but agronomically inferior while the other parent is opposite. From F2 to F4 generation, the progenies were screened by artificial inoculation of race I and II of pathogen C. *hibisci*. The anthracnose-resistant kenaf varieties “Yueyuan No.5” and “Meifeng No.4” and kenaf varieties “Broad Leaf kenaf” and “Xiang No.1” were developed in a similar way.
2. Transfer disease resistance from an agronomically undesirable variety to a susceptible but otherwise desirable variety by backcrossing. “Guangba Dwarf”, a dwarf mutant of only 1 meter high but nearly immune to C. *gloeosporioides*, was crossed with the high-yielding “Mali Olitorius”. The resulting hybrid was backcrossed with the latter recurrent parent for three generations. Subsequently, a new high-yielding and disease-resistant variety “Xiang No.1” was selected through the mass-pedigree method.

## 3.11 Breeding for Photoperiodic Insensitivity in Kenaf

The currently used cultivars are all highly sensitive to short day-length. When the high-yielding, late-maturing varieties are cultivated in North China, they do not have yield mature seed. The seed has to be imported into these regions from South China, which requires lot of expenses on manpower and facilities. Moreover, whenever the seed production in South China and low latitude countries, Malaysia, etc., is insufficient, the overall kenaf acreage shrinks which results in shortage of raw material for the kenaf mills. In South China, on the other hand, when these photo periodically sensitive varieties are sown earlier than late March they flower prematurely, but when sown late the fiber yields are low and also the transplanting of autumn rice is affected. To solve the seed production problem in the north and the premature flower problem in the south, the answer seems to be the selection of problem in the south; the answer seems to be the selection of a photo periodically insensitive variety with high yield.

The sensitive variety is controlled by a single recessive gene or possibly by oligogenes. The sensitive plants selected in F2 show stable insensitivity in F3.

A few insensitive lines have been evolved or screened and crosses involving these lines have been made. However, except for the extremely early mature lines, all of the other derived lines are only partially insensitive to photoperiod and show slow growth under different photo thermal conditions. Therefore, effective transfer of this insensitive characteristic to high-yielding cultivars is still a prior breeding objective in the world.

## 3.12 Objectives and Strategies of Kenaf Breeding

Cultivating Kenaf has a history of one hundred years, Kenaf breeding has gone through several development stages, including the introduction of system identification, system selection, cross-breeding, mutation breeding, heterosis utilization of breeding, and transgenic breeding. In China, people has accomplished a series of breeding achievements in high yield of Kenaf, high quality of Kenaf, multi-resistance cultivars, which made China become the world leader in Kenaf breeding and the level of unit yield. In recent years, with the progress of breeding technology and the advancement of the level of science and technology, people has made new progress in heterosis utilization of Kenaf, transgenic breeding, and aerospace breeding. We should have new adjustment and improvement in regard to the direction goals and strategies of the Kenaf breeding, because of agricultural structural adjustment, the planting area is gradually shifted from the coastal and central regions to the Midwest, and the new discoveries of efficiently comprehensive use of bastose and higher requirement of Kenaf breeding.

Thanks to the development of modern biological technology and the progress of science and technology, modern development of science of Kenaf is based on differentiation and integration, namely to the development of the integrated system as features. Therefore, establishing perfect system of efficient pyramiding kenaf breeding in which the point is the comprehensive application of modern breeding techniques, the high quality, high yield, disease resistance, resistance (resistance to insects drought, salt) breeding technology, and the choice of simple genetic traits polymerization to promote the breeding technology of high differentiation kenaf and the height of the comprehensive co-exist and complementary. So the next stage of development direction of Kenaf breeding should combine conventional breeding with modern biotechnology breeding (including transgenic breeding and molecular design breeding). Sterile Line Breeding, development inspecial germplasms, and application of heterosis are very important to further improve level and efficiency of Kenaf breeding.

## *3.12.1 Objectives of Modern Kenaf Breeding*

### 3.12.1.1 High Quality, High Yield, Resistance to Insects and Disease, Selection of New Variety of Kenaf Breeding

In the future, an important goal and the major direction of Kenaf breeding is to enhance all stalk and fiber production, breeding new strains of the fiber production 10 % more than the contrast variety yield, a increase of 8 % in production output dry stems above; fiber quality request count reaching the 300-or so, strong reaching 430 N or so; resistance to kenaf anthracnose, high roots nematodes, fungus diseases, strong resistance; wide adaptability of new varieties. Resistance of anthrax raise a level compared with root nematode in control ability; The resistance is mainly alkali and drought resistance, of which the requirement of resistance to salt should be in 0.4–0.5 % to grow normally and obtain the relative higher yield; drought resistance requires to plant and grow normally in dry land or the western region.

### 3.12.1.2 High Quality Textile Fiber Special for Selection of New Varieties of Kenaf Breeding

Selecting out high fiber index, high degree of single to grow new kenaf varieties, of which the quality of fiber should be up to textile fabrics high-end textiles. The index of breeding production increase by 5 % compared with the variety and fiber count more than 350 teams.

### 3.12.1.3 Breeding of Super High-Yielding Combinations Hybrid Kenaf

The point is the selection and utilization of High-Yielding Combinations and Three Lines System of kenaf Male Sterile. Its advantageous index is hybrid Kenaf

F1 combination advantage than promotion check varieties in yield increases more than 20 %.

## *3.12.2 Strategies of Modern Kenaf Breeding*

### 3.12.2.1 Biotechnology Breeding Research

Because traditional agriculture is being rapidly converted into techno-agriculture, developing genetic resources and new plant varieties through genome research progress have been prevalent. With the development of new technology, the range of DNA polymorphism assays has been expanded to the field of genetic mapping, marker-assisted plant breeding, genome fingerprinting, and study of genetic relationships (Rafalski et al. 1996; Vogel et al. 1996). The random amplified polymorphic DNA (RAPD) technology provides a powerful tool for the identification of genetic variation of organisms (Welsh and McClelland 1990; Williams et al. 1990). This technology is easy to handle and cost-effective, it uses only a single RAPD primer but enables the detection of variations at multiple loci. The RAPD assay has been used for studying genetic diversity studies of many crop species, such as soybean, rice, rose, and mustard (Fujishiro and Sasakuma 1994; Takeuchi 1994; Lin et al. 1996).

However, genetic information for kenaf, especially, at the molecular level is limited. To better understand the genetic basis of kenaf for the improvement of production and to lay the foundation for molecular breeding efforts, Chen et al. (2011a) constructed a primary genetic linkage map which was using sequence-related amplified polymorphism (SRAP), inter-simple sequence repeat (ISSR), and randomly amplified polymorphic DNA (RAPD). Cultivar ‘Alian kenaf’ and ‘Fuhong 992’ were used as parents to construct an F2 population consisting of 180 plants. They selected 494 SRAP, 60 ISSR, 120 RAPD, and 300 two-primer RAPD mixture primers that amplified 396 polymorphic loci in total. At a logarithm of the odds (LOD) score threshold of 5.0 and at a maximum map distance of 25 cM, these 396 loci were used to construct the genetic linkage map with MAPMAKER/EXP 3.0, a total of 307 loci were grouped into 26 linkage groups that spanned a total map length of around 4924.8 cM with a mean density of 16.04 cM per locus. These markers were distributed randomly in all linkage groups without any clustering. The construction of the kenaf genetic linkage map will be useful for further genetic studies including mapping both qualitative and quantitative traits, marker-assisted selection program, and comparative genomics analysis.

Kim et al. (2010) tried to grow seventeen kenaf varieties collected from several regions around Asia and Europe in Korea and analyze their genetic diversity using morphological characters and AFLP technique. In the morphological analysis, the 17 varieties were divided into two major groups according to stem diameter, plant height, and flowering periods. The late varieties, which could yield more biomass compared with the early–medium varieties, were included in one of two major groups. Nonetheless, it is difficult to identify individual varieties based on morphological characters because of their limited variation. For the AFLP analysis, 34 primer combinations generated a total of 3,193 polymorphic bands (out of 3,914) with a polymorphic rate of 82 %. The clusters were divided into two major groups with a similarity coefficient of 0.63 by UPGMA analysis method; but each group did not show a common tendency. Additionally, the results of the AFLP analysis did not show similar tendency compared with morphological data, a result that might be explained in terms of convergent evolution, i.e., the acquisition of morphologically similar traits between distinctly unrelated varieties.

In order to find a proper method for identifying kenaf varieties and studying their variation, morpho-agronomic characters and random amplified polymorphic DNA (RAPD) markers were analyzed among 14 kenaf varieties commonly used in Japan by Cheng et al. (2002) Data from morphological analysis showed that the included kenaf varieties could be divided into three major groups. The characters, such as middle stem diameter, whole stalk weight, and days to 50 % flowering, are highly responsible for the variation of the kenaf varieties, but it is difficult to identify individual varieties merely by the morpho-agronomic characters. On the other hand, clearly separation of the kenaf varieties was achieved based on the RAPD variation patterns. Genetic relationship of the kenaf varieties can also be traced through the analysis of RAPD and morpho-agronomic variation. It is concluded from the present study that RAPD analysis is an effective tool in identifying kenaf varieties and determining their genetic relationships, particularly when combined with the analysis of morpho-agronomic characters.

Applying the ISSR technique, Huo and Li (2009) set up two gene pools from two different male sterilized kenaf varieties. He found a primer which can show the difference between the sterile gene pool and fertile gene pool. The ISSR primer is U859. The result showed the kenaf male sterility line is cytoplasmic nuclear interaction male sterile, and the male sterility is steady. The ISSR primer U859 is linked with genetic-male sterility.

Analysis the genetic diversity among kenaf germplasm resources and the phylogenetic relationships of main plum species by using molecular marker will help us to understand the molecular mechanism. In the near future the kenaf breeding aim is to strengthen the resistance to insect, herbicide resistance, resistance to salt and drought tolerant transgenic breeding, cloning kenaf functional gene, construction of molecular marker genetic linkage map, and localization of QTLs for some important economic traits of kenaf.

#### 3.12.2.2 Mutation and Space Breeding Research

Adopted the method of physical and chemical mutagenesis, special germplasm resources is an important component of kenaf germplasm resources, and it is paid more and more attention because of its special characters for special breeding purposes and important study value. Breeding in outer space, which has made significant achievements on crops seeds, is one of the most important projects in the global competition for exploitation of outer space. Space breeding provides a new technical platform for agricultural scientists to explore the mechanism of crop mutation induced during spaceflight and breeds new varieties of crops. It is important to develop the space breeding industry, serve agricultural production better, promote world's sustainable and healthy agricultural development, and ensure national food safety.

Li Defang found a kenaf male sterilized mutant named KCNms from kenaf 151 in Hainan Province in China in 2003. After genetic analysis and cytological observation, they found the mutant was cytoplasmic-nuclear male sterile line. They were using LC0301, YA1, 261N5-18, and 261N5-19 as current parent and using KCNms as donor parent. Then, backcross breeding. After 4 years, our research group had successfully bred 4 different male sterilized varieties: LC0301A, YA1A, 261N5-18A, 261N5-19A. There are new kenaf male sterilized varieties with high yield, disease-resistance, lodging resistances, high quality, and wide adaptability. It was a great breakthrough in the heterosis utilization after chemical induction of male sterility. Their methods supplied a new way to be widely used in hybrid kenaf breeding and production.

#### 3.12.2.3 The Establishment of System of Efficient Polymerization Breeding Technology

Combining modern breeding technologies with traditional breeding technologies is to accelerate breeding technology integration and method innovation. Establishing the system of efficient polymerization breeding technology is to improve the efficiency and level of kenaf breeding and shorten the number of year and cycle of breeding.

#### 3.12.2.4 The Identification and Innovation of Germplasm

Continuing research in resources collection, introduction, and identification is to carry on a planned way the system of the identification and evaluation of the existing kenaf germplasm resources. Explore wildlife and cultivation of the specific favorable genetic material to provide the breeding utilization. Further using modern biological technology to develop the innovation of germplasm and its utilization is to provide advantageous genes germplasm for hybrid breeding and hybrid advantages.

## 3.13 Conclusions

Kenaf breeding is the art and science of changing the genetics of plants in order to produce desired characteristics. Plant breeding can be accomplished through many different techniques ranging from simply selecting plants with desirable characteristics for propagation, to more complex molecular techniques. By using the breeding technology, we successfully made new development on breeding of novel materials specialized for textile or papermaking(or both), which have features of anti-disease, lodging resistance, new species of high yield with wide range of adaptability, super-high yield type of hybrid kenaf, and kenaf photo periodical insensitivity and root-knot nematode resistance. In the upcoming future, a great achievement can be made in the improvement of kenaf varieties with the development of science and technology.

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# Chapter 4
# Crop Management

**E. Alexopoulou, Y. Papatheohari, D. Picco, N. Di Virgilio and A. Monti**

**Abstract** The determination of the appropriate crop management is a key factor for the successful insertion of the crop in the existing cropping systems with economic benefits. Research on crop management has been conducted when kenaf was evaluated as an excellent cellulose fiber source for a large range of paper products (in 1960s). The most important parameters in the crop management that should be followed are the site of its cultivation and the final end use. New kenaf varieties have been released that were resistant to pests and diseases with improved resistant to drought, and with higher yields. The plant density and the fertilization need to be varied according to its final use of the crop. When it is cultivated for its fiber stem the plant population should be from 170,000 to 350,000 plants per ha and with row spacing 35–50 cm. In areas where the precipitation is limited irrigation is needed to achieve high yields. It is a crop very sensitive to nematodes, especially when it is cultivated in areas with sandy soil and this should be taken under consideration on the rotation system that will be followed. Harvesting time and methods can be adjusted according to the use of the crop (fiber, seeds, fiber and seeds, forage).

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## 4.1 Introduction

Kenaf (*Hibiscus cannabinus* L)is non-food crop that grows quickly and in 4–5 months can reach a height 3–5 m depending on the area of its cultivation. Its roots are in ancient Africa and although is cultivated long (3500–4000 BC) is considered as an old–new crop. Soon after its introduction in USA (in 1940s) efforts to bring kenaf from experimental crop status to an accepted alternative in established cropping systems were started and are still in progress. In order the crop to compete successfully with the existing crops and maximize monetary returns, the effects of agronomic practices on yield and crop quality must be better understood.

The selection of the best-adapted variety for each site significantly contributes to the yields maximization and thus the highest economic returns can be provided (Bhangoo and Cook 1998a). At sowing the ground temperature should be at least 15 °C. The warmer temperatures result in an increase in growth rate. Seed should be planted less than 1 inch deep, if the soil moisture and seedbed are suitable. When kenaf is cultivated for its fiber stems, the stems should be unbranched and plant populations around 200,000 plants per ha are required. Row spacing and population density are implicated in dry matter yield, and therefore, bast fiber production.

Haarer (1952) stated that a well-distributed rainfall of about 125 mm for each month during the growing season leads to optimum yield. Kenaf requirements for nitrogen are high depending on the yield of the crop at harvest. As nitrogen fertilizer can constitute up to 20 % of the kenaf production cost grown for paper pulp production and thus accurate prediction of optimal rates of application is needed. One of the major problems in.kenaf growing is its susceptibility to root-knot nematodes (Wilson and Summers 1966; Adenyi 1970; Adamson et al. 1974; Pate et al. 1958). Harvesting is the key point for kenaf like all the other fiber crops because it is the step connecting production with processing through the delivery of the material to the factory with specific features.

## 4.2 Kenaf Varieties

The selection of the best-adapted variety for each site is very important in order to achieve the maximum yields and to provide the highest economic returns (Bhangoo and Cook 1998b). Breeders have produced many varieties, which vary in the form and color of the leaves, stems, flowers and seeds and in their response to soil conditions, climatic conditions and daylength, as well as in the quality and yield of the fiber which they produce (Catling 1982).

Significant improvements in kenaf germplasm have been made since the first projects were initiated in the 1940s in the USA. Major gains have been made in improving yield, bast fiber percentage, anthracnose resistance, lodging resistance, and tolerance to the root-knot nematode and soil fungi complex (Cook et al. 1998). Although the present varieties are capable of achieving high biomass yields, there is interest in pursuing further improvement of both productivity and fiber quality through breeding activities because genetic gains can be exploited without a concomitant increase in the cost of the crop management (Pate et al. 1958).

High degree of heterosis has been observed in kenaf (Pate and Joyner 1958; Nelson and Wilson 1965; Srivastava et al. 1978; Patil and Thombre 1980) and when the problem of manual pollination was solved many kenaf hybrids were realized and cultivated (Li 2002). The development of superior hybrids contributed to the improvement of kenaf productivity. Plant height, basal stem diameter, dry bark weight, and the ratio between dry bark weight and the core weight are the major components of fiber yield and quality. Kenaf hybrids are very popular in some countries, like China, Russia, and Thailand. About 1000 tons of hybrid seed is sold in China every year.

In the USA there are more than 240 varieties but the commercially grown ones are around 10. In the USA the varieties used most extensively are those developed by USDA Agriculture Research Service (ARS) researchers in Florida; named Everglades 41 and Everglades 71. Both varieties were characterized as high resistant to anthracnose. Currently (USA), the principal commercial varieties are Everglades 41, Everglades 71, Tainung 1, Tainung 2, Gregg, Dowling, SF 459, and Whitten. In small quantities the photo-insensitive variety Guatemala 4 can be obtained.

The newly released varieties Gregg and Dowling (Scott et al. 1999) found to be more productive compared to the traditional kenaf varieties (Everglades 41, Everglades 71, Tainung 1 and Tainung 2) in the later harvest. Both of these varieties reported with high stalk production, yields stability, high bast fiber percentage, moderate tolerance to the root-knot nematode, and improved resistance to Cristulariella moricola. Dowling (a cordate leaf genotype) was released not only because of the improved total stalk fiber yield and its greater bast fiber percentage but also for its less susceptibility to lodging (Cook et al. 1999).

The variety named SF 459 combines the high biomass yields and the high resistant to nematodes and apart from USA it was tested for a period of four subsequent years in Greece (BIOKENAF project, www.cres.gr/biokenaf) and both high yields and high resistant to nematodes were also recorded.

The variety Whitten was developed through the research efforts of Mississippi State University and so far has shown great promise in trial plots. Whitten leaves resemble those of a cotton plant. Whitten was derived and selected as a single plant from the S2 (F3) segregating array of a cross of E41, an improved cultivar with undivided leaf shape, and a powdery mildew resistant selection of ‘Guatemala 45’ made during the 1994 growing season (Baldwin et al. 2006).

Kenaf varieties, according to their reaction to flowering, are divided in two groups the early and the late-maturity kenaf varieties.

### 4.2.1 Early Maturity Kenaf Varieties

The flowering for the early maturity kenaf varieties is irrelevant to the daylength. In the pedoclimatic conditions of the Mediterranean region, the flowering in the early maturity varieties begins from mid-July to mid-August. The duration of their vegetative cycle may be 75–105 days (early varieties) or 105–120 days (semi-early varieties). Early maturity varieties have been produced for the Asiatic regions of the former USSR.

In most research works, it is reported that the early maturity kenaf varieties are less productive than the late-maturity kenaf varieties due to the fact that they have a shorter vegetative phase. Adamson et al. (1972) found that the early maturity kenaf varieties (PI 329195, PI 323129, PI 343139, PI 343142, and PI 343150) that have been tested among other kenaf varieties gave dry matter yields and were always significantly lower (7.64 Mg/ha versus 17.9 Mg/ha) than the recorded yields for the late-maturity kenaf varieties (C-2032, Everglades 41).

The G-4 is the only variety that combines a short growing cycle and a high productivity similar to those recorded for the late-maturity kenaf varieties. In central north Italy (Petrini et al. 1994) has been reported dry yields of 24 Mg/ha for G-4. Grandall suggested that G-4 is a photoperiod-insensitive cultivar. According to Belocchi et al. (1998), the early maturity G-4 variety (in the Mediterranean region) needs from emergence to anthesis a period of about 130 days. Although in the United States and Southern Europe G-4 is characterized as photo-insensitive with short growing cycle, in Australia it appears to be the opposite. The difference of the flowering of G-4 between Australia and United States is due to the amphiphotoperiodic response that appears to alter the photoperiodic response in the two photoperiod regimes (Williams 1994). However, in the areas of the United States the research for kenaf has been carried out by G-4 flowers relatively rapid, due to the long days, with little radiation in thermal time to flower among sowings.

### 4.2.2 Late-Maturity Kenaf Varieties

The flowering in the late- maturity kenaf varieties strongly depends on the daylight length and the first flowers appear when daylength is less than 12 h and 30 min. The duration of the vegetative cycle for the late-maturity kenaf varieties is 120–140 days. In the pedoclimatic conditions of the Mediterranean region the flowering for the late-maturity kenaf varieties did not begin until the middle of September and thus the seed set on the top part of the stem did not ripen because of the beginning of the cold period (Siepe et al. 1997).

The late-maturity kenaf varieties due to the fact that the vegetative growth lasts for two more months produced significantly higher yields. It is reported (Petrini and Belletti 1991) that there is a positive relation between kenaf productive and absence of the flower indication (Alexopoulou et al. 2000a, b). This correlation can be understood when taking into consideration that kenaf has an indeterminate type of growth, which is rather rapid, until the first flowers appear. Afterwards, vegetative growth does not stop, but its growth rate decreases.

Among the late-maturity kenaf varieties, the most known are Everglades 41, Everglades 71, Tainung 1, and Tainung 2. A large number of research works has been carried out with the aforementioned kenaf varieties. Between the kenaf varieties Everglades 41 and Everglades 71, it is reported that in most of the cases Everglades 71 was more productive. In Arizona (McMillin et al. 1998) Everglades 41 gave 23.4 Mg/ha dry matter yields and Everglades 71 24.0 Mg/ha. The superiority of Everglades 71 over Everglades 41 was also reported in another research work (Webber 1993) with yields 15.9 and 14.5 Mg/ha, respectively. In central Greece, Everglades 71 gave 20.58 Mg/ha dry matter yields and Everglades 41 18.14 Mg/ha.

Between the kenaf varieties Tainung 1 and Tainung 2 the second was the most productive. In north-central Italy Tainung 2 gave almost 24 Mg/ha dry matter yields, and Tainung 1 produced 21 Mg/ha (Petrini et al. 1994). In Mississippi (Ching et al. 1993) both varieties (Tainung 1 and Tainung 2) had yielded the same.

## 4.3 Sowing Dates

Kenaf seeds are relatively small and require good seed-soil contact for germination. Therefore, a fine, firm, well-prepared seedbed is necessary. The ground temperature should be 15 °C at least as warmer temperatures result in an increase in growth rate. Under favorable soil conditions kenaf seeds emerge after two to four days. In the United States and South Mediterranean countries, kenaf can be planted in spring once the soil has warmed to 13 °C and there is no threat of frost (April–May). Seed should be planted less than 1 inch deep (between 1.25 and 2.5 cm), if the soil moisture and seedbed are suitable. Kenaf can emerge from a depth of 2.5 inches under the most favorable conditions.

Planting can be carried out by using standard planting equipment in a wide range of distances between the rows and can be planted on both raised beds and on flat ground. The kenaf seeds are approximately 6 mm long and 4 mm wide (35,000–40,000 seeds/kg) and are quite similar in size with the seed of grain sorghum (*Sorghum bicolor* L.). The use of high quality seed, (germination over 80 %) the use of the appropriate equipment that gives uniform seed placement, and the good seed-soil contact should be overemphasized. It should be noted that warm, moist soils are the ideal planning conditions for kenaf.

Kenaf plants that had been grown under no-till conditions resulted in lowest biomass accumulations. No-tillage systems may be a viable option in increasing acreage of kenaf, if weed problem is controlled and water is not a limited factor.

The sowing date strongly depends on the specific pedoclimatic conditions of the area of cultivation. Early planting dates often result in poor emergence and slow non-competitive growth. On the other hand, the late-planting dates will often result in reduced yield potential due to the reduced solar radiation availability. Due to the fact that the vegetative growth for the late-maturity kenaf varieties continues until the appearance of the first flowers the sowing should take place as soon as the soil temperature is higher than 15 °C in order the vegetative stage of the crop is as long as possible.

## 4.4 Plant Densities

Kenaf is self-thinning crop and reduces its population during the growing season. When kenaf is cultivated at high plant populations, ranging from 300,000 to 500,000 plants/ha, it is required at a total quantity of 10–15 kg seed/ha, while when it is cultivated to achieve final plant populations of 185,000–370,000 plants/ha a quantity of about 8–12 kg/ha seed is needed.

A large number of research works have been carried out worldwide in order to determine the appropriate plant population that results in maximization of the crop's yield. Plant populations between 99,000 plants/ha and 932,000 plants/ha have been tested for several kenaf varieties (Muchow 1979a, b, c). In most of these research works it is reported that the increase of the plant density from 150,000 to 350,000 plants/ha resulted in increase of the yields (Higgins and White 1970; White 1969; White et al. 1971; Clark and Wolff 1969; Campell and White 1982; Bhangoo et al. 1986; Sarma and Boldoloi 1995; Sarma et al. 1996). Sahih (1978, 1982, 1983) reported that for maximum kenaf dry production in Sudan plant populations between 250,000 and 500,000 plants/ha were recommended for commercial production.

At high densities the number of branches per plant was decreased (Scott 1990; Fahmy et al. 1985). Higgins and White (1970) and White et al. (1971) found that when the plant populations were increased the plant height and the basal stem diameter significantly decreased, while the percentage of dry matter at harvest increased (Naffes and Kanzanda 1983). The bast to core ratio was not found to be affected by the increase of the plant populations and the decrease of the row spacing (Graham and Baldwin 1999). Plants in stands that are too dense for the cultivar or seasonal growing conditions tend to be short, spindly, and week-stemmed. Plants in stand that are too sparse produce branches that are too heavy. In both cases lodging is inevitable.

The distance between the rows seems to play an important role not only in the total dry matter yield, but also in total harvestable bast per ha. In a study where four row spacing were tested (35.5, 50.8, 71, and 101.6 cm) it was found that in the narrowest row spacing the yields both total and bark yields were significantly higher (Baldwin et al. 2006). Thus, the decreasing of row spacing is the most effective cultural practice for increasing total dry matter accumulation per ha and bast yield per ha. Maximum yields can be achieved with row spacing from 35 to 50 cm.

## 4.5 Fertilization Requirements

Kenaf, unlike traditional agricultural crops that are grown for their seed, is grown mainly for its fiber stems and recently it is grown for both (stems and seeds). When the crop is harvested after the first killing frost the stems are defoliated.

It has been estimated that the leaves drop returns significant quantities of nitrogen (as high as 4.0 % by weight; Hollowell 1997) calcium, magnesium, phosphate, and potassium back to the soil where the stalks that remain prevent them from blooming away. Standing in the field allows return of nutrients not only from the leaves that have already fallen but also from the degradation of the non-fiber content of the bark. In this case at the time of the harvest the only thing removed from the kenaf field are the fiber stems (cellulose, hemi cellulose, lignin = carbon, hydrogen, and oxygen) (Dubard and Baldwin 1999).

Kenaf's response to added fertilizers depends on the soil nutrient levels, cropping history, and other environmental and management factors. A range of fertility responses has been reported. In general, when the added nitrogen is increased the yields were also increased. Three important factors should be taken into consideration when the kenaf fertilization is designed. First of all, it should be considered in the fertility program if it will focus on vegetative needs of the crop than the grain or in reproductive needs. Second, if kenaf with its deep taproot and wide-spreading lateral root system is considered to be an excellent user or residual nutrients from previous crops. Last but not least, it should be taken into consideration the fact that the leaves that left in the field after the harvest can return 60–120 pounds of N/acre (Bhangoo et al. 1986) or 50–100 pounds of N/acre (LeMahieu et al. 2000).

According to Wood and Angus (1976), kenaf requirements for nitrogen are high, up to 30 kg N per ton of stem. Wood and Muchow (1980) also reported that the crop has a high requirement for nitrogen fertilizer; the amount depends on the yield of the crop at the harvest. As nitrogen fertilizer can constitute up to 20 % of the cost of production of kenaf grown for paper pulp production, accurate prediction of optimal rates of application is needed.

As with other crops proper fertility maintenance, especially for supplemental nitrogen application, is needed to optimize kenaf yields and minimize production cost. Reports so far are inconsistent relative to the effects of N on kenaf stalk yields (White and Higgins 1965); researchers in Georgia have reported both positive (Adamson et al. 1979; Amankwatia and Takyi 1975; Lakshminaray et al. 1980) and no benefits (Massey 1974, Webber et al. 1996).

Studies in Florida demonstrated that the positive response to N applications on stalk yields were dependent on the soil type (Joyner et al. 1965), while kenaf grown on a sandy soil reported to N and did not respond to N on a peat soil. Bhangoo et al. (1986) in California and Sij and Turner (1988) in Texas increased stalk yields with the addition of N to soils with low available nitrogen. Stalk yields in Missouri (Ching and Webber 1993) on a silty clay soil and in Nebraska (Williams 1966) on a silty clay loam soil did not benefit from N applications. Stalk yields have also reported differently to N on the same location and soil throughout the years (Hovermale 1993).

Chew et al. (1982) found that the nitrogen fertilization increased the plant height and the fiber yield of kenaf to the highest rate studied (112 and 120 kg/ha, respectively). K fertilization increased kenaf height and fiber yield to 100 kg/ha at the 1-bloom stage, but to only 70 kg at the 5–10-bloom and seed set stages kenaf increased in height and fiber yield between the 1-bloom and seed set stages.

In a study that was carried out in Northern Territory of Australia where kenaf crop yields 10 Mg/ha under rain fed growing conditions applied the following fertilizers: Phosphorus: 30 kg/ha, Sulfur: 30 kg/ha, Potassium: 50 kg/ha, Nitrogen: 230 kg/ha, and Copper: 3 kg/ha.

Whitely (1981) reported that one recommended fertilizer application could be 35–70 kg N/ha, 40–60 kg $P_20_5$/ha, and 45–65 kg $K_20$/ha. In the same study it has been estimated that for the production of 50 MT/ha green plants kenaf withdraws from the soil about 175 kg N/ha, 15 kg P/ha, and 75 kg K/ha and 30 kg Mn/ha.

In sandy soil in Florida, 140–160 N lb/A and 90 lb/ha $P_20_5$ was applied when the soil tests showed <16 mm Mehlich-1 P, and 60 when Mehlich-1 was between 16 and 30 ppm. 100 lb/A $K_20$ was also applied when Mehlich-1 K <35 and 70 was between 35 and 60 ppm. It is reported that the soil is not expected to respond when the soil tests shows P above 30 ppm and K above 60 ppm.

## 4.6 Irrigation Needs

Crane (1947) stated that 500–625 mm of rainfall over a period of 5–6 months is essential for a successful production of kenaf fiber. Haarer (1952) stated that a well-distributed rainfall of about 125 mm for each month during the growing season leads to optimum yield. In a study in central California (Banuelos et al. 2002); kenaf required 780–1200 mm of water for optimal growth and production applied through irrigation or by precipitation.

A series of research works has been carried worldwide in order to determine both the maximization of the yields and the minimization of the applied irrigation water. Where irrigation water is scare or expensive (Muchow and Wood 1981), the development of an effective water management strategy needs to consider both the crop response to irrigation frequency and the associated water application efficiency. When water is both plentiful and cheap the efficiency of application is of less significance but it is still of some economic importance. The efficiency of water application is inversely related to the frequency of application, and also usually inversely related to crop yield.

It has been reported in several research works that when the kenaf plants are irrigated well higher dry matter yields were achieved (Muchow 1992; Robinson 1990; Evans and Hang 1993; Manzanares et al. 1993; Mambelli and Grandi 1995; Danalatos and Archontoulis 2010). It is reported that the dry stem yields were linearly associated with the added irrigation water (Manzanares et al. 1993; Mambelli and Grandi 1995).

According to Banuelos et al. (2002) kenaf production in central California increased as irrigation was increased incrementally from 25 to 125 % crop evapotranspiration (etc), while water application at 150 % etc, had no increased benefit. It should be pointed out that in the same study the bark:core ratio was unaffected by the level of irrigation.

Ogbonnaya et al. (1998) observed that the water deficit significantly reduced the height and collar diameter growth of kenaf. Kenaf could be described as opportunistic in relation to water availability, with a high rate of stomatal conductance and transpiration when soil water is available but with markedly reduced leaf conductance and transpiration rate when water is limited. Kenaf was also observed to roll its leaves during drought. Muchow (1992) found that although the water deficit markedly reduced biomass production, the crop was able to recover following rewatering.

A water potential of 0.5 MPa was bracketed as the critical water potential, below which the plant would be stressed and the leaf temperature would increase above ambient air temperature (Ogbonnaya et al. 1998). The stressed plants, therefore, began to face another kind of stress the heat stress. High temperature accompanying drought causes release of ammonia from decomposition of protein that injures plant tissues (Weiland and Stuttle 1980).

Water stress is not always injurious. Although it reduces vegetative growth, it sometimes improves the quality of plant products. It can be generally hypothesized that some level of stress may be required to improve the fiber qualities of crop plants. This level of stress, which does not affect growth, however, has to be worked out for each plant (Ogbonnaya et al. 1997).

According to Muchow and Wood (1980), the water stress resulted in shorter kenaf plants, lower leaf area index, thinner stems, and thicker leaves. The percentage of bark in the stem material decreased only in the most stressed irrigation regime. This was associated with an increase in the dry matter content of the harvested material.

It has been reported (Cook et al. 1998; Bhangoo and Cook 1998a) that kenaf can be grown successfully on a saline soil (Francois et al. 1990) when the irrigation water has good quality.

## 4.7 Weed Management

Like any other crop, weed control is vital to successful crop production. Kenaf is a vigorous growing plant and under optimum conditions it can form a canopy over the row middles in as little as 5 weeks (Neil and Kurtz 1994). Once kenaf shades the row middles low, growing weeds and grasses are shaded out and there is no need for additional weed control.

A pre- or post-emergence herbicide can be used, or a single hoeing after germination may prove sufficient for combating weeds. If a more persistent weed problem is present, hoeing twice may be necessary. This would be done after the kenaf is at least 15 cm high and the weed is in the germination leaf to 2-leaf stage. Because of kenaf's fast growth, weeds are not much of a problem once the plant is established.

In warm climates kenaf emerges and grows so rapidly that it competes with weeds effectively. In cooler climates and with earlier planting dates, cultivar and/or chemical weed control measures are more important. One weed species, which is especially competitive with kenaf, is velvetleaf, a relative of kenaf. At the seedling stage, velvetleaf and kenaf are very similar in appearance and in rate of growth. Fields with high populations of this weed are not recommended for kenaf production.

Cultural practices that are available to a producer (such as timely planting, narrow-row spacing, optimum fertilization, optimum plant populations, etc.) should be used to reduce weed problems. In the absence of herbicide registration for kenaf and particularly in cooler climates if the development of the crop is slow the mechanical weed control should be used.

It should be noted that few herbicides are available for weed control in kenaf. In the USA, Treflan EC, Treflan MTF, Treflan 5, Treflan TR-10, Trilin, Bueno 6, and Fusilade 2000 are currently labeled for use in kenaf. The last two herbicides are for post-emergence weed control, while the others are used for pre-plant weed control (Kurtz 1994a, b).

A number of research works have been carried out in order to find out the best pre- or post-emergence herbicides for kenaf. According to Hickman (1990) the herbicides alachlor and metolachor may be the best solution for season long weed control of kenaf. It is also reported (Webber 1994) that triflualim and metolachlor provided excellent (>90 %) weed control for moderate weed problems in stem yields. The herbicides cyanazine, diuron, fluometuron, lactofen, or prometryn can be used in the safety of kenaf production (Kurtz 1996; Kurtz and Neill 1990, 1992). If registration is obtained for these herbicides, they would very effectively control a broad spectrum of grass and broadleaf weeds.

## 4.8 Crop Rotation

The insertion of kenaf into the existing cropping systems has been studied in USA, although the available information about the rotation effects of kenaf is still limited. Because the crop host the root-knot nematodes, *Meloidogyne incognita*, *M. javanica,* and *M. arenaria* crops that are sensitive to these should be avoided to follow kenaf cultivation such as cotton and peanut (Zhang and Noe 1996; Robinson and Cook 2001). When kenaf is rotating with a legume (like soybean) the stunt nematode (*Tylenchorhynchus* spp.) that is responsible for the most soybean yields losses can be reduced (Webber 1999; Webber et al. 2002; Kemble et al. 2002). Therefore, kenaf may not be suitable for rotations with cotton and peanut but with soybean. To reduce the incidence of nematodes in affected areas, kenaf could be planted following maize and sorghum (Glaser and Beach 1993). Another non-food crop that could be used as nematicide is hemp, especially when rotated with susceptible crops such as potatoes, maize, peas, grains, and pastures (Ronson et al. 2002; Kok et al. 1994; McPartland and Glass 2001) but as indicated before, specific data on the subject is not available.

In China in order to reduce the nematodes populations it is proposed to rotate kenaf with non-host nematodes crops such as groundnut, rice, maize, and sesame (Yu 2004). Maize is a good rotation crop to follow kenaf in high-infested nematodes.

In the southern areas of Europe, for example, the combination of conventional (wheat, legumes, maize, sunflower) and new energy crop species (sweet/fiber sorghum, kenaf) in rotation would optimize the utilization of soil resources and fit the prevailing climatic conditions (Zegada-Lizarazu and Monti 2011). In 4FCROPS European project (www.4fcrops.eu) the following rotation systems were proposed for kenaf: (a) sweet sorghum—cereal (wheat)—soybean—hemp (kenaf), (b) sweet sorghum—cereal (wheat)—hemp (kenaf)—cereal (barley).

## 4.9 Insects and Diseases

### *4.9.1 Nematodes*

Experience elsewhere has shown that one of the major problems associated with the growing of kenaf is its susceptibility to root-knot nematodes (Wilson and Summers 1966; Adenyi 1970; Adamson et al. 1974; Pate et al. 1958). Ibrahim et al. (1982) found that kenaf was susceptible to the root-knot nematodes caused by *Meloidogyne incognita*, *Meloidogyne javanica,* and *Meloidogyne arenaria*. Nematodes are multicellular, microscopic, worm-like animals that feed mainly on plant root systems (Lawrence 1994). Leaves on plants infested with nematodes are yellow and fall. The infested plants are stunted and in case of a heavy infestation the plant may eventually die.

The problem is particularly severe in light, sandy soils. Disease epidemics probably develop relatively slowly in compacted clay soils because their texture appears to limit the capacity of nematodes to move from plant to plant (Wood and Angus 1976).

The problems from nematodes could be managed by a combination of crop rotation and chemical control. Another approach is the development of nematode resistant varieties. The variety SF 459 is reported as nematode resistant. It is reported (Webber 1999) that the rotation kenaf/soybean was successful in terms of yields but did not reduce stunt nematode populations.

### *4.9.2 Diseases*

Kenaf is resistant to most plant diseases. One serious disease of kenaf, anthracnose, caused by *Colletotrichum hibisci*, was reported in the U.S.A. in 1950. It should be noted that the commercial used kenaf varieties (Everglades 41, Everglades 71, and Tainung varieties) are highly resistant to anthracnose. Damping-off is a moderate concern during seedlings stages and seed treatments are being tested and registered for use. Kenaf is also susceptible to a cotton isolate of *Rhizoctonia solani*. Therefore, kenaf following cotton, or other situations of enhanced disease pressure, may lead to severe seedling problems. According to Cook (1981), all the known kenaf diseases are those that listed in Table 4.1.

**Table 4.1** List with kenaf diseases

| Disease name | Disease cause |
|---|---|
| Bacterial wilt | *Pseudomonas solanacearum* |
| Phytophthora collar rot and wilt[a] | *Phytophthora parasitica* Dast. *nicotianae* |
| Powdery mildew | *Leveillula taurica* |
| Rust[a] | *Aecidium garkeanum* P. Henn. |
| Target spot | *Thanatephotorus cucumeris, Pellicularia filamentosa* (Pat.) |
| Anthracnose[a] | *Colletotrichum hibisci* Pollacci. |
| Botrytis disease (Gray mold) | *Botrytis* sp. |
| Cercospora leaf spot | *Cercospora* sp. |
| Cristulariella leaf spot[a] | *Cristulariella pyramidalis* Waterman & Marshall |
| Stem canker | *Thanatephotus cucumeris* and *Botryobasidium rolfsii* |
| Volutella brown rot | *Volutella* sp. |
| Dry root | *Macrophomina phaseolina* |
| Leaf blight | *Phyllosticta hibisci* Peek |
| Stem root | *Diplodia hibiscina* Cke. and Elb. |

[a] Resistant varieties to these diseases have been released

### *4.9.3 Insects*

Most insect problems with kenaf are likely to occur at seedling emergence and seedling growth. Cut worms, leaf miners, and other chewing/sucking insects are potential problems. However, the kenaf plant tolerates a fairly high population of chewing and sucking insects, and since the production emphasis is biomass, the required level of insect protection for kenaf may be much less than the most commercial crops.

## 4.10 Harvesting and Storage

### *4.10.1 Harvesting*

Harvesting is the key point for fiber crops because it is the step connecting production with processing through the delivery of the material to the factory with specific features. The characteristics of the harvested biomass are determined by the transformation industry that must give inputs to the production. Harvest conditions are influenced by factors as moisture content, dry matter losses, structure of harvested material, and impurities (Huisman and Venturi 2003).

The most important commercial part of kenaf plant is the stalk, even if the leaves that are rich in proteins could be useful for livestock feed its seeds could be used for oil production. Kenaf stems are composed of two district fibers, bark and core, which comprises approximately 35 and 65 % of the stalk mass, respectively (Dempsey 1975; Baldwin et al. 1996; Columbus and Fuller 1999). Bast is characterized as a bark, containing long fibers, with the core being physically similar to the balsawood, containing soft, short fibers.

The quality of the product harvested is deeply influenced by environmental factors, the varieties used, the agricultural practices which affect the thickness and the quality of kenaf fiber: these characteristics could cause difficult during the mowing operation and could make easy the winding around the moving parts of the harvest machinery (Bentini et al. 1994).

There are several times and methods to harvest kenaf, depending on the production location, the equipment availability, the processing methods, and the final use.

#### 4.10.1.1 Harvest Time

The selection of the harvest date is very important because it has strong effects on the biomass productivity and biomass quality. Kenaf biomass is usually harvested after leaf fall, because, unlike traditional crops, kenaf is grown mainly for its vegetation stalk. The standing of the kenaf plants in the fields until the defoliation of the stem, also allows the return of the nutrients, from the fallen leaves, back to the soil (Fernando et al. 2004a).

In order to cover the processing needs, either the combustion or pulp production, at the moment of the harvest, crop should have low mineral and water contents. In terms of the biomass quality, the composition of the biomass changed over the course of the growth period as nitrogen and water content decrease and organic matter increase (Fernando et al. 2004b).

When harvesting kenaf for fiber use, moisture content and equipment availability are important considerations. Kenaf can be harvested for fiber when it is dead, due to a killing frost or herbicides, or when it is actively growing. The dry standing kenaf can be cut and then chopped, baled, or transported as full-length stalks. If the kenaf drying and defoliation process is dependent on a killing frost, the harvest date will vary according to the environmental conditions of the area, including the time of the killing frost and the time required for the kenaf to dry. Soil type and seasonal weather may delay harvesting and drying, especially on high clay soils in areas that receive excessive rainfall during harvest. Actively growing kenaf can be cut and then allowed to dry in the field. Once dried, the kenaf can then be chopped, baled, or transported as full-length stalks. The availability of in-field harvester/separators will add to the harvesting options (Webber et al. 2002).

One of the disadvantages of leaving the crop in the field so late in the season is the risk of biomass yield loss (mostly tops and leaves) which occur as a result of unfavorable weather conditions during winter. However, the low moisture content of the harvested material in early spring is considered to compensate for the biomass losses which occur during the winter (El Bassam and Huisman 2001).

The harvesting time will also be dependent on whether the crop is grown and the soil conditions. The soil conditions at the time of the harvest must be assessed in order to minimize the damage caused by the weight of the harvesting machines on the soil structure.

#### 4.10.1.2 Harvesting Techniques

One important consideration of all harvesting and processing system is the moisture content of the kenaf plant material. The moisture content of actively growing plants at harvest is normally about 75 %. The mowing machines encounter an easier cutting process with growing, high moisture kenaf plants, but allowances must be made in the harvesting and processing system for either drying the plant material or handling and storing high moisture material. If dry, dead kenaf stalks are harvested, the harvesting equipment will encounter tougher stalks with a greater likelihood that the long, twine-like fiber strands in the bark will wrap around rotating equipment parts (Webber et al. 2002).

The kenaf harvest can be performed either with multi-phase or single-phase procedure. In the case of multi-phase procedure a whole stalk harvester is being used, which involves mowing, followed by windrowing and pick-up, compacting and baling (forage type harvester and baling equipment). The separation takes places in the field of the bast from the core, which involves mowing followed by mechanical scotching and baling. In the single-phase procedure (systems which use one machine) can be done (a) mowing and chopping; (b) mowing, chopping, and baling; (c) mowing, chopping, and pelleting line; or (d) a sugarcane-type harvester can be used.

#### 4.10.1.3 Whole Stalk Harvester

Forage type harvesting and baling system have been widely evaluated for use in kenaf production, harvesting, and processing system. Standard forage cutting or mower conditioner and baling equipment can be used for harvesting kenaf as either forage crops (Webber and Bledsoe 1993). Kenaf can be bailed in both small and large square bales and large round bales. Compressing of kenaf in bales serves to increase the bulk density of the kenaf for storage and transportation purpose.

According to Bentini et al. (1994), kenaf stems must be swathed before baling in order to allow the baler to pick-up the material. If swathing is not included in the harvesting process, the bulk and the length of kenaf stems will lead to obstruction of the pick-up unit of the baler. Swathing of kenaf is necessary for undisturbed pick-up of the stems by the baling machine.

To improve the drying process in the field in case of high moisture kenaf stem harvesting it is important the windrowing operation which allow the complete elimination of the dry leaves.

There are a number of baling machines which produce different kind of bales (e.g., rectangular bales, round bales, and compact rolls). The production of bales, which have high dry matter densities, is advantageous for further handling, transport and storage (El Bassam and Huisman 2001).

The USDA has developed a whole stalk harvesting system that cuts the stalks and lays them in an orderly fashion at right angles to the row. Stalks are allowed to dry for around 2 weeks and are then gathered by machine that picks up the stalks and arranges them in large bundles; the bundles are transferred to the field trailers. The tractor-dawn field trailers haul the bundles to the field margin where they are stacked for shredding (CSRS 1988).

#### 4.10.1.4 Separation in Field of the Bast Fiber from the Core

This harvest system derives from the technologies studied in the past for the hemp harvest. The different phases of this kind of harvest are: stem mowing and swathing, hacking, drying in the field, and baling only the bast fiber. The mowing-swathing machine cuts the stems and arranges it in a longitudinal position as to the machine feed; afterwards the hackling machines separate the bast fiber from the core.

The final phases of this harvest line are similar to the ones previously described, with further difficulty owing to the core absence and the easiness of the bast fiber around the rotating equipment part (Bentini et al. 1994).

Researchers at Mississippi State University (Chen et al. 1995) have patented a machine to separate the bast and the core fibers of kenaf. This machine moves through the field, cuts the stalks, and separates nark and core fibers in one operation. The kenaf stalks are crushed as they enter the machine and then passed through beaters. The short core fibers drop to the bottom of the machine and are blown into a wagon pulled alongside. The long fibers pass out the back of the machine and fall on the ground. The bast fibers are left to dry and then baled with a hay baler. The core fibers are transported to a drier and dried (Chen and Pote 1994).

#### 4.10.1.5 Chopping Line

Usually for a single-phase chopping line a forage harvester (normally used for maize harvesting) with an adapted mower is used. In most cases the use of a row-independent attachment allows to harvest the crops with different distances between the rows. This kind of mower is able to cut and chop the stems; the chopped stems are then transported by a pneumatic conveyer to a trailer.

The low matter density of the chopped biomass, about 30–40 kg $m^{-3}$ with a moisture content of 20 % according to the length at which the stems are chopped (2–4 cm), is the limit of this kind of harvest. This low matter density of the chopped material necessitates a large transport and storage capacity. With this kind of chopper is possible to harvest both the fresh biomass in autumn and the biomass in winter, when it has low moisture content.

This method has been used to harvest the crop. This method can be used in colder areas where the crop is allowed to dry after being killed by frost or by desiccant. The chopped kenaf is stored and transported in cotton modules with the same equipment used for harvesting cotton (Baldwin et al. 1996).

The opportunity to bale is one phase the biomass usually used to harvest Miscanthus: this machine is a self-propelled big baler/harvester which enables mowing, pick-up, compaction, and baling of Miscanthus in one drive. Due to the kenaf stems characteristics it is possible to suppose that this machine is able to harvest the kenaf biomass. The harvester combines the advantages of the single-phase procedure with the baling line and is characterized by very low biomass losses during the entire harvesting process (El Bassam and Huisman 2001). The crop may also be chopped and baled with forage equipment and, if covered, can be stored as large round or rectangular bales on field edges.

Considering kenaf as an energy crop, another product can be obtained from its herbaceous biomass: pellets. The pellets advantage is the reduction of the bulk density of the harvested material which consequently leads to the reductions in a transportation and storage requirements. Pellets are easier to handle than chopped material or bales and there is potential for the development of automatic handling system for such pellets (El Bassam and Huisman 2001). However, the process is very expensive and requires a lot of energy.

Different industries request kenaf stems with a length of 10 cm and more. Forage harvesters, characterized by high efficiency and low cost; cut kenaf stems into too short fragments. The sugarcane harvester enable to harvest while avoiding cutting stems into short fragments (Kobayashi et al. 2003).

Sugarcane harvesters could be used unmodified or simply modified. This machinery use rotating knives or circular cutting blades to sever the base of the kenaf stem and to cut off the low fiber, high foliage, and top portion of the plants. These long stems then pass through the equipment in an upright fashion and then are laid down in a long windrow piles to fields-dry. Once these stalks have been field-dried on the ground other sugarcane equipment with articulating claws can be used to pick the kenaf stalks and place them in sugarcane wagons. This type of system can be used to harvest both live and dead stalks. If kenaf stalks are already dry at the harvest, the harvesting system can be reconfigured to immediately transfer the long cut stalks to in-field wagons traveling with the harvesting equipment or existing sugarcane harvesters could be adapted to cut the kenaf stalks in smaller segments (e.g., 30 cm segments) prior to transferring then to in-field collection wagons (Webber et al. 2002).

There are some problems to introduce this kind of machine in our areas ascribable to the considerable dimension and the high costs of the machine (Bentini et al. 1994).

## 4.11 Drying

In the production chain of the fiber crops, conservation is an important operation in order to control the quality when the product is to be used some time after harvest. Many different methods are possible. The most usual method of conservation is drying. This can be done in the field as standing crop when delayed harvest is possible, but also after mowing in a swath (Huisman and Venturi 2003). When weather condition has been bad, artificial drying can also be required in order to reach the low moisture content to avoid mold growth and losses during long storage by natural or forced ventilation.

### *4.11.1 Moisture Content*

The moisture content of the biomass material determines its stability during storage. At high moisture content (>50 %), microbiological activity begins immediately. The most evident consequence of microbial activity is the loss of dry matter, transformed by respiration into heat, water, and carbon dioxide (Kristensen 1999).

The maximum moisture content at storage will depend, as far other herbaceous crops, on the application of mechanical ventilation and the accepted level of loss. Although exact data are not yet available, it can be concluded that bundles of whole stem, loose bales, and chopped material can have higher moisture contents that high density bales of chopped material and/or bales of compact rolls (El Bassam and Huisman 2001).

### *4.11.2 Drying Methods*

Drying involves the extraction of moisture from the product by natural ventilation and radiation or by artificial ventilation with ambient or heated air. Different methods could be applied for the drying of kenaf to a moisture content which allow storage of the harvested biomass in a stable manner. The different methods which are described are: drying in the field, drying in the storage, and drying in industrial installations.

The most cost-effective way of drying kenaf is by using the ambient air and solar radiation to dry the material in field. Drying of the standing crops starts in the late autumn after the crop has died (usually appointed by the first killing frost that usually causes defoliation of the stems).

It can be seen that there is a decrease in the moisture content of the standing crop from the late autumn to winter. It can be concluded that harvesting should take place during the February, if there is good weather conditions, when the biomass presents low moisture content if no additional drying process is planned. Mowing and drying in a swath could be also used: drying in a swath is advantageous in the sense that it will allow more homogeneous drying of the biomass (including leaves which have fallen and are raked together in the swath). A disadvantage of this method is that more soil or stone mineral is taken up during collection which may cause problems in processing machinery, particularly in case of energy conservation.

The methods employed for drying in storage depend on the condition of the harvested biomass. When the moisture content of the biomass is high, heated air is required to dry the biomass rapidly to a level where fungal growth will not occur. However, when the moisture contents are close to 25 % unheated air is sufficient to dry the biomass (El Bassam and Huisman 2001).

As far other crops (e.g., Miscanthus), the form of the harvested biomass is also an important determinant of drying method. Whole stems can be dried from high moisture contents as they are stored in a well-ventilated situation (even natural ventilation). Mechanical ventilation is needed to ventilate air through high density bales. Drying of low density biomass like chopped material is possible, with natural ventilation and low pressure mechanical ventilation.

A wide range of dryers are available for artificial drying in industrial applications. Some of these may be applicable for drying of bulky material like kenaf. These include rotary drum, band, pneumatic, stream recompressive, and fluidized den dryers. These types of dryers could be of interest if waste heat were to be used as an energy source (El Bassam and Huisman 2001). If waste heat is used for drying kenaf, the type, capacity, and energy input of the dryer will depend very much on the specific situation and process. No research has been carried out on this aspect on kenaf.

## 4.12 Storage

The preliminary objective during the storage of kenaf is the maximization of biomass quality while promising costs and dry matter losses.

When the harvested kenaf biomass is relatively dry, no concrete floor is required for storage. However, if the biomass is wet and soil traffic ability is poor, a concrete floor is recommended. In addition, easy access for loaders and trucks is required to allow quick and easy loading and unloading should only be carried out when soil condition are good.

A large storage area will be required as the density of harvested kenaf biomass is low (e.g., chopped material). It is estimated that over 420 $m^3$ is required for the storage of every hectare of chopped kenaf biomass (assuming a biomass yield of 15 Mg/ha, with a water content of 15 %, and biomass density of 35 $kg/m^3$).

Kenaf can be stored in open air (with or without covering) or in buildings. When bales, whole stems or chopped feedstock are stored in very large piles in the open without covering, rainfall will only moisten relatively small amount of the total pile. Depending on the climate, the growth of fungi and algae will form a hardening layer in the top section of the pile.

The covering of silage with plastic is very common in agricultural practice. It should also be possible to cover kenaf with this type of plastic. Piles of dry chopped could be completely covered by plastic while it is only necessary to cover the top of piles of bales (the sides can be left uncovered since rain will not penetrate deeply). The covering of biomass pile with plastic sheeting may be labor-intensive; however this depends on the volume of biomass and the weather conditions. The cost of storage, therefore, depends on the price of the labor and the anchoring measures taken, in addition to the plastic costs.

The use of existing farm buildings for storage of kenaf will probably be restricted to small amounts of kenaf.

## 4.13 Conclusions

The determination of the appropriate crop management is a key factor for the successful insertion of the crop in the existing cropping systems with economic benefits. A lot of research has been carried out worldwide in order to identify the best crop management. The final end use of the crop is a key parameter in the crop management that will be followed (fiber production, seed production, seed and fiber production, forage production). The selection of the appropriate variety is strongly connected with the area of its cultivation as well as with its final end use. Recently, new high varieties have been developed that are resistant to pests and diseases with improved resistant to drought. In order to be obtain high yields, late-maturity varieties should be cultivated if its specific climatic conditions allow that. When it is cultivated for its stem the plant population should be from 200,000 to 500,000 plants per ha and with row spacing 35–50 cm. In areas that the precipitation is limited irrigation is needed to high yields. Kenaf has high nitrogen fertilization needs that closely connected with the produced yields and the end use. It is a crop very sensitive to nematodes, especially when it is cultivated in areas with sandy soil. This should be taken under consideration in rotation and crops such as cotton and peanut should be avoid, while kenaf can be cultivated after maize or sorghum. The harvesting time, the harvesting method (for fiber production, for seed production, for seed and fiber, for forage use and/or for energy production) as well as the drying and the storage strongly depend on the final end use as well as on the cultivation site.

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# Chapter 5
# Environmental Aspects of Kenaf Production and Use

**A. L. Fernando**

**Abstract** This chapter outlines the environmental aspects of kenaf production and utilization, focusing on the impact on biotic and abiotic resources, through the analysis of the crop's interaction with its environment and management practices. In this study, the assessment of data retrieved from literature was supplemented with results obtained from the Biokenaf project. As a bioenergy and biomaterials carrier, kenaf offers ecological advantages over fossil sources by contributing to reduction of greenhouse gases and energy savings. Nevertheless, a negative impact may be perceived in terms of acidifying emissions. Although the different indicators did not yield a common pattern, overall results suggest that kenaf crop have an advantage over other annual energy crop systems, namely regarding pesticides and fertilizers inputs. However, risks associated with soil quality, erodibility, use of resources, and biodiversity are equivalent to most annual energy crops. Crop management options can influence the outcomes, but site specific factors should be accurately assessed to evaluate the adequacy between crop and location. In addition, environmental hot spots in the systems are detected and options for improvement are presented.

**Keywords** Acidification potential • Acidifying emissions • Avoided greenhouse gas emissions • Biodiversity • Bioenergy • Biological diversity • Biomaterials • Bioproducts • $C_2H_4$ equivalent • Carbon savings • Carbon sequestration • CFC-11 equivalent • $CO_2$ emissions • Desertification • Drought toleration • Emission of gases • Energy balance • Energy crops • Energy efficiency • Energy savings • Environment • Environmental aspects • Environmental impact • Erodibility • Erosion risk • Eutrophication • Eutrophication potential • Fiber crops • Fiber materials • Fossil energy sources • Greenhouse gas emissions • Groundwater depletion • Kenaf • Land use • Landscape diversity • LCA • Marginal land • Mineral resources • $N_2O$ emissions • Natural fibers • $NH_3$ volatilization • $NH_4$ leaching • $NO_3$ leaching • $NO_x$ emissions • Nutrient

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status • Ozone depletion • Pesticide emissions • Photochemical ozone creation potential (POCP) • Phytodepuration • Phytoremediation • Salinity tolerance • $SO_2$ emissions • Soil pH • Soil quality • Soil salinity • Summer smog • Surplus land • Sustainability • Waste generation • Waste production • Waste utilization • Water consumption • Water quality • Water requirements • Water resources • Water use

## 5.1 Introduction

Relationships between the environment and energy crops are varied and complex. It is generally considered that the production and use of biomass crops have more beneficial than harmful effects on the environment. However, the outcomes can significantly be influenced by site-specific factors and by management options. This chapter outlines the environmental aspects of kenaf production and utilization, focusing on the impact on biotic and abiotic resources, through the analysis of the crop's interaction with its environment and management practices. The following variables were selected as categories: replacement/conservation of fossil energy sources, emission of greenhouse gases and acidifying gases, effects on the quality of soil and water, use of resources, waste generation and utilization, biodiversity, and landscape. In this study, the assessment of data retrieved from literature was supplemented with results obtained from the Biokenaf project. In addition, through an integrated approach, minimization of environmental hot spots in the systems and options for improvement are indicated, in order to provide new insights for the future development of this crop in a sustainable agriculture context.

## 5.2 Replacement/Conservation of Fossil Energy Sources

The use of kenaf for energy or for biomaterials production may contribute to replace or conserve fossil fuels. In each application, the evaluation of the energy budget of the cellulosic kenaf fiber production and use requires comparison with competing synthetic or mineral products. The quantification of this energetic budget has to be evaluated from the production of raw materials to the manufacture of the end-product, following the "cradle to grave" approach. The whole life cycle of the products: the cultivation of the plants, production and transportation, the utilization, and the disposal, has to be assessed. Several factors may affect the amount of fossil energy sources replaced/conserved, such as the crop management and biomass yield (which is highly dependent on geographical location), the conversion technologies and its use for bioenergy, biofuels or bioproducts (Biewinga and van der Bijl 1996; Rettenmaier et al. 2010b).

Searching the literature on fiber crops, only limited quantitative information is available on comparative life-cycle energy assessment. Webber (1993) indicates that kenaf requires less energy and chemicals to process as pulp for paper than wood fibers. Cherubini et al. (2009) reported the fossil energy savings for electricity and heat generation from combustion of kenaf. According to these authors, the use of kenaf for electricity and cogeneration saves 85–180 GJ/ha/year, lower than if used for heating generation only (160–295 GJ/ha/year). Results presented for kenaf are similar to those reported for wood chips and wood pellets, hemp and cardoon, but lower than those reported for *Miscanthus*, switchgrass, giant reed and fiber, and sweet sorghum, by means of the same energy generating technologies (Cherubini et al. 2009). The same study reports that electricity generation from kenaf may achieve larger reductions of fossil energy consumption per unit of land area, or at least comparable, than transportation biofuels or biogas. Venturi and Monti (2005) also reported the net energy (energy output minus energy input) associated with the thermochemical conversion of several annual and perennial energy crops. Kenaf ranged 130–313 GJ/ha, in between the lower results stated for hemp and cardoon and the higher results listed for sweet and fiber sorghum, *Miscanthus*, switchgrass, reed canary grass and giant reed, among others, showing equivalent outcomes to the work of Cherubini et al. (2009).

Ardente et al. (2008) in their work defined the energy profile of a kenaf-fiber insulation board, from kenaf production and board manufacture by an Italian firm, to use and for disposal. Results show that the Global Energy Requirements (GER) is 59 $MJ_{Prim}$/mass (kg) of insulating board which involves a thermal resistance $R$ of 1 ($m^2$ K/W)—the functional unit (f.u.), but this value can be reduced to 17 $MJ_{Prim}$ when incineration with energy recovery is assumed as a disposal option of the board and biomass residues at the end-life. A further reduction can be obtained with the introduction of recycled polyester materials into the manufacture process or with the local production of kenaf plants. According to the same study, an energy saving of about 2481 $MJ_{Prim}$/f.u. is estimated during the building operating time, fixed in 30 years. This saving is largely higher than the global energy consumption related to the board life cycle. Kenaf board have been compared with the performances of various replaceable products, as polyurethane (58 $MJ_{Prim}$), flax rolls (50 $MJ_{Prim}$), glass wool (47 $MJ_{Prim}$), paper wool (26 $MJ_{Prim}$), mineral wool (25 $MJ_{Prim}$), and stone wool (21 $MJ_{Prim}$) (Ardente et al. 2008). Such a comparison showed that the kenaf fiber-based products become widely the less impacting ones if board and the biomass residues are incinerated. The synthetic polyurethane foam has the largest impacts in terms of consumed energy due to the large use of fossil fuels during the production process.

In the work of Fernando et al. (2008), based on the Biokenaf pilot fields results obtained in Portugal, the utilization of biomass from kenaf plants to produce solid fuel as well as thermal insulation materials weres analyzed. Main focus of this investigation was the comparison of the products with their conventional counterparts (synthetic polyurethane foam and fossil fuel). Detailed consideration of the energy balances suggests that the use of kenaf-fibers for the production of energy (167 GJ/ha of net avoided fossil energy), is favored when compared with its use as an insulation board (102 GJ/ha of net avoided fossil energy). But, if we take into consideration the energy saving (11506 $GJ_{fossil}$ per ha) in the building operation time (fixed in 30 years) then the energy benefits related to the employment of kenaf boards are higher than its use as solid fuel. Results also show that the use of kenaf natural fibers in insulation boards involves a significant reduction of the fossil energy inputs (178 $\mathrm{GJ}_{\mathrm{fossil}}$ per ha) when compared to the employment of synthetic insulating materials (synthetic polyurethane foam, 361 $\mathrm{GJ}_{\mathrm{fossil}}$ per ha). This is in line with the comparative study cited by van Dam and Bos (2004), on the environmental implications of polypropylene (PP), high density polyethylene (HDPE), and polyurethane (PU) as substitutes for natural fiber-based products. Their conclusion was that natural fiber production requires less than 10 % of the energy used for production of PP fibers (ca 90 GJ/ton) and ca 15 % when the use of fertilizer was included. Rettenmaier et al. (2010a) and Pervaiz and Sain (2003) also reported that biomaterials from fiber crops (e.g., hemp and flax) are superior to their fossil or conventional equivalents in terms of energy savings. In the study of Pervaiz and Sain (2003), a 60 % net energy savings was stated by using 65 % natural fibers (hemp) instead of 30 % glass fibers in thermoplastic matrix.

A further and deeper study, also based on the Biokenaf pilot fields results obtained in Portugal, intended to evaluate the energy balance of cultivation and use of kenaf in the production of integrated thermal insulation boards based on life cycle analysis (Correia 2011). Several scenarios were considered in this study. Two hypotheses were tested in the production of insulation boards: (a) fully bark kenaf fiber-based (b) incorporation of polyester into bark kenaf fiber. As the core fiber has a very high heat capacity, which can be economically tapped for energy production, two solutions were also studied: (1) the core fiber is used by the board producer in a small thermal power plant, in order to generate energy inside the industrial unit, (2) the core fiber is channeled into the production of pellets, which are marketed to be burned in home systems. Scenarios studied mixed the several hypotheses: Scenario I: a.1; Scenario II; a.2; Scenario III: b.1, and Scenario IV: b.2. The results showed that the energy efficiency is greater than unity and the energy balance is positive in all scenarios (Scenario I: 76 GJ/ha; Scenario II: 80 GJ/ha; Scenario III: 44 GJ/ha; Scenario IV: 47 GJ/ha). The most advantageous scenario, in terms of energy budget, was the one in which no polyester is incorporated into the insulation board and where the core fiber residue is conducted into the production of pellets (Scenario II). In terms of energy efficiency, Scenario I, where waste is burnt in a small central unit located in the boards manufacturing unit, was the most promising. In this scenario, the total energy consumption is the lowest, although in terms of energy production, pellets are more productive due to the higher efficiency of the boiler. The incorporation of recycled polyester into the panel is a disadvantage because its production has a high energy cost (Scenarios III and IV).

According to some study (Correia 2011), the energy needed for production, transport, and conversion of kenaf into energy and insulation panels were analyzed in detail for the different Scenarios. Results showed that irrigation (for all scenarios), the production of pellets (in sets II and IV), and production of polyester (in scenarios III and IV) are the factors that most contribute to energy consumption. In the sensitivity analysis, Correia (2011) studied the influence of some variables on energy efficiency. Lowering the level of nitrogen and the level of irrigation, at the cultivation phase, increases the energy efficiency, despite the yields reduction observed with lower addition of water (Fernando et al. 2008). Delaying the harvest from October to December reduces the energy efficiency, but not significantly. The reduction of the transport distance, the improvement of the thermal efficiency of power generating units and the possibility of energy recovery associated with insulated panels in the end of its life cycle can positively affect the efficiency of the system (most significantly the energy recovery) (Correia 2011).

Yields can also affect significantly the energy efficiency and the energy balances (Correia 2011). The higher the yield of the crop, the higher is the energy efficiency of the system and the amount of fossil energy saved. In the Mediterranean region, geographical position has significant impact on yield: in the framework of the Biokenaf project, highest yields were obtained in Spain and the lowest ones in Portugal (Alexopoulou et al. 2009). Crop management factors can also influence the yields, and thus the energy efficiency and balance. Higher yields were recorded when the sowing date is between end April to middle May, when plant density is high (20–40 plants/m$^2$), when the cultivated variety is late-maturity and when water for irrigation was available (300–400 mm of water) (Alexopoulou et al. 2009). Alexopoulou et al. (2009) also indicate that the nitrogen fertilization did not play an important role in the biomass yields, but results were related to 3 years experiments only. Extending the field experiments to a longer time may result in different conclusions. As the degree of mechanization of the various cultivation systems may also differ strongly in the Mediterranean region, the input energy can diverge substantially.

## 5.3 Emission of Gases

Shifting society's dependence away from fossil to renewable biomass resources, e.g., energy crops, is generally viewed as an important contributor to provide an effective management of GHG emissions (Ragauskas et al. 2006), once this substitution results in significant avoided emissions (such as been seen in the works of Rettenmaier et al. 2010a, b).

Biomass use for energy generation is considered "carbon neutral" over its life cycle as all carbon emitted by direct or indirect combustion of biomass has been captured from the atmosphere and has been photosynthetically transformed into biomatter (El Bassam 2010; Spiertz and Ewert 2009) using solar radiation, water, and external inputs (e.g., fertilizer, pesticides, machinery, fuel for farm vehicles, etc.). But, the balance of energy production from biomass is not exactly zero, since a portion of $CO_2$ (a relevant GHG) is emitted during the cycle of biomass production and use: external fossil fuel inputs are required to cultivate and harvest the feedstocks, in transport, and in processing and handling the biomass for energy production (OECD/IEA 2007, Atkinson 2009; Spiertz and Ewert 2009 and Picco 2010). The amount of avoided GHG emissions, is then dependent on yields, crop management options, and the conversion technologies (Biewinga and van der Bijl 1996;

Rettenmaier et al. 2010b). End use, for bioenergy or for biomaterials, can also differentiate GHG life cycle results.

Other gases can also contribute to the greenhouse effect such as $N_2O$ and $CH_4$ (FMW 2007), which can be quantified in terms of $CO_2$ equivalents.

Methane is released in bioenergy process chain through combustion of fossil fuels, anaerobic decomposition of organic feedstocks, and emissions from soil organic matter (Cherubini et al. 2009). Regarding the production and use of energy crops, $CH_4$ emissions are usually considered as negligible (Kaltshmitt et al. 1996; Delucchi and Lipman 2003), if the land use change is not being considered. In general, cultivated soils show lower $CH_4$ uptake rates than soils under native conditions (Mosier et al. 1998). This fact may play an important role if tropical peat soils are involved: they represent a large storage of carbon and small losses may have a big influence on GHG balances (Cherubini et al. 2009).

$N_2O$ emissions are attributed to the nitrification and denitrification processes occurring during crop cultivation (Biewinga and van der Bijl 1996), evolving from nitrogen fertilizer application and organic matter decomposition in soil (Stehfest and Bouwman 2006). $N_2O$ emissions occur also during conversion processes to bioenergy or biomaterials, but are very much dependent on the technique used and may be neglected (Biewinga and van der Bijl 1996). According to IPCC (2006), $N_2O$ emissions can be calculated based on the nitrogen fertilization level, estimating emissions derived from the $NH_3$ volatilization, the $NH_4/NO_3$ leaching and run-off, and directly from soil. As annual energy crops present higher fertilization rates than perennial energy crops (Zegada-Lizarazu et al. 2010), the impacts of $N_2O$ emissions associated with may be especially significant. But, regarding kenaf, low nitrogen requirements are attributed to this fiber crop (50–100 kg N/ha, Alexopoulou et al. 2009), equivalent to those reported for perennial lignocellulosic crops, such as *Miscanthus*, switchgrass, and giant reed (Fernando et al. 2010b). If IPCC factors are applied, the range of $N_2O$ emissions derived from its cultivation is 0.7–1.3 kg N/ha/year, a result considered low, thus not representing a major threat on accounting GHG avoided emissions (1.5–3 % of the GHG savings presented by Cherubini et al. 2009). However, $N_2O$ is also an ozone-depleting gas, and its emission represents a negative aspect associated with the cultivation of energy crops (Oliveira et al. 2001).

The quantity of avoided greenhouse gas emissions resulting from the combustion of kenaf was studied by Cherubini et al. (2009), together with other renewable and fossil systems. According to these authors, the use of kenaf for electricity and cogeneration saves 1–20 $Mg_{CO2\text{-}eq\ saved}$/ha/year, lower than if used for heating generation only (10–33 $Mg_{CO2\text{-}eq\ saved}$/ha/year). The study claims that energy generation from kenaf biomass may achieve larger reductions of GHG per unit of land area, particularly compared to some first-generation biofuels and wood chips and wood pellets. Kenaf results were similar to those reported for hemp and cardoon, but lower than those presented for *Miscanthus*, switchgrass, giant reed and fiber, and sweet sorghum (Cherubini et al. 2009).

The high energy demanding building sector and the long useful life of buildings involve a relevant share in the EU energy balance and in the $CO_2$ emissions scenario (Directive 2003/87/CE ). The use of thermal insulation materials in building walls and roofs is a relevant tool to improve energy performance, by reducing the resources consumption and the associated environmental burdens arising from the combustion of fossil fuels. Furthermore, the use of thermal insulating materials reduces the heat losses from buildings, involving considerable energy and costs savings for air conditioning and heating during the building lifetime. Innovative building biomaterials, based on biological resources such as kenaf, involves several environmental benefits during the whole life cycle, namely, reduction of resource consumption, energy saving, and less environmental impacts and recovery, re-use and recycling of the products before the final disposal. According to Ardente et al. (2008), kenaf-fiber insulation board, from kenaf production and board manufacture by an Italian firm, represents a Global Warming Potential (GWP) of 3.17 kg $CO_{2\ eq}$/mass (kg) of insulating board which involves a thermal resistance *R* of 1 ($m^2$ K/W)—the functional unit (f.u.). The highest share in the lifecycle phases to the total GHG emission is caused by the manufacture of input materials and, in particular, of the polyester fibers, which account for about 39 % of the total. Transports account for 23 %, while the final disposal accounts for 25 % of the total GHG emission, because of the combustion of the polyester fibers (Ardente et al. 2008). The GWP can be reduced to 0.36 kg $CO_{2\ eq}$ when incineration with energy recovery is assumed as a disposal option of the board and biomass residues at the end-life. A further reduction can be obtained with the employment of recycled polyester fibers or with the local production of kenaf plants. The avoided C emissions in the overall life cycle of about 135 kg$CO_{2\ eq}$/f.u. was estimated during the building operating time, fixed in 30 years. This saving is largely higher than the GWP related to the board life cycle. A comparison with the performances of various replaceable products, as polyurethane (3.2 kg $CO_{2\ eq}$), flax rolls (2.4 kg $CO_{2\ eq}$), glass wool (2.2 kg $CO_{2\ eq}$), mineral wool (1.7 kg $CO_{2\ eq}$), stone wool (1.5 kg $CO_{2\ eq}$), and paper wool (0.82 kg $CO_{2\ eq}$), showed that the kenaf fiber-based products become widely the less impacting ones if board and the biomass residues are incinerated (Ardente et al. 2008). Pervaiz and Sain (2003); Rettenmaier et al. (2010a) and others, also claim that natural fibers have excellent potential to reduce not only $CO_2$ emissions but also save nonrenewable resources (e.g., by substituting glass fiber reinforcements in automobile thermoplastics).

Fernando et al. (2009) quantified the magnitude of greenhouse gas emission reductions possible from utilizing kenaf-fibers as a source of electricity and heat (when used as a solid fuel in a combined Heat and Power Plant) or as thermal insulation boards (as a fiber reinforced composite made by kenaf vegetable fibers which are incorporated in a polyester matrix). Based on the Biokenaf pilot fields results obtained in Portugal, the study indicates that the use of kenaf-fibers as solid fuel (8.4 $Mg_{CO2\text{-}eq\ saved}$/ha/year), is favored when compared with its use as a thermal insulation board (4.3 $Mg_{CO2\text{-}eq\ saved}$/ha/year). As solid fuel, the highest impact in $CO_2$ emissions is due to the drying of plants prior to its use in the combined heat and power plant. As a thermal insulation board the highest impact in $CO_2$ emissions derive from the introduction of polyester fibers as filler of the kenaf insulation board. The drying of residues in the use and disposal of the kenaf board also represents a high impact. According to Fernando et al. (2009), modification of the production process by employing recycled polyester fibers (residues from textile companies, for example) can decrease the total $CO_2$ emissions for the production of this raw material by 40 %, and the net avoided GHG emissions can increase by a significant 130 % (reaching 9.9 $Mg_{CO2\text{-}eq\ saved}$/ha/year). The same study indicates that if plants and residues are left in the field until moisture content is about 40 %, the net avoided emissions can increase by nearly 90 % (reaching 8.0 $Mg_{CO2\text{-}eq\ saved}$/ha/year), if kenaf will be used as insulation mat, and by 60 % (reaching 13.4 $Mg_{CO2\text{-}eq\ saved}$/ha/year), if kenaf will be used as solid fuel. The incidences of yields and irrigation on the eco-profile have also been evaluated. Net avoided emissions were relatively insensitive to variation in irrigation (avoided emissions increase by ≈10 %, when fields are not irrigated), but highly sensitive to stem yields (extra 0.5–0.7 $Mg_{CO2\text{-}eq}$ per Mg of yield increase, can be avoided, which represent ≈10 % increment, for each extra Mg biomass production) (Fernando et al. 2009). The use of kenaf natural fibers in insulation boards also involves a significant reduction of the GWP when compared to the employment of synthetic insulating materials (PUR): nearly 30 $Mg_{CO2\text{-}eq}$/ha/year can be avoided. Fernando et al. (2009) also indicated that the avoided emissions (825 $Mg_{CO2\text{-}eq\ saved}$ per ha) in the building operation time (fixed in 30 years), by reducing the resources consumption and the associated environmental burdens arising from the combustion of fossil fuels, benefits kenaf boards versus kenaf solid fuel.

The emission of acidifying gases leads to several harmful effects such as eutrophication, decreased tree vitality, dissolution of metals (e.g., aluminum), and declines in fish populations in lakes. In general major acidifying substances are $NH_3$, $SO_2$, and $NO_x$, and the acidification potential is measured in $SO_2$ equivalents. Other substances such as HCl and HF play a role as well but are of minor importance (Biewinga and van der Bijl 1996).

Concerning energy crops, the acidification potential is essentially determined by $NO_x$ and $SO_2$ emissions released during the combustion of the biomass material. Acidifying emissions can take place at several other phases in the production and conversion of energy crops such as the production of nitrogen fertilizers, which is a source of $NO_x$ and $NH_3$ emissions, and most of these emissions are linked to the energy use. From conversion of energy crops HCl emissions can occur; however, with simple techniques HCl can be removed from exhaust gases easily (Biewinga and van der Bijl 1996).

$SO_2$ emissions form a smaller proportion of the total acidification potential of energy crops than $NO_x$ emissions, partly due to the low sulfur content of energy crops compared to fossil fuels (Oliveira et al. 2001). On the other end, energy crops can emit higher levels of NOx, since nitrogen is a main constituent of biomass (Biewinga and van der Bijl 1996). An overview of the chemical composition of different grasses shows that kenaf sulfur content is 0.15 % (dry ash-free basis), similar to perennials such as *Miscanthus*, *Arundo* and reed canary grass, a little bit higher than the value reported for switchgrass (0.11 %), but much lower than what is commonly reported for coal (1.7 %) (Vassilev et al. 2010).

The same study indicates that the nitrogen content of kenaf grass is 1.0 % (dry ash-free basis), comparable to the average results for different grasses (0.9 %), yet higher than perennials *Miscanthus* (0.4 %), *Arundo* and switchgrass (0.7 %) results, but smaller than that of coal (1.3 %). The chlorine content of kenaf grass is 0.17 % (dry basis), in between the higher results of *Arundo* (0.2 %) and the lower results of *Miscanthus* (0.13 %), but much higher than coal results (0.03 %) (Vassilev et al. 2010). According to these results, acidifying emissions due to combustion of kenaf, can be equivalent to those obtained with perennials such as *Arundo*, *Miscanthus,* and switchgrass (even if final results can be a bit higher). Nevertheless, the intensive management associated with an annual crop, such as kenaf, increments the acidifying emissions associated with its cultivation by comparison with perennials.

The acidification potential through the substitution of fossil sources with biomass for energy and biomaterials production depends not only on the crop, but also, on the conversion technology, the method of biomass cultivation and the fossil source which is substituted (Kaltschmitt et al. 1996; Rettenmaier et al. 2010b). Globally, the acidifying emissions resulting from the production and use of energy crops have a negative impact because they are higher than those of the corresponding uses obtained from fossil sources (Rettenmaier et al. 2010b).

The acidification potential associated with the production and use of kenaf as a thermo-insulating board biomaterial was studied by Ardente et al. (2008), together with other renewable and non-renewable systems. Production of kenaf-fiber insulation board represents an Acidification Potential (AP) of 27.4 g $SO_{2\ eq}$/mass (kg) of insulating board which involves a thermal resistance *R* of 1 ($m^2$ K/W)—the functional unit (f.u.). The life cycle inventory results per f.u. shows that $NO_x$ emissions represent the highest proportion of the acidifying emissions (17.2 g), followed by $SO_x$ (14.6 g). Ammonia (0.33 g), HCl (0.13 g), and HF (0.004 g) represent a minor influence on the acidification potential. A comparison with the performances of various replaceable products, as polyurethane (27.9 g $SO_{2\ eq}$), flax rolls (17 g $SO_{2\ eq}$), stone wool (12.3 g $SO_{2\ eq}$), glass wool (8.4 g $SO_{2\ eq}$), paper wool (5.5 g $SO_{2\ eq}$), and mineral wool (4.9 g $SO_{2\ eq}$), showed that the kenaf fiber-based products (with polyurethane) are the highest impacting ones (Ardente et al. 2008). The negative impact of acidifying emissions associated with the use of fiber crops for the production of insulation mats was also reported by Rettenmaier et al. (2010a) with hemp and flax, by comparison with other biomaterials produced from fiber crops such as fiber composites, which presented a positive impact.

Production and use of energy crops may also contribute to the depletion of the ozone layer (measured as CFC-11 equivalent) and to summer smog (measured as $C_2H_4$ equivalent). According to Rettenmaier et al. (2010a, b), production and use of fiber crops (hemp and flax) for biomaterials (fiber composites and insulation mats) is inconclusively related to summer smog. In the work of Ardente et al. (2008), the production of kenaf-fiber insulation board represents a photochemical ozone creation potential (POCO) of 2.2 g $C_2H_{4\ eq.}$/f.u. This negative result is exceeded by the replaceable products stone wool (4.6 g $C_2H_{4\ eq.}$), mineral wool (3.7 g $C_2H_{4\ eq.}$), and glass wool (2.5 g $C_2H_{4\ eq.}$), but alleviated in the case of polyurethane (1.4 g $C_2H_{4\ eq.}$), flax rolls (0.5 g $C_2H_{4\ eq.}$) and paper wool (0.2 g $C_2H_{4\ eq.}$). The ozone depletion potential (ODP) associated with the production of kenaf-fiber insulation board was considered negligible by Ardente et al. (2008), in contrast with the negative impact results reported by Rettenmaier et al. (2010a, b) associated with the production of fiber crops (hemp and flax) for biomaterials (fiber composites and insulation mats).

## 5.4 Effects on the Quality of Soil and Water

The production of biomass can be relatively land-intensive and therefore presents a risk of soil and groundwater pollution with fertilizers (N, P, K) and pesticides. Common cropping management activities and crop characteristics can also affect soil quality through the change of nutrient, organic matter (SOM), structural and acidic statuses, and erosion potentials. But the cultivation of energy crops, especially perennials, may also present benefits toward soil quality (erodibility, compaction, fertility, carbon sequestration) (Fernando et al. 2010c; Boléo 2011).

Kenaf crop present agronomical features of considerable environmental effects, such as: the possibility to use extensive techniques with modest use of technical means (e.g., fertilizers and pesticides) (Alexopoulou et al. 2009) and therefore, with positive economic and environmental feedback (lower losses by leaching and atmospheric emissions): kenaf N inputs (50–100 kg/ha/year) (Alexopoulou et al. 2009) represents less than half of that used traditionally for the production of corn (200–300 kg/ha) (Picco 2010). The N inputs, and the corresponding N losses related, are comparable to perennials, such as *Miscanthus*, switchgrass, and giant reed, and to the needs of the fiber crop flax and the oil crop sunflower, and lower than those associated with the perennial cardoon, sugar crops like sugar beet and sweet sorghum, and oil crops like rapeseed and Ethiopian mustard (Fernando et al. 2010a).

According to IPCC (2006), most of the N applied to kenaf fields can be lost by leaching/runoff (15–30 kg/ha/year), 10 % can be lost by volatilization (5–10 kg/ha/year) and $N_2O$ emissions are a negligible part of the N emissions (0.6–1.2 kg/ha/year). Nonetheless, IPCC emission factors do not take into account root and rhizome dynamics and N runoff and leaching can be lower due to the root system characteristics. Several works on kenaf (Fernando et al. 2011, 2012) suggest that ammonium and nitrate leaching are easily trapped and filtered by the underground root system. In these studies, kenaf cropping has been linked with wastewaters treatment. Fernando et al. (2011) and Barbosa (2010), shows a 70–100 % removal of ammonium ion in the leaching water and the works of Fernando et al. (2012) and Ferreira (2011) indicate that the system biomass-soil contributes to the removal of nitrates from wastewater−80 to 100 % at the stages of plants major development and average 35 % at the end of plants growth. The work of Abe and Ozaki (2007) also shows the ability of kenaf to remove nitrogen and phosphorus from wastewaters in constructed wetlands systems. Phytodepuration with kenaf crop can also contribute to lowering the water resources consumption and to improve the water quality. The nutrients can be recycled and any possible health concerns from viral and bacterial infections are avoided as the crop is not part of the food chain (OECD/IEA 2007).

Based on the Biokenaf pilot fields results obtained in Portugal (Fernando et al. 2006), the difference between N-input (fertilizers) and N-output (emissions and crop uptake) was estimated, and the small but negative result of −12 kg/ha/year (N) was obtained. This means that in these conditions, soil N reserves can become depleted, but such was not observed (Fernando et al. 2007). These results are better than the average N deficit (−43 kg/ha/year, N) observed for the cultivation of 15 energy crops in Europe, better than the results reported for hemp (−17 kg/ha/year, N), but worse than those reported for flax (+5 kg/ha/year, N) (Fernando et al. 2010b).

Concerning P and K emissions, while P surplus from artificial fertilizer remains relatively inert in the soil, provoking no noteworthy effects, K surplus may contribute to eutrophication of terrestrial ecosystems. Based on the Biokenaf pilot fields results obtained in Portugal (Fernando et al. 2006), the difference between P and K-input (fertilizers) and P and K-output (crop uptake) was estimated, and the negative results of −22 kg/ha/year (P) and −380 kg/ha/year (K) were obtained. This means that in these conditions, soil P and K reserves may result depleted. These P and K results present a higher negative impact than the average P surplus (+15 kg/ha/year, P) and K deficit (−42 kg/ha/year, K) observed for the cultivation of 15 energy crops in Europe. A comparison with the results reported for hemp (+12 kg/ha/year, P; −30 kg/ha/year, K) and flax (+6 kg/ha/year, P; +37 kg/ha/year, K), also shows that kenaf presents a worse result (Fernando et al. 2010b).

Regarding the P and K deficit observed in the kenaf fields in Portugal, it is possible to influence the outcomes by increasing P and K input, thus reducing the impact associated. This indicates that site-specific factors should be accurately assessed to evaluate the adequacy between crop, location, and crop management. Nevertheless, neither P nor K soil depletion was observed in the experimental fields in Portugal during the 4 years of the Biokenaf project (Fernando et al. 2007).

There are few studies that report the eutrophication potential of production of kenaf crop for energy and biomaterials. In the work of Ardente et al. (2008), the production of kenaf-fiber insulation board represents an eutrophication potential of 2.4 g $PO_4^{3-}{}_{eq.}$/f.u. This negative result is only exceeded by the replaceable product polyurethane (2.94 g $PO_4^{3-}{}_{eq.}$). All other products (renewable and non-renewable), present better results than kenaf (glass wool, 1.3 g $PO_4^{3-}{}_{eq.}$, flax rolls, 1.22 g $PO_4^{3-}{}_{eq.}$, stone wool, 1.16 g $PO_4^{3-}{}_{eq.}$, mineral wool, 0.8 g $PO_4^{3-}{}_{eq.}$. and paper wool, 0.7 g $PO_4^{3-}{}_{eq.}$). Eutrophication negative impact results associated with the production of fiber crops (hemp and flax) for biomaterials (fiber composites and insulation mats) were also reported by Rettenmaier et al. (2010a). In this study, it was also concluded that, in terms of eutrophication, production of fiber composites presented a better profile than insulation mats.

Regarding pesticide use, kenaf seems to have a low susceptibility to pests and diseases and thus has low pesticide requirements (van Dam and Bos 2004; Singh et al. 2010), reducing the risk of groundwater contamination and consequent risks to water and soil organisms. A survey on the substances applied, their amounts, and traits were carried out by an extensive bibliographic research in peer-reviewed journals, scientific reports, agricultural databases, and own field experience. Multiple references often document for kenaf the application of different pesticides with similar functions, or the application of the same pesticide in different quantities, or the needlessness of pesticide use. Based on the methodology applied in the work of Fernando et al. (2010c), a pesticide score was determined for kenaf resulting from pesticide application. This pesticide score was attained through the quantification of active substances applied, and a survey on physical specifications, effects on the environment, fauna, and human health of each active substance. Results obtained ranged from 0 (no disease control and/or chemical weeding) to 8, with an average result of 4. This indicates that kenaf present a low pesticide impact, reflecting its low susceptibility to pests and diseases. The pesticide score associated with the production of kenaf is comparable to the score reported for flax (6) but higher than what was reported for hemp (0, because no pesticide application is mentioned in hemp fields in Europe) (Fernando et al. 2010b). This score is also much lower than the average pesticide score (12) reported for the cultivation of 15 energy crops in Europe (Fernando et al. 2010b). Energy crops that present a higher score than kenaf are sunflower (18), sugar beet (41), wheat (17), and potato (74) (Fernando et al. 2010b). However, the estimated pesticide risk depends on the intensity level of pest control practices. This implies that, kenaf may have low impacts to moderate if managed in that manner.

Common cropping management activities such as harvest and site preparation and the sheer prevalence of certain species can affect soil structure, pH, and organic matter dynamics. These factors interact with, influencing nutrient availability, thus soil fertility. Assessing the impact of crops on soil organic matter content, structure and pH is highly dependent on local conditions. Nonetheless, there are generic trends documented in literature that allow a qualitative assessment of the kenaf crop.

Soil revolving by tillage and ploughing and litter removal are more intensive in annual systems (Fragoso et al. 1997). Thus, annual crops are more likely to induce soil quality depletion through loss of organic matter and structure than perennial grasses and trees (Börjesson 1999; Zan et al. 2001). The short permanence of annuals is also a contributing factor to the soil quality depletion. Regarding kenaf, this impact is minor due to the prolific root system with a long taproot and wide-ranging lateral roots (Lauriault and Puppala 2009), which improve structure and, being left in the ground after harvest, enhance organic matter content. If litter (mostly senescent leafs) is left on field, the negative impact associated can also be minored. This was supported by Fernando et al. (2007). In their work, they verified that the presence of the crop in the Biokenaf fields experiments, did not affect the soil organic matter. Some other annual energy crops present the same benefits (Fernando et al. 2010b): Rapeseed, Ethiopian mustard, and flax benefit from roots and part of the stem left on the ground. Hemp and sweet sorghum have deep roots that improve structure and enhance organic matter content, if left in the ground after harvest. The same happens with sunflower, although with less extent because of bigger spacing and smaller roots.

Regarding soil pH, intensive soil amendment in annual systems may lead to sharp pH variations from the native status of the soil. Regarding Biokenaf field experiments in Portugal, it was reported as a significant reduction in pH, played by soil amendment, due to the high alkalinity of the soil (8.6), at the beginning of the experiments. Nonetheless, kenaf cultivation data indicated negligible fluctuations in pH along the time (Fernando et al. 2007).

The use of annual crops in soils at risk of erosion may contribute significantly to the soil loss and its associated nutrients (Picco 2010). Considering that soil erosion is a particular problem in the Mediterranean region, which is characterized by long drought periods followed by heavy bursts of rainfall falling on steep slopes with unstable soils (EEA 2006), choice of a crop is also important to reduce erosion risks.

The erosion risk associated with kenaf crop can be assessed by means of the methodology applied in the work of Fernando et al. (2010c). In this erosion impact analysis it was only considered as the exposure of the soil to rainfall, crossing the potential damage caused by pluviosity with the soil cover characteristics of kenaf during their cultivation cycle. Being site-specific, naturally owing to the weight of pluviosity, in the Mediterranean, the estimated harmful rainfall associated with kenaf was 389 mm/year, comparable to flax and hemp. Lignocellulosic and woody crops, and fallow field, exhibit average lower erodibility potential (100–200 mm/year, Boléo 2011) owing to greater interception of rainfall and more surface cover for a longer time period (Kort et al. 1998). The continuous presence of an underground biomass in the soil also contributes to these findings. Ethiopian mustard, rape seed, and sugar beet, also showed lower impact (<300 mm/year, Boléo 2011), owing to the fact that these are cultivated as a winter crops, and its permanence in the soil is very long. In contrast, potato, sunflower, and sweet sorghum (annual crops) pose higher erosion risk (>400 mm/year, Boléo 2011) than kenaf. But, kenaf may have a positive impact on reducing soil erosion due to the development of its dense and deep root systems (Lauriault e Puppala 2009), which could actively hold earthy masses during the rainier autumn and winter periods. Crop management options can also have a big impact on the erosion potential of this crop. Delaying the harvest, can minimize it, but the use of heavy machinery for activities such as ploughing, spreading of organic manure, and harvesting, may enhance it, due to soil compaction, as it has been observed with sugar beet and potato, since they have a high harvesting weight that requires the use of heavy machinery (EEA 2006; FAO 2003).

## 5.5 Use of Resources

Kenaf has shown good potential as a low input alternative agricultural crop (Alexopoulou et al. 2009). The N fertilizer requirements of this crop are low by comparison with other energy crops, as mentioned in the previous sections. Since synthesis of nitrogen fertilizers are energy demanding, the low kenaf N requirements, equivalent to those reported for perennial lignocellulosic crops (Fernando et al. 2010b), consequently represent low energy input needs associated with. Regarding P and K fertilizers they are usually extracted from mineral ores, which are limited. Hence, lower P and K requirements implicate ore conservation and energy savings to mine them. Average P and K fertilizer inputs, expressed as $K_{eq}$, for the cultivation of kenaf in Europe were quantified and compared with the P and K fertilizer inputs of other energy crops reported in Fernando et al. (2010b). Results of this comparison indicates that the exhaustion of mineral ores associated with the P and K fertilization of the kenaf fields (226 kg $K_{eq}$ $ha^{-1}$), is below the average observed for the cultivation of 15 energy crops in Europe (262 kg $K_{eq}$ $ha^{-1}$), comparable to hemp fertilization (222 kg $K_{eq}$ $ha^{-1}$), slightly higher than flax fertilization (173 kg $K_{eq}$ $ha^{-1}$), but much lower than PK use intensities associated with sweet sorghum (583 kg $K_{eq}$ $ha^{-1}$) and potato (757 kg $K_{eq}$ $ha^{-1}$) crops. Being less input intensive, kenaf also generate less waste in the form of pesticide and fertilizer disposed packages, by comparison with other more demanding crops.

On the other hand, the specific water requirements of kenaf (300–400 mm of water, Alexopoulou et al. 2009) could be a limiting factor which might contribute to groundwater depletion. Effects of increased water abstraction include salinization and water contamination, loss of wetlands, and the disappearance of habitats through the creation of dams and reservoirs and the drying-out of rivers (EEA 2006). Irrigation also penalizes the energy balance. These aspects are of particularly importance in southern Europe, where in summer the soil water content is less than the specific water requirements of the crop.

Kenaf is described as opportunistic in relation to water availability, with a high rate of stomatal conductance and transpiration rate when water is not limited, and a markedly reduced stomatal conductance and transpiration rate when water availability is restricted (Patanè and Sortino 2010). Moreover, the crop tolerates drought (Bañuelos et al. 2002) and is able to recover following re-watering (Muchow 1992). Additionally, timeliness of water availability is not as critical for kenaf, which is a vegetative crop, as it is for the predominant grain crops, wheat and grain sorghum that require water at pollination and grain-filling (Ogbonnaya et al. 1998). Impacts on water use by kenaf cultivation may also be minimized due to the high cellulose content of this biomass, which allows the plant to stand upright at low water contents, as it was referred to herbaceous perennials (Lewandowski et al. 2003) and due to high water use efficiency, owed by their deep and well-developed root system (Lauriault e Puppala 2009). Subtracting kenaf water needs from available rainfall within the limits of crop growth would reveal a deficit in supply or the accommodation of the requirement by the availability. Assuming that the resulting calculus would correspond to groundwater balance (Fernando et al. 2010c), expressed in mm, the result obtained for kenaf in the Mediterranean region shows a deficit of 117 mm $year^{-1}$. This result is comparable to the average water exhaustion potential of different annual energy crops studied ($-117$ mm $year^{-1}$) by Boléo (2011) across Mediterranean. In the same study, Boléo revealed that perennial grasses and woody species show positive water balances and that hemp and potato, high water demanding crops, presented the most severe exhaustion potential ($-467$ mm year$^{-1}$ and $-389$ mm year$^{-1}$, respectively). Flax, another fiber crop, presented a more balanced amount ($-31$ mm year$^{-1}$), lower than the deficit presented by kenaf.

There are few studies that report the water consumption and the wastes generation of production and use of kenaf crop for energy and biomaterials. In the work of Ardente et al. (2008), the production of kenaf-fiber insulation board represents a water consumption of 10.7 kg/f.u. This result is exceeded by glass wool (27.0 kg) and mineral wool (25.6 kg) and highly exceeded by the replaceable product polyurethane (298 kg). Other products present better results than kenaf (flax rolls, 5.7 kg, stone wool, 3.9 kg, and paper wool, 0.8 kg). In terms of wastes production, Ardente et al. (2008) indicates 2.0 kg, lower than the result attributed to glass wool (6.6 kg) and to mineral wool (2.7 kg) but higher than the values attributed to stone wool (0.054 kg), flax rolls (0.122 kg), paper wool (0.032 kg), and polyurethane (0.32 kg).

Water consumption impact results associated with the production and use of fiber crops for biomaterials were also reported by van Dam and Bos (2004). In their study, they stated that the water retting process of jute (15–18 days) in ditches or ponds consumes large amounts of water, causing pollution of surface waters. Organic degradation products of decomposing plant tissues and accumulation of microbial biomass are not considered toxic, but the process causes oxygen depletion and foul smell emission. Therefore, novel and less damaging methods for fiber extraction need to be implemented, as well as to equip processing facilities with adequate exhaust hoods. In their revision, van Dam and Bos (2004) also indicated that the impacts of waste production (air and water pollution and solid waste production) were higher for synthetic products than for natural fiber-based products: the water pollution of production processes of natural fibers was recognized to be high, but considered to consist of biodegradable compounds in contrast to the release of persistent chemicals (heavy metals) in the effluent of chemical plants. The wastewater treatment for natural fiber production therefore would be technically easier and cheaper. In the same revision, it was also stated that products made of fibers like kenaf will pose lesser health problems to workers than, for instance, glass fibers, which cause skin irritation, or the hazardous asbestos fibers.

The application of treated wastewater to the soil kenaf system may contribute to mitigate the scarcity of water resources and to reduce the fertilizers needs, with global positive environmental outcomes. Irrigation with wastewaters may provide readily available adequate amounts of N, P, and K and also sufficient quantity of organic matter that improves the soil structure and other soil properties related to availability of water and nutrients. According to Khan et al. (2009), the use of treated wastewater may increase the total carbon, the total nitrogen concentration, and the mineral content along with the microbial activity in soil that helps in nutrient availability to plants.

Kenaf cropping has been linked with wastewaters irrigation (e.g., Barbosa 2010; Ferreira 2011; Fernando et al. 2011, 2012). The aim of the referred works was to evaluate growth responses, as well as the quality and biomass productivity of the G4 variety of kenaf, irrigated with wastewaters presenting different ammonium ion concentrations and nitrate ion concentrations. Results indicate that the increment of ammonium ion up to 60 mg dm$^{-3}$ ($NH_4$) in the wastewaters led to the decrease in biomass productivity (Barbosa 2010, Fernando et al. 2011). Irrigation with wastewater enriched with nitrate ion did not affect the growth and productivity of kenaf, within the levels of nitrate studied (maximum concentration 100 mg $dm^{-3}$ $NO_3$) (Ferreira 2011, Fernando et al. 2012). In terms of biomass quality, an increased accumulation of biomass ash and nitrogen was observed, due to the irrigation with these wastewaters, and this fact may penalize its use for combustion purposes.

Land used for energy cropping competes with conventional agriculture, forest production, and urbanization, as well as for nature protection and conservation. Kenaf crop to be used for bioenergy and bioproducts of increased value, should therefore be produced in a sustainable land use way: a) by using land not required for food and feed production (Krasuska et al. 2010); by using land in a way that the minimum direct and indirect negative effects are being produced due to Land Use Change (LUC) (Fritsche et al. 2010). These conflicts might be solved through spatial segregation of food/feed and energy producing areas by continuing producing food on established and productive agricultural land and growing dedicated energy crops on so called “surplus” land. But adequacy between the bioenergy cultivation systems and the respective types of surplus land should be taken into account, namely, issues such as yields, inputs, and costs, as well as potential environmental and socio-economic impacts (Dauber et al. 2012).

Regarding the use of surplus land, kenaf has been recognized as tolerant to soil salinity (Francois et al. 1992) and as a biomass crop for soil phytoremediation (Bañuelos et al. 1997). Francois et al. (1992) described a 2-year experiment with two cultivars (Everglades-41 and 7818-RS-10) grown with six salinity treatments imposed on a silty clay soil. Soil salinity ranged from 5.4 to 12.6 dS $m^{-1}$ the first year, and from 6.0 to 14.9 dS $m^{-1}$ the second year. The mean dry weight yields of the stems during the 2-year experiment were reduced 11.6 % for each unit increase in soil salinity above 8.1 dS $m^{-1}$, placing kenaf in the salt tolerant category. Increased salinity did not significantly affect fiber length but excessive Cl accumulation occurred in the leaf tissues at high soil salinity levels.

Regarding phytoremediation, it was reported that successively planting kenaf in Se-laden soil has the potential to reduce total soil Se. The cultivation of this crop led to a significant reduction of total soil Se between preplant and the final harvest by 23 %, over a 1-year-period under greenhouse conditions (Bañuelos et al. 1997). But, the seleniferous soil ($\sim$40 mg $kg^{-1}$ soil) reduced significantly the shoot yield. Effects observed might be also due to the high salinity of these soils ($\sim$8 dS $m^{-1}$).

The effects of different heavy metals on growth, productivity, and biomass quality of several varieties of kenaf (Tainung 2, Everglades 41, Gregg, Dowling, SF 459, and G4) were reported in the studies of Catroga et al. (2005) and Catroga (2009). Zn was the metal that most negatively and significantly affected the productivities obtained. In contrast, kenaf showed high tolerance to Hg, Cd, Cu, and Cr soil contamination. Higher productivities were observed with Tainung 2, especially, in soils contaminated with Cu, Cr, and Cd. Dowling was the most productive variety in Zn contaminated soils and Everglades 41 the most productive variety in Hg contaminated soils. Mineral matter accumulation was also influenced by heavy metals soils contamination. Contamination with copper, chromium, and mercury resulted in a higher removal and accumulation by the roots. Soils contaminated with zinc and cadmium, resulted not only in a high accumulation by the roots but also in the aerial fraction of the kenaf plants. Tainung 2 was the most efficient variety in the phytoextraction of Cu and Cd from soils, Everglades 41 the most efficient for the Zn and Cr phytoextraction from soils and Dowling the most efficient on the removal of Hg. Results presented in those studies also indicate that this biomass can be further valorized for energy production or fiber, once soils contamination did not influence the calorific value and the fiber content of kenaf plants.

The potential of kenaf for phytoremediation of lead (Pb) on sand tailings was also investigated by Ho et al. (2008). In Pb-spiked treatments, roots accumulated more than 85 % of total plant Pb which implies that kenaf root can be an important sink for bioavailable Pb. The ability of kenaf to tolerate Pb and avoid phytotoxicity was attributed to the immobilization of Pb in the roots and hence the restriction of upward movement, indicating its suitability for phytoremediation of Pb-contaminated site.

It was also argued that kenaf cropping can be used as a strategy for combating desertification (Barbosa et al. 2012). Increasing vegetation, like the cultivation of energy crops on marginal and degraded land, could be a way to combat desertification or land degradation (Cortina et al. 2011), because some of these cultures are able to restore soil properties. This practices could be suitable, mainly if the species being introduced have low water and nutrient exigencies (Kassam et al. 2012), such has been observed with kenaf, show adequate physiological and anatomic features to control water and wind erosion, and if the practices by which these cultures are established, allow to increase the levels of organic matter on soil and increase the soil moisture content.

Regarding land use, kenaf could fit well into crop rotations where it may serve as break crop for the control of pests (e.g., nematode, in a rotation with soybean or following maize and sorghum; weeds, due to the release of phytotoxic compounds and high planting density and rapid early growth), improve soil fertility (re-incorporation of residues), maintenance of the long-term productivity of the land, and consequently increase the yields and profitability of the rotation (Zegada-Lizarazu and Monti 2011). In their extensive review on energy crops in rotation, Zegada-Lizarazu and Monti (2011) indicated that kenaf is best fitted to follow shallow-rooted crops because the deep-rooted kenaf can use water and nutrients that moved to deep soil layers during the previous season, thus improving the overall efficiency of a rotation system. According to the same work, in the southern areas of Europe, the combination of conventional (wheat, legumes, sunflower) and the new kenaf crop, in rotation, could optimize the utilization of soil resources and fit the prevailing climatic conditions.

## 5.6 Biological and Landscape Diversity

Extensive farming systems are important for maintaining the biological and landscape diversity of farmland. However, these systems have been threatened, either by intensification and abandonment (EEA 2005). Landscape configuration and habitat richness have an impact on its community's diversity (Dauber et al. 2003). It is agreed that more complex structure and heterogeneity of a vegetation system have a positive influence on its cover value for wildlife (Smeets et al. 2009). Hence, compared to a natural system even if fallow land, any energy crop will have negative effects and they will be more severe the farther the system shifts from the native conditions. Facing the lack of local onset data and extensive and systematic reference studies for kenaf, a generic approach was implemented.

Annual crops have been reported as source of seemingly biodiversity loss. Literature asserts that perennial grass and tree plantations support more, microfauna, soil fauna, and bird species due to higher permanence on soil and thorough management, including low agrochemical inputs, ploughing and tillage, and lower removal of litter soil cover (Fragoso et al. 1997; Börjesson 1999; Berg 2002). Nonetheless, annual crops that undergo a flowering period should attract insects and birds, increasing their diversity and numbers. Such has been reported in sunflower fields (Jones and Sieving 2006) and is likely to happen in other colorful blossomed annual crops such as kenaf.

In general terms, establishment of a kenaf monoculture result in a higher impact, also due to use of fertilizers and pesticides in the production, but, on the other hand, these plants have a high above and belowground biomass, leading to high soil organic matter content due to root biomass accumulation and litter deposition. These conditions favor diversity and occurrence of soil microorganisms and soil fauna (Börjesson 1999). Also, kenaf plants, which can grow up to two meters in height, provide shelter and protection from predators as well as from climatic influences (such as wind), as it was observed for perennials (Oliveira et al. 2001; Rowe et al. 2009).

Widespread cultivation of kenaf cropping systems might have an impact on the landscape. However, crop planting should be carried out in order to ensure that adverse landscape impacts are minimized. Landscape impact assessment can be performed by comparing the crop with fallow land, being the structure and color chosen as criteria to evaluate landscape quality (Fernando et al. 2012). According to these, a kenaf plantation may have a somewhat negative impact on the landscape as the crop does not have a great variation in structure, if we consider the homogeneity and openness of the crop. But positive impacts yielded from increases in height, density, and the presence of structures, such as inflorescences, with distinct coloration.

## 5.7 Conclusions

This chapter has outlined the environmental aspects of kenaf production and use. The assessed impact pathways rely primarily on management intensity and on the crop traits, and second on the processing and use systems. Kenaf can be considered as a more environmentally acceptable crop than other annual energy crops, since it requires fewer inputs (fertilizers, pesticides). But, due to the short permanence period in the ground, it stands out to be as burdening as other annual crops regarding erodibility and biodiversity. Risks associated with losing soil quality and use of water, nutrients, and land are also comparable to most annual energy crops. Impact reduction strategies are limited to crop management options which can influence emissions, nutrient status, and mineral ore depletion. All other impacts are site-specific dependent, intertwined with the crop traits. Therefore, the implementation of an impact-lean kenaf system should root also on the adequacy between crop and location.

In addition, the substitution of fossil fuels and materials through the use of kenaf can lead to energy savings and reductions in greenhouse gas emissions, but a negative impact can be witnessed in terms of acidifying emissions. It is worth nothing, however, that environmental benefits will occur only if the production and conversion processes are carefully managed and guidelines are adhered to. Caution must be applied, nonetheless, considering that the studied crop has not yet been upscaled to a commercial level in Europe.

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# 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

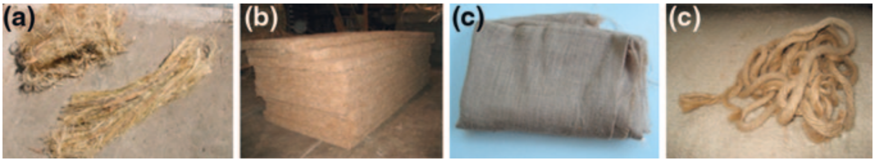


**Fig. 6.1** Kenaf fibres (**a**), insulation mats (**b**), textile (**c**), ropes (**d**)

**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).

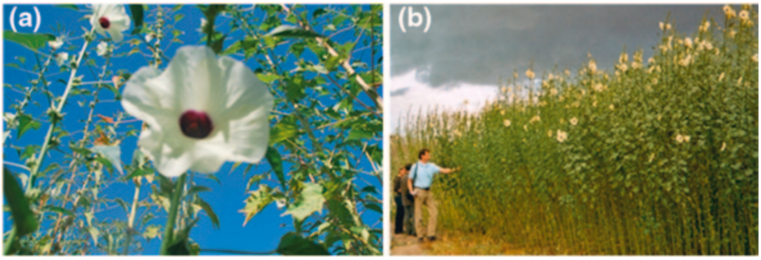


**Fig. 6.2** **a** Kenaf flower and **b** crop inspection in the field

### *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.

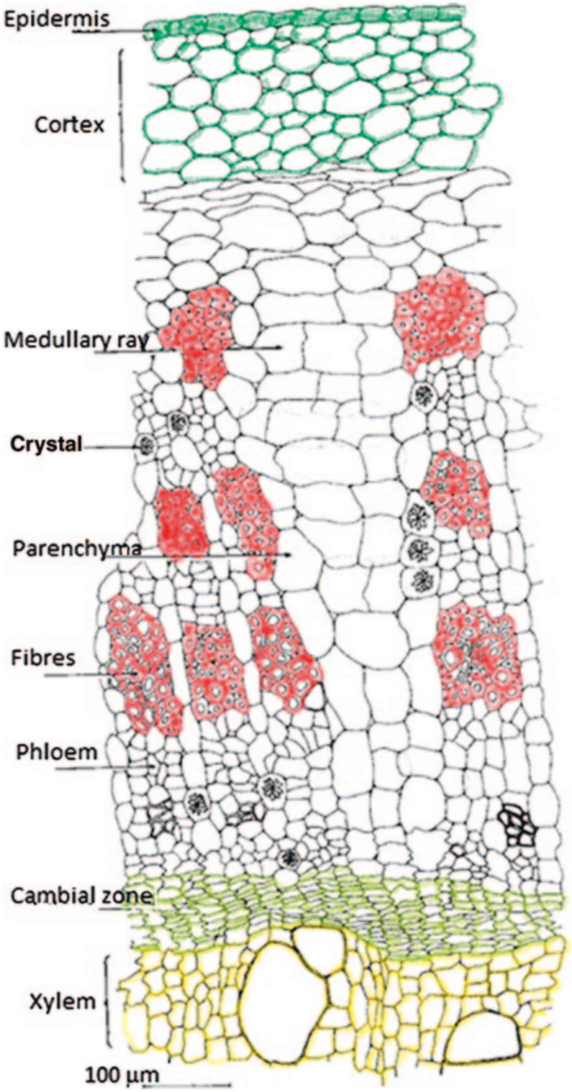


**Fig. 6.3** Transverse section of *H. sabdariffa* stem (after Catling and Grayson 1982)

### 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)

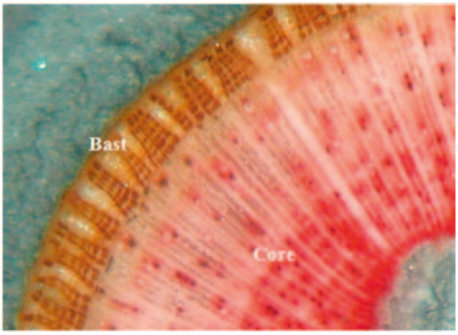


**Fig. 6.4** Transverse section of the kenaf stem stained for lignin

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)

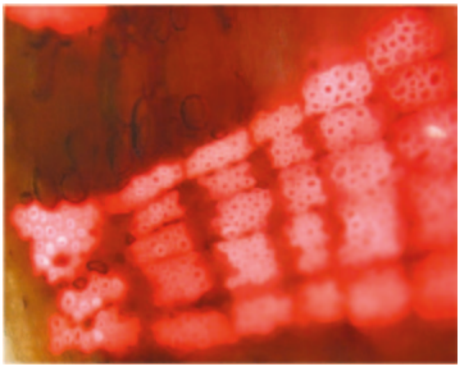


**Fig. 6.6** Fibre bundle of kenaf

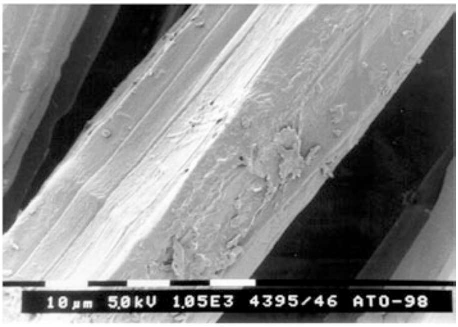
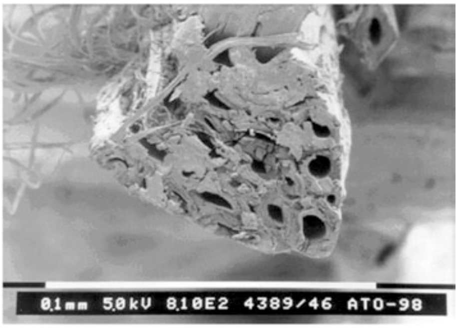


**Fig. 6.7** Fracture surface of a fibre bundle



(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

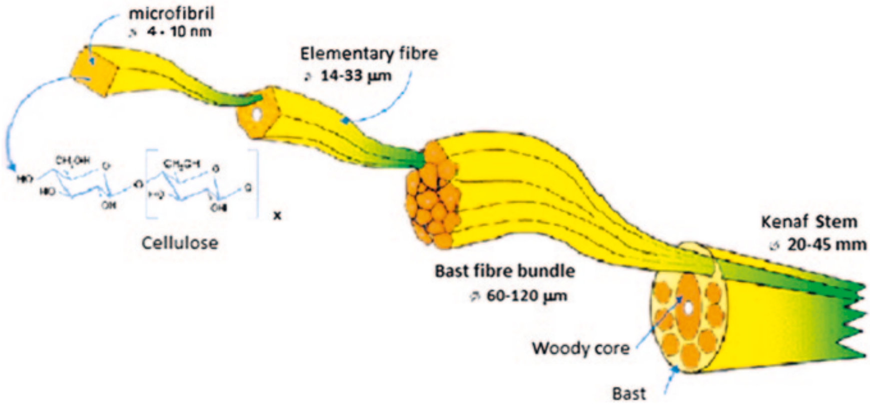


**Fig. 6.8** Schematic structural composition of kenaf stem and *bast fibre*

**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.

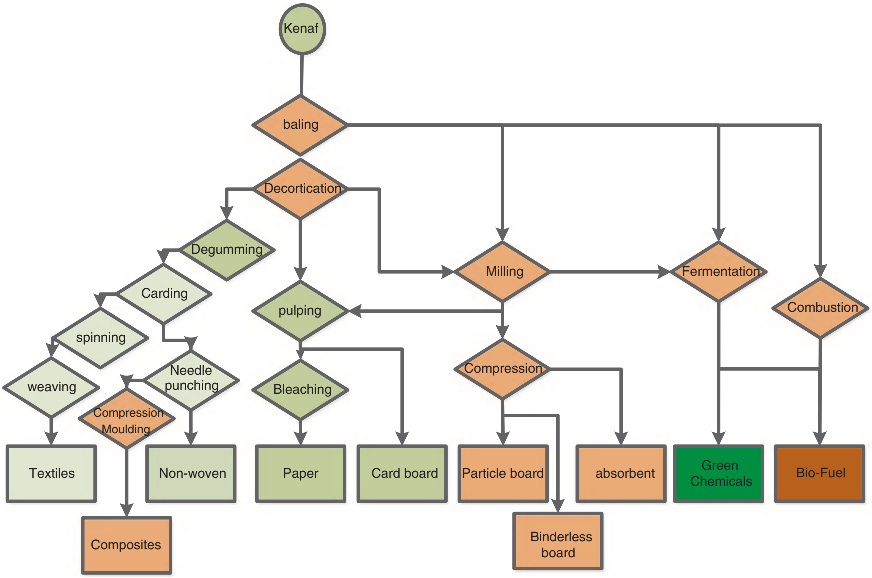


**Fig. 6.9** Flow scheme of kenaf fibre processes and products

**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

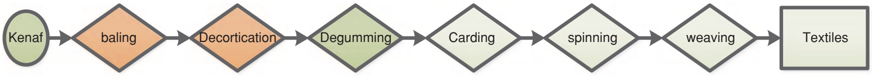


**Fig. 6.10** Flow scheme kenaf to textiles

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

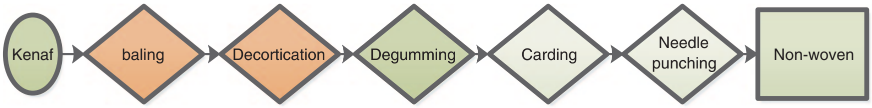


**Fig. 6.11** Flow scheme kenaf to non-woven

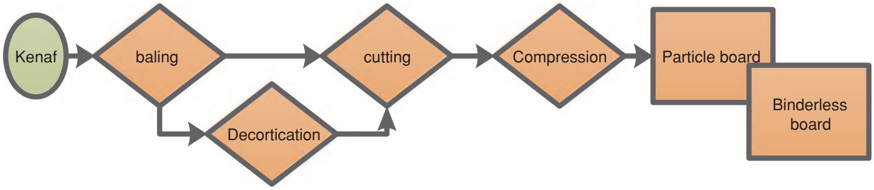


**Fig. 6.12** Kenaf to fibreboards

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.

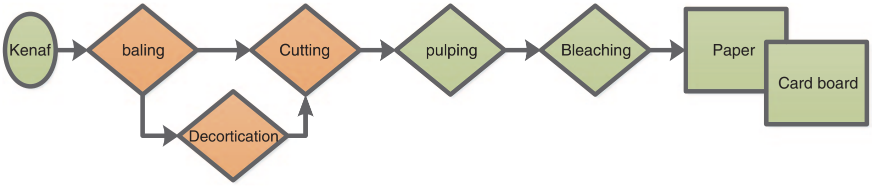


**Fig. 6.13** Kenaf for pulp and paper application

### 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).

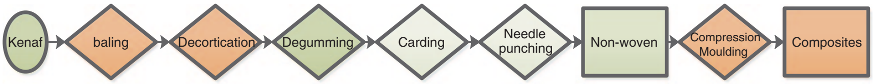


**Fig. 6.14** Kenaf to polymer composites

## 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.

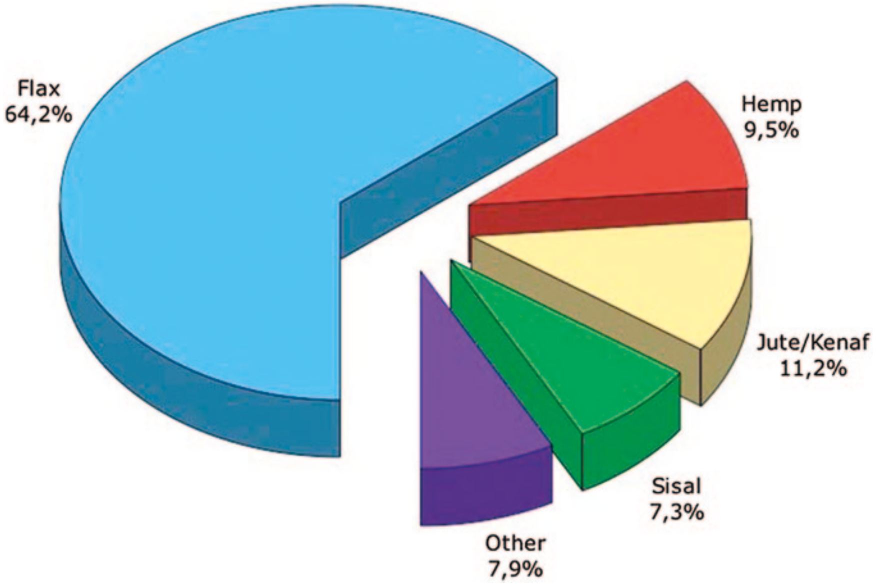


**Fig. 6.15** The use of natural fibres for automotives in Germany (Kaup et al 2003, 2006)

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,

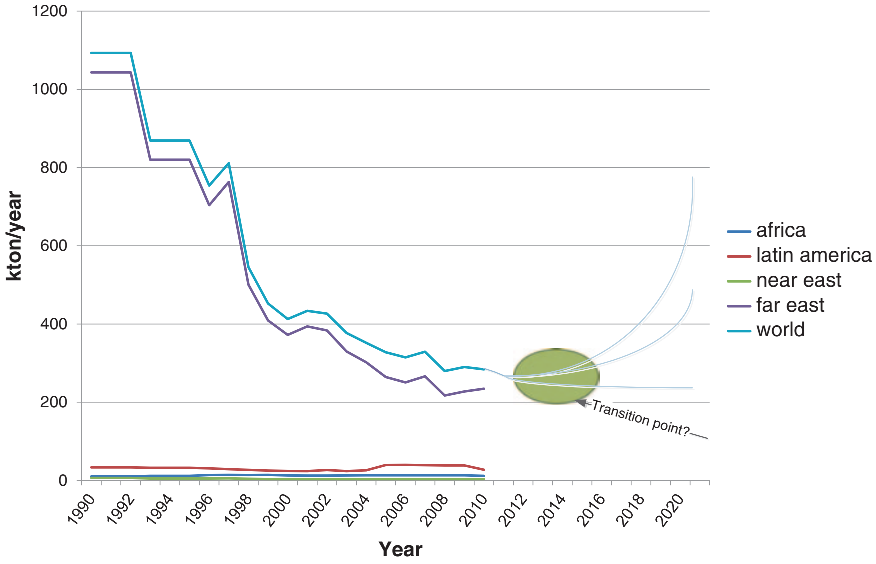


**Fig. 6.16** The global kenaf production statistics and prospect scenarios for 2020

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.

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# Chapter 7
# Economic and Financial Analysis: The Farmer's Point of View

**P. Soldatos**

**Abstract** The purpose of this chapter is twofold. First, to introduce the reader to some simple basic economic concepts used in financial analysis and project evaluation, and second to bring together in a new analytical framework, significant pieces of information from recently published research findings on the economics of kenaf production. The BIOKENAF research and experimentation project (QLK CT2001 01729, 2003–2007), which is the most relevant recent scientific work from the point of view of geography and approach, has provided most of the basic material for this chapter. The findings of BIOKENAF are updated and compared with other related bibliographical evidence, concentrating on the farmer's point of view. This chapter will objectively re-examine the financial implications of kenaf production and hopefully guide the reader on how to make his own budgets and set up business plans for his farm.

**Keywords** ABC • Activity based costing • Kenaf • Kenaf economics • Fibre crops economics • Cost analysis

## 7.1 Introduction

The goal of economic analysis, in the general sense of the term, is composite. It incorporates technical, marketing, financial and economic information and attempts to define optimal decisions for the activity or project under examination, in view of the existing constraints and preferences. A number of steps are required for the analysis:

1. Market analysis identifies the markets that the product(s) is or will be directed to and estimates potential demand. Demand relates to the nature of the product, the needs of buyers, the intensity of competition in each market that the product is launched and the price at which the product is marketed.

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2. Estimation of project profitability is probably the most popular step in economic analysis. Profitability is measured by the difference between revenues and costs. Selling at a price higher than the cost is essential for the survival of any economic activity, because it insures payment of its costs and generates some return (profit) to invested capital. In the case, that costs cannot be recovered by the proceeds of the activity, someone will have to pay for them, be it the investor or the taxpayer, and none will be particularly happy to bear the losses of an unprofitable operation. Cost analysis measures all costs and identifies critical cost categories by splitting expenses into fixed and variable, paid and imputed, direct and indirect, operating (recurring) and investment costs, etc. The purpose of cost analysis is not only to estimate total cost per unit of product, but also to identify cost reduction opportunities and support profit maximisation strategies. Product selling prices are in most cases determined by the market where the product is sold and by the level of existing competition, but they should at the same time be sufficiently high to cover costs.
3. However, profitability alone is not sufficient for the viability of the examined activity or project. If revenues are not received promptly, the project will not be able to meet its obligations in time, and this may lead to overborrowing or bankruptcy. Therefore, the examination of cash flows[1] is an essential part of economic analysis. In effect, the analysis of cash flows is considered much more reliable and has become the standard method of project evaluation (Discounted Cash Flows—DCF methodologies). The rationale of DCF methods is that they assess the time value of money, e.g. by discounting all payments to the present, and propose solutions based on the examination of criteria measuring the significance of cash returns spread through time with regard to the required capital investment, which is usually paid in advance.
4. In addition to profitable and timely cash flows, in most cases, the activity is expected to be sustainable into the future, with regard to socio-economic, institutional and environmental issues, which are becoming more and more important in our days.
5. Finally, the risk undertaken by all involved in the activity should be evaluated and incorporated in the decision-making process. To take an example from agriculture, establishing a permanent plantation is more risky than growing an annual crop which may be replaced at any time with minimum financial loss.

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[1] Cash Flows record the timing of actual money receipts and payments (inflows and outflows) which is in general different from costs and revenues which are recorded in the period of the transaction (not the payment). Only if all payments are "cash payments", i.e. no credit, revenues and expenses coincide with inflows and outflows.

## 7.2 Methodology of Economic Analysis of Agricultural Projects

*Economic Analysis* seeks the determination of optimal strategies for the achievement of project objectives. This is done by optimising the use of scarce resources, which are sacrificed in order to meet set goals, and which may include financial, social, environmental and sustainability dimensions.

The basis of economic analysis is the *analysis of Costs and Revenues (or Income and Expenses)* of projects. Costs and revenues are generated through time according to the nature of each project and because of the *time value of money,*[2] it is important to know *when* each cost or revenue item is generated and when it is actually paid. Therefore, projects are examined over a period of several years, in order to capture the variability of their financial performance from year to year. Just to make things a little more complex, costs and revenues are not necessarily paid when they are generated. They are sometimes paid *in advance* (advance payments) or, more frequently, sometime *after* the transaction (credit purchases or sales). The distinction between costs and revenues on the one hand and cash flows (cash inflows and outflows) on the other is important and there are different financial approaches associated with each category.

Economic analysis examines the *profitability* of projects by comparing Costs and Revenues (or Income and Expenses) in order to estimate various levels of Profit (Gross Profit, Net Profit before or after Tax, etc.). Profitability is essential for project viability, because if cost recovery is not possible, the project will soon run into liquidity problems and eventual bankruptcy. However, as has already been stated, profitability alone does not guarantee the viability of the project, because delayed inflows may reduce liquidity and consequently the ability to pay maturing cash obligations.

In addition, economic analysis examines the *desirability of investing* (investment appraisal) in a particular project by measuring the present value of incremental[3] future *net* cash flows generated by the project (*Net Present Value*). Additionally, it examines the length of time required for amortisation of the invested capital (*payback period*) and estimates the interest rate at which the project pays the investor for the invested capital (*Internal Rate of Return*).[4]

### *7.2.1 Profitability Analysis*

Revenues (Income) are estimated for each accounting period (e.g. each year or month). The main source of revenues is the sale of products and by-products

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[2] Consult any book in Financial Management, e.g. Brigham (2013).

[3] i.e. over and above Cash Flows that would otherwise be generated without the project.

[4] For a detailed exposition of the subject, see for example Barry and Ellinger (2012).

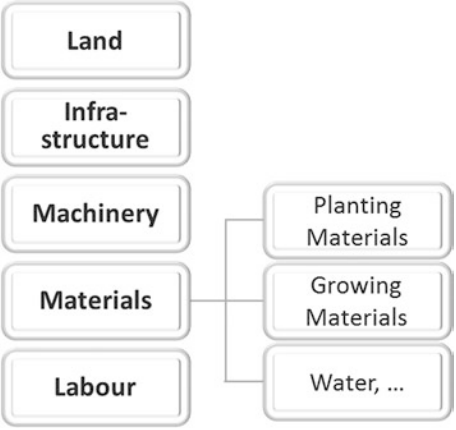

**Fig. 7.1** Agricultural project production requirements

produced by the project (volumes times selling prices). Similarly, associated costs are also analysed and recorded in each accounting period, e.g. each year (Fig. 7.1).

The typical agricultural project requires an *initial expense* (investment), such as the cost of establishing the plantation, purchasing of durable equipment, etc., for items that will serve the project for more than one period. On the other hand, the project generates a stream of *recurring* annual income and expenses during its life span, such as revenue from sales of products and direct and indirect operating expenses. Direct expenses are those that can be traced directly to the product(s), such as husbandry, harvesting, etc., while indirect expenses (for example selling expenses, overheads, etc.) are more general in nature, cannot be traced directly to the products and are allocated with pre-specified rules. The direct costs (or expenses) of goods that have been sold in an accounting period are also known as "Cost of Goods Sold". Recurring costs and revenues are not necessarily the same in each year because of the peculiarities of the various projects. This necessitates the estimation of periodic financial tables of income and expenses in some detail.

The part of the cost of agricultural projects, which is spent at the beginning of the project on durables that will serve the project for some time in the future, is as already stated, the required *investment*. The purchase of land, the construction of the necessary infrastructure and the purchase of machinery and equipment that will be used by the project are typical examples of the initial investment. If the crop is annual, one may assume that all years are similar and it may be sufficient to examine only one "typical" year.

*Recurring costs* are generated regularly, e.g. every year, or irregularly as the case may be. In the case of crop rotation, the project time span expands to include at least one full cycle of all rotated crops in order to capture the whole of costs and returns variability.

For each year of the project life span and for each project *activity*[5] (or *operation*), the requirements in labour, machinery and materials are defined in volume.

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[5] Activity-Based Costing.

**Table 7.1** Layout of profit and loss account

| | | | |
|---|---|---|---|
| | *SALES REVENUE*<br>*(volume x price)* | = | Net Sales |
| | *Minus* | | |
| Variable Expenses | *Cost of Materials* | : | *Seeds, fertilisers, water, etc.* |
| | *Minus* | | |
| | *Cost of Agric. Applications* | : | *Sowing, fertilising, irrigating, etc.* |
| | *Minus* | | |
| | *Cost of Temp. Labour* | = | Gross Profit or Gross Margin (Return above Variable Expenses) |
| | *Minus* | | |
| Fixed Expenses | *Cost of Permanent Labour* | : | *Payment of Salaries* |
| | *Minus* | | |
| | *Annualised Cost of Fixed Assets* | : | *Fixed assets Annual equivalent* |
| | *Minus* | | |
| | *Land Rent etc.* | = | Net Profit bef. interest & tax |
| | *Minus* | | |
| Financial Expenses | *Interest on Capital Employed* | = | Net Profit before tax |

Note: *Gross Margin or Gross Profit* is equal to Return above variable Expenses *minus* Direct Fixed Expenses, i.e. directly attributable to the product.

Then, they are multiplied by the corresponding acquisition prices to calculate costs in money terms (Table 7.1).

*Rent* is the annual charge for occupying buildings and the land which is cultivated for the purposes of the project. It is the actual rent paid, or, if there is no rent, it is the imputed (opportunity) cost of owner occupied buildings and land, i.e. the cost of *not* being able to use buildings and land differently. For example, if a piece of land is withdrawn from the cultivation of, say, wheat, then its opportunity cost is equal to the profit forgone, i.e. the profit that would otherwise be made from the cultivation of wheat. In other words, land rent is the minimum profit that would offer sufficient incentive to the farmer in order to change the current use of his land.

The annual cost of owned durables, such as buildings, constructions, machinery and equipment, etc., can also be estimated as the sum of their *capital service costs* and their *operation & maintenance expenses,* O&M (Eidman et al. 2000). The capital service cost (*annual equivalent cost*[6]) is estimated by "annualising" the relevant purchase cost, i.e. spreading it over the years of the asset's economic life. O&M costs are annual recurring costs, such as cost of machinery operators and fuel, maintenance of equipment and buildings, etc. Accounting depreciation of fixed assets is not included, because the Capital Service Cost automatically includes depreciation and interest.[7]

Annual Cost of Durables = Capital Service Cost + Operation & Maintenance Cost.

Once total direct[8] annual costs have been calculated, they are compared to sales revenues in order to estimate Gross Profit or Gross Margin (=Sales revenue − Direct costs), which is the amount that remains available to pay indirect costs, and hopefully leave some (net) profit for the project. Subsidies increase bottom line results, but their impact should better be added after the *market profit* has been calculated. A positive profit before subsidies ensures market viability of the crop, irrespective of any (otherwise welcome) subsidies.

In spite of the current convention in Farm Accounting,[9] we strongly suggest *not* to include direct or indirect subsidies in the first lines of the Profit and Loss account in order to be able to define *market* profitability, i.e. the profitability of the project before any kind of subsidisation.

### *7.2.2 Project Evaluation (Investment Appraisal)*

To evaluate the financial impact of an agricultural investment project, the *present value* of its stream of net inflows[10] (inflows minus outflows) over the years *of the life of the investment*, including initial investment *and* subsidies, is estimated by introducing the time value of money into the calculation.[11] The resulting figure is

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[6] The annual equivalent cost of the disbursement for an investment asset with an economic life of $n$ years is equal to $\frac{d}{1-(1+d)^{-n}}C$, where $C$ is the investment cost, and $d$ is the discount rate.

[7] This mechanism has been implemented in the ABC package for project evaluation, a self-explanatory freeware software of economic appraisal of agricultural projects developed at the Agricultural University of Athens (ABC® 2012).

[8] "Direct" costs are those that can be attributed to the product and form its inventorial cost (cost of goods sold). Indirect costs are those not directly traceable to the product, such as cost of selling, borrowing, taxation, etc.

[9] DEFRA (2006).

[10] For Project evaluation purposes Cash Flows are more appropriate than Profits, because they represent actual cash on hand, not money that may be debited or credited. Cash flows reveal how available liquidity sources are managed and help the evaluation of the unit's financial position.

[11] $NPV = \sum_{t=0}^{n} CF_t \times (1+d)^{-t}$, where $\mathrm{CF}_t$ is the net Cash Flow in year $t$, $\mathrm{CF}_0$ is the initial investment cost (negative), $n$ is the number of years of the project and $d$ is the discount (interest) rate. $d$ reflects the alternative (opportunity) rate of return of the investors, and is directly comparable to the average annual return of the project.

the *Net Present Value* (NPV) of the project, theoretically the most appropriate index for projects evaluation. If one assumes that all transactions are on a near "cash" basis, *net inflows* are equivalent to *net profits*.

A positive NPV implies a higher value of inflows over outflows in present value terms. This is equivalent to comparing the present value of all future net inflows to the value of the initial investment outflow necessary for the project. If the present value of generated net inflows is higher than the required investment, we conclude that the initially invested capital is rewarded at a rate higher than its opportunity cost (discount rate) and therefore the project is financially attractive.

Besides NPV, two other popular investment criteria are of interest to the investor. The first is the "*Payback Period*", which measures the time it takes until net project inflows accumulate to the value of the initial investment. This investment criterion is simple and easy to calculate and because of its simplicity, it is easily understood by investors and is very popular. In addition, the "payback period" criterion promotes the selection of low risk projects by recommending investments that recover the initial expense in the shortest time periods.

The second is the "*Internal Rate of Return*". IRR is the value of the discount rate ($d$) at which the Net Present Value of the project is equal to zero. This is a consequence of the nature of most investment projects, i.e. the fact that investment capital is paid in advance, while benefits (net inflows) are generated later ("pay now, enjoy later"). The higher the discount rate, the less attractive a project appears, because the value of its future inflows is drastically reduced due to powerful discounting. As a result, at low discount rates a project may generate a positive NPV, but as the discount rate increases, penalising future benefits, NPV is gradually being reduced until it becomes zero (when $d$ is equal to IRR) and for even higher values of the discount rate, NPV becomes negative.

## 7.3 Kenaf, a Fibrous Plant

Kenaf is an annual fibrous, fast growing plant yielding annually between 10 and 25 dry tonnes[12] of dry biomass per hectare depending upon the cultivar, harvest timing and geographical region. It grows well in humid and relatively warm climates, such as in Africa and South East Asia, but it can also be cultivated in southern Europe with satisfactory yields.

The outer part of kenaf's stem consists of the *bark*, which weighs about one-third of the stem, and the *core*, which comprises the remaining of the weight. Reports from plantations around the world record annual dry material yields as low as a few tonnes and as high as almost 30 tonnes per hectare (e.g. Stricker et al. 2006; FAO 2003; CRES et al. 2007, Kenaf Handbook; Zucchini and Renders 2011). Naturally, yield figures depend upon many parameters, technical and economic and usually observations of experimental plantations include extreme

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[12] 1 tonne = 1 Mg = 1.1025 ton.

values which are not feasible under real market economic conditions. A pragmatic overall figure for commercial kenaf production in European farms could be in the range of 10–20 dry tonnes per hectare (CRES et al. 2007, Kenaf Handbook) or even less if we take into account the harvesting left overs and the probability of unfavourable climatic conditions.

Kenaf is primarily cultivated as a fibre crop with two distinct types of fibre. *Long*, between 2 and 3 mm on average ("bast fibre") and *short*, less than 1 mm ("core fibre"). The first, comprising one-third of Kenaf stalk biomass, is an excellent raw material for the paper and pulp industry, fabrics and reinforcement of plastic and construction materials, while the second is most appropriate for composite materials, oil absorbent and other uses.

Harvested kenaf dry biomass consists of 26 % leaves and 74 % stalks (Webber 1993). The bast and core mass proportions in the stalks are 35 and 65 %, respectively (CRES et al. 2007, Kenaf Handbook; FAO 2003). Over 57 % of the weight of the bark consists of the longer fibres, while 45–50 % of the core is made up of short fibres (Walsh 2007) and 41 % is recoverable by chemical pulping (Karlgren et al. 1991; Kaldor et al. 1990; Webber et al. 2012). Eventually, only up to 40 % of the stalk can give usable fibre (which however is twice that of jute, hemp and flax) and which makes kenaf fibre quite economical (Composites Technology 2006; Kaldor et al. 1990). Nevertheless, statistical sources show that the fibre extracted from 1 ha of kenaf plantation is in the range of 1.5–2.5 or 3 tonnes (Blackburn 2005; Di Virgilio et al. 2006; Agbaje et al. 2008; FAO 2010; Zucchini and Renders 2011), i.e. between 13 and 33 % of harvested dry stalks (Fig. 7.2).

Kenaf is one of the fastest growing plants on earth, and is usually harvested after 5–6 months from plantation or even earlier, depending upon the products that will be produced from its biomass. It provides the pulp and paper industry with raw material for the production of many types of paper and the automotive factories for the preparation of car interior fibrous materials (dashboards, panels,

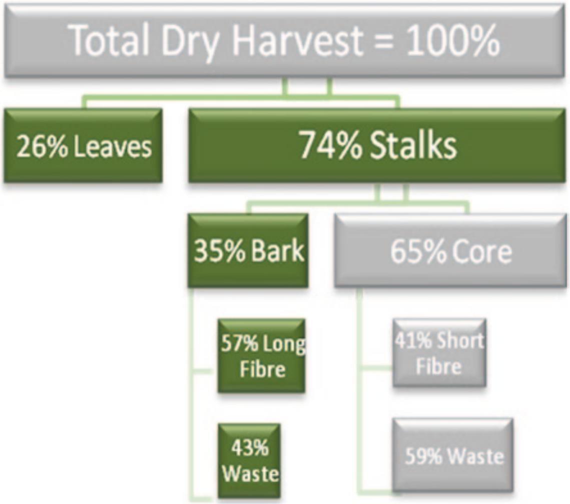

**Fig. 7.2** Fibre content of kenaf dry biomass

**Table 7.2** Kenaf dry yields

| Region | Total biomass yield (dry tonnes/ha) | Reference |
|---|---|---|
| Greece | 8–18 | Cres et al. (2007) |
| Italy | 12–17 | Cres et al. (2007) |
| Spain | 13–24 | Cres et al. (2007) |
| Portugal | 12–20 | Cres et al. (2007) |
| Florida | 15–27 | Stricker et al. (2006) |
| Texas irrigated[a] | 15.0 | Scott and Taylor (1997) |
| Texas non irrigated[a] | 11.0 | Scott and Taylor (1997) |
| California | 20.0 | Robinson (1988) |
| Tennessee | 16.3 | Bazen et al. (2007) |
| Mississippi | 17.4 | Rochelle et al. (2000) |
| Italy | 15.0 | KEFI S.p.A (2009) |
| Georgia, USA | 17.9 | Kaldor and Hodges (1998) |

[a] Corrected for moisture content

mats, etc.). Due to its high absorption capability, it is also used as animal bedding and oil spill cleaning material with excellent characteristics.

After several years of experimentation in south Europe within the framework of the BIOKENAF project (CRES et al. 2007) a number of kenaf yields have been recorded for the Italian, Spanish, Greek and Portuguese conditions. They are shown in the following table for comparison with yield observations and estimates from other researchers in the US and elsewhere (Table 7.2).

## 7.4 Market Overview

Today, the world total fibre market consumes more man-made fibres (polyester, polyamide, polypropylene, etc.) than natural (cotton, wool, jute, flax, kenaf, etc.). The global market share of natural fibres has dropped below 50 %, with cotton and wool maintaining the lion's share among natural fibres, with just less than 40 % of the world fibre market and over 80 % of the natural fibres sales (Mackiewicz-Talarczyk et al. 2008).

Sales of all other natural fibres (jute, flax, hemp, kenaf, ramie, etc.) are squeezed within an 8 % of the world fibre market with jute being the major competitor holding 75 % of this market niche (Fig. 7.3).

Jute is cultivated in India and Bangladesh while Flax and Hemp are cultivated in colder climates. In Europe, France is the major producer of Flax and Hemp, growing one-quarter of the world's plantations (about 200,000 out of 800,000 tonnes of world production). Also, several other European countries produce flax and hemp at smaller quantities (Belgium, Netherlands, Poland, etc.) raising total European production to a total of over 250,000 tonnes per year. Therefore, flax and hemp are of interest in Europe.

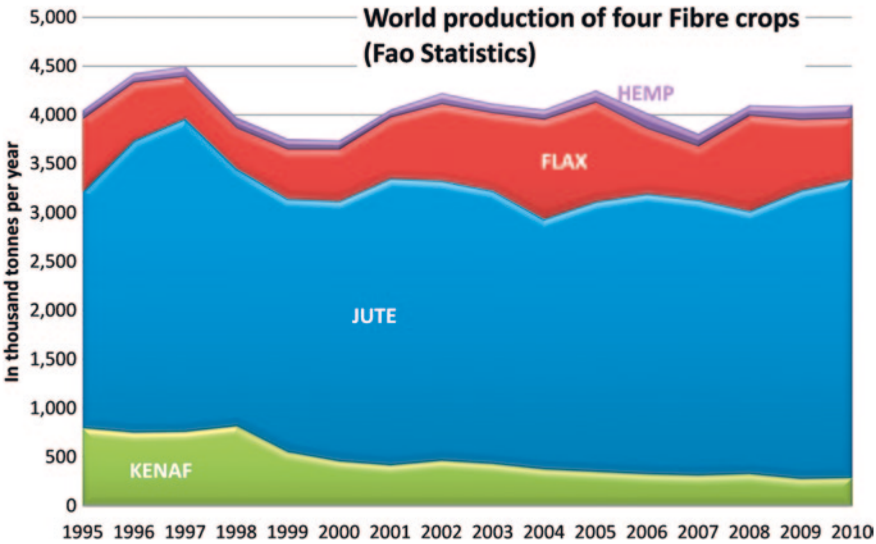

**Fig. 7.3** World production of fibre crops, Source FAO (2010)

World production of kenaf has been diminishing since the beginning of the 1990s when it was about 1 million tonnes. Today, kenaf production is maintained at a level below the 300,000 tonnes per year (284,000 in 2011) having shrunk by an average 7 % annually. Currently, three-quarters of the world production of Kenaf is grown in India and China, while only small experimental plantations exist in Europe. However, it has been proved that in southern Europe, kenaf can give very satisfactory yields, higher than the yields of flax, and at comparable cost. Given the moderate input requirements for the cultivation of kenaf and the wide range of its applications, it appears as a sensible choice for south European regions. Besides, kenaf today may supply a large number of different industrial product chains, while 50 years ago, it was used only as a cordage crop for the production of rope, and sack fabrics (Webber et al. 2012) (Fig. 7.4).

The dramatic drop of demand (and production) of kenaf has been caused mainly by the widespread use of synthetic fibres, which have gained a substantial share of kenaf's market as a cordage and gunny fabric crop.

Lately, the combined effect of kenaf's merits as a natural fibre with many diversified uses, other than cord and rough fabric, coupled with increasing concern over the pollution of the environment, and its low cost of production is reducing the rate of kenaf's market losses. For the past 3 years, its production has been stabilised just under the 300,000 tonnes.

Kenaf is being used today by a large number of different industrial processes. The choice of marketing kenaf determines some cultivation options (choice of cultivar, harvest timing, etc.) and the price at which it may be sold. Therefore, its economic value is very much case dependent. Kenaf, being a truly multipurpose crop, may be used for food, feed, fibre and fuel. It is particularly friendly to the environment due to its low input requirements and substantial $CO_2$ absorption capability.

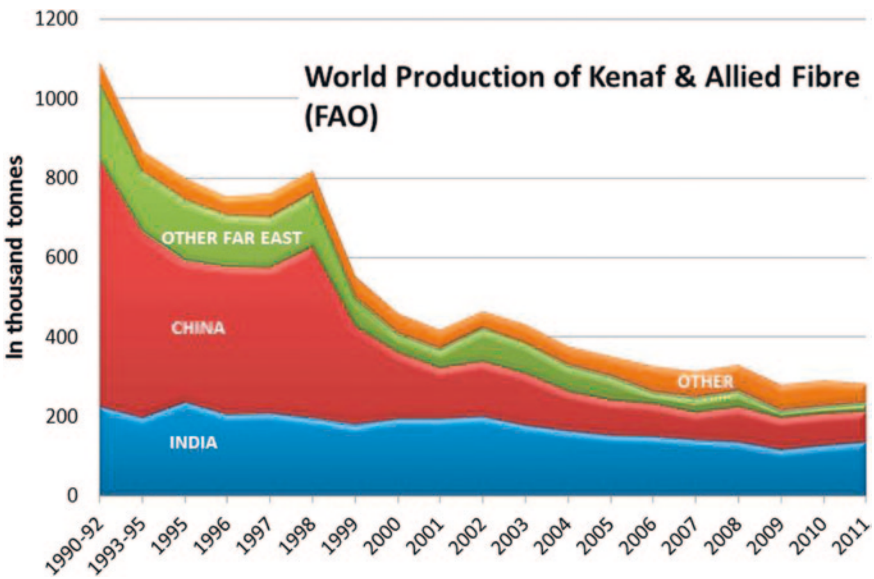

**Fig. 7.4** World production of kenaf, Source FAO (2010)

Some of the possible marketing options for kenaf today are:

*Long (bast) fibre …*

- Production of special types of paper with superior characteristics (newsprint)
- Substitution of Carbon, Fiberglass, etc. in automotive interior panels and components
- Fibrous reinforcement and insulation improvement of construction materials, particle boards
- Cordage, carpets

*Short (core) fibre …*

- Production of special type paper, packing paper, bags
- Industrial absorbent materials (e.g. chemical and oil absorbent)
- Composites with polypropylene
- Horse bedding, cat and poultry litter
- Particle boards

*Energy …*

- Cellulose material for energy production (e.g. compare with miscanthus and switchgrass yields)
- Biofuel from kenaf seeds

*Textiles and fabric …*

- Raw textiles and fabric
- Gunnysacks, Gunny fabrics

*Seeds production …*

- Cultivation for the production and sale of seeds

*Livestock feed …*

- Leaves protein in the range of 14–34 %

European farmers, who will consider cultivating kenaf, would probably need to be offered long-term sales contracts at reasonable prices before allocating part of their land for the cultivation of a new, practically unknown crop. They will also expect that the return to their land (profit before land rent) will be comparable to the return they receive from alternative crops that they might decide to cultivate.

The price which the mills would be willing to pay for kenaf, very much depends upon their own economic calculations and upon the prices of competitive raw materials such as jute, hemp, flax and wood. Since there are no dedicated kenaf processing factories in Europe today, there is no systematic demand for kenaf on a commercial basis. In several cases, kenaf is used as additional raw material in the existing industrial chains, e.g. pulp and paper, composite construction materials, automotive parts, etc.

## 7.5 Cost of Production in South Europe

Kenaf has attracted attention as an alternative source for paper pulp, composites and building materials. Being a fast growing annual crop it gives high yields from the first year of cultivation and especially its bast (long) fibre is of excellent quality with superior physical characteristics. Therefore, economic analysis will concentrate on its cultivation for utilisation as fibre crop.

In Europe, kenaf is planted sometime in spring (April) and harvested in early autumn. During this short period of around 150 days, it consumes moderate amounts of agricultural production inputs and grows by almost 1 m per month. The required agricultural operations (husbandry) can be classified as follows:

1. Ground preparation and sowing
2. Fertilisation
3. Weeding, Pesticides, Insecticides
4. Irrigation
5. Harvesting
6. Husbandry

Each of the above operations requires *labour*, *machinery* and *material inputs*, such as fertilisers, pesticides, irrigation water, etc. From an economic point of view, the optimal quantity of each input is the level at which the additional (marginal) benefit it generates equals the additional (marginal) input cost (i.e. when marginal benefit drops to the level of marginal cost).

*Ground Preparation and Sowing*

It has been established (CRES et al. 2007, Kenaf Handbook) that for European conditions, plant densities between 20 and 30 per m$^2$ (15–20 kg of seed per hectare) the plantation gives reasonably high biomass production, whereas higher densities only marginally improve yields. Note that in the BIOKENAF economic analysis a lower figure is used. However in Italy, Di Virgilio et al. (2006) suggest even higher densities of 30–50 plants per m$^2$, which corresponds to using 20–30 kg of seed per ha. The above values are much higher than earlier suggestions in many, mainly American, publications (see for example Webber et al. 2002, Scott and Taylor 1997, Walsh 2007, etc.). An average amount of seeds around 15 kg/ha seems to be a meaningful value for achieving good yields. Suggested seed rates in bibliography range from 5 to 8 kg/ha (Cook 2007; Bazen et al. 2007), to 20–30 kg/ha (Di Virgilio et al. 2006).

Kenaf seeds can be purchased today around 5 €/kg,[13] which makes a total cost for seeds equal to 15 kg/ha × 5 €/kg = 75 €/ha (see for example www.kenafseed.com). By adding the cost of ground preparation (60 €/ha) and sowing (30 €/ha), this amount rises to 165 €/ha. (See CRES et al. 2007; Oliveros 1999; Scott and Taylor 1997; Kaldor and Hodges 1998).

*Fertilisation*

Kenaf yields are related to the amount of fertilisation supplied to the crop. Nitrogen though, which supports the development of the plant, has been found to be less important than in other plantations. Several publications discuss nitrogen fertilisation practices on different soils, although its effect on yields does not seem to be very significant (see for example CRES et al. 2007, Kenaf Handbook; Walsh 2007).

Various levels of Nitrogen fertilisation have been tested in the BIOKENAF Project, ranging from 0 to 150 kg/ha. The Kenaf Handbook concludes at a dose of 75 kg/ha (Alexopoulou et al. 2007). Di Virgilio et al. suggest a Nitrogen dose of 50 kg/ha at the time of crop establishment. Adamson et al. (1979) have tested the effect of Nitrogen fertilisation on yields in southeast US. The tests have shown that the estimated benefits may or may not exceed the corresponding cost of applying increased amounts of nitrogen, depending upon emerging prices of nitrogen fertilisation and kenaf selling price.

Additional fertilisation with Phosphorus, Potassium and Calcium may be needed depending on the type of soil.

The cost of fertilisers differs from country to country and this is one of the reasons of cost differentiation among countries.

*Weeding, Pesticides, Insecticides*

Kenaf is a very fast growing plant, growing faster and stronger than most weeds and so there is little need for weed management. Some herbicide is usually offered at the early stages of the plantation.

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[13] Much higher prices were quoted in private communication of the author with one American seed producer, who was unwilling to give more explanations with regard to price differences.

It is also resistant to pests and insects and most plant diseases. Nematodes can be dealt with rotation and chemicals (Stricker et al. 2006). In some cases no weeding, pesticides and insecticides are reported, unless they are included in items such as husbandry or ground preparation, due to relative financial insignificance.

In Europe, the cost of weeding and herbicides seems to be around 5 % or less of total costs (CRES et al. 2007, Kenaf Handbook).

*Irrigation*

The level of irrigation required for growing plants depends upon soil and climatic conditions, and therefore it is best described as a percentage of Possible Evapotranspiration (PET), which depends upon those two factors. The BIOKENAF project has examined various levels of irrigation of the plantation in south Europe and has concluded that kenaf requires at least 250 mm of water during the summer months for moderate yields (CRES et al. 2007, Kenaf Handbook), especially in areas where temperatures exceed 30 °C. The cost of irrigation in the Biokenaf experiments in Spain was very high (360 €/ha), about half the total cost of production (excluding land cost).

In another study (Banuelos et al. 2002), after experimenting in California with temperatures well below 30 °C, concluded that maximum yields were achieved with total water supply (irrigation plus precipitation) in the range between 780 and 1,200 mm. (Scott and Taylor 1997) examined the effect of irrigation on kenaf yields in Texas and estimated that anticipated profits were higher by 25 % due to increased production in comparison with the “no-irrigation” scenario.

*Harvesting*

The crop can be harvested with the use of a common maize harvester or forage chopper (which may already be available in the farm). The stalks can be baled, bundled or chipped depending upon the harvesting method and the consequent treatment or transport. The freshly harvested crop may remain on the field to dry and be picked up later (Stricker et al. 2006; CRES et al. 2007).

Harvesting is one of the most expensive operations in kenaf cultivation (KEFI 2009). The BIOKENAF project reports figures between 72 and 250 €/ha.[14] American sources also give wide ranges of harvesting costs (Rochelle et al. 2000; Kaldor and Hodges 1998). Some of them do not include harvesting in the list of expenses, assuming that the farmer will only grow the plantation as contractor, and at harvesting time the buyer will harvest and transport the crop to the mill.

*Husbandry*

All other everyday management of the plantation.

As it will be apparent, the economic reports are not always in some standard form (as for example standardised in accounting), and therefore the economic

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[14] The 250 € figure has been charged in Italy. The reason is that kenaf was chipped while harvested, and the cost was quite high. See also KEFI (2009).

analyses that will be reviewed below, should be examined with care before making any "horizontal" comparisons. Also note that:

1. Cost estimates come from very different geographical regions with different soil and climatic conditions that dictate significantly different agronomic practices.
2. Not all economic analyses include the same cost structures (some exclude harvesting or land rent or imputed costs, etc.) A commonly acceptable complete list can easily be defined, but information is not always available.
3. Monetary magnitudes have different values in different currencies and at different times. Proper exchange rates and suitable deflators are not always easy to find.
4. Agronomic practices are not standardised. They differ from place to place especially in cases of new crops.
5. Experimental cultivations are treated less favourably by suppliers of agricultural inputs, in comparison with large commercial plantations with significant economies of scale.
6. Costs paid by experimental small enterprises are much higher than the costs paid by large commercial plantations for the same agricultural inputs.

## 7.6 Review of Kenaf Economic Literature

Literature on kenaf is very limited. Although the crop has been cultivated for centuries in some parts of the world, mainly as a gunny fabric and cordage crop, it was only around the middle of last century, that kenaf started being systematically studied as a multipurpose plant mainly in the USA and Europe.

Most of the existing literature relates to technical information and the agricultural characteristics of the crop and there is very limited material on the economics of kenaf cultivation, probably because it has not yet been actually commercialised, at least in Europe. Published work on economics inevitably relates to the regions where the authors have been experimenting, and because of the very small number of relevant publications, and the significant dispersion of numerical results, there is still substantial uncertainty with regard to the relationship between agricultural inputs and yields, costs and benefits, expenses and profits. Economic literature on the cultivation in China and India, the major kenaf producers, is much more limited.

In this section, a number of the existing economic analyses of kenaf are briefly presented as they appear in respective publications, with minimum adjustments in order to have all figures on a common basis, i.e. in euros (at constant exchange rate to US$ equal to 1.25) and in tonnes per hectare rather than tons per acre or tons per hectare.

It is emphasised that comparisons of volumes of inputs and outputs between studies are reasonably acceptable, although they may refer to different countries, soils, climates or production technologies. However, when it comes to compare monetary values, figures are less comparable. The experiments, observations and analyses prepared by researchers have been made at different points in time, in different countries, at different currencies and exchange rates, different price levels and under many other unequal economic realities. For this reason, the reader will find for each case reviewed below, fairly detailed economic tables that allow a more comprehensive understanding of the situation.

Here, we do not attempt to bridge the gap among the differences in the studies which are presented because the reader will probably be more confused. The aim is to present in more or less compatible format what has appeared in the literature to date and facilitate the understanding of the production financial and physical interrelationships in order to assist the preparation of more meaningful farm budgets.

The following conversion factors have been used in all cases:

| Conversion factors |
|---|
| 1 € = 1.25 US$ |
| 1 ha = 2.47 acres |
| 1 lb = 0.4536 kg |
| 1 gallon = 3.79 l |
| 1 ton = 2,000 lb |
| 1 ton/A = 2.24 tonnes/ha |

### *7.6.1 Production Cost of Kenaf in Northern Italy (KEFI S.p.A. 2009)*

KEFI (Kenaf Eco Fibers Italia S.p.A) established in 1999 in Northern Italy have cultivated and processed kenaf for the production of composite materials (sound and thermal insulation materials, automotive parts and other kenaf-based products).

The company has published an analysis of kenaf production expenses with relatively high costs, e.g. in comparison to the American literature, and an average yield of 15 tonnes/ha. It also reports a high harvesting cost (252 €/ha) which includes chipping and loading the material.

The list of production expenses does not include cost of land, interest on capital employed and overheads, which would be of the range of almost 300 €/ha raising total production costs to roughly 1,200 €/ha with a consequent margin of 700 €/ha.

The kenaf selling price (124 €/tonne) for the estimation of a profit margin for growing the crop is also high, but pragmatic, since the company has been paying such amounts. Naturally, the price very much depends on who the buyer or what the agro-industrial chain is. Other researchers assume much lower prices based on the prices of competing products, e.g. for the paper pulp industry.

Unfortunately, not much detail is given with regard to further economic evaluation of the plant.

The table below has been calculated based on the economic analysis of the BIOKENAF project (CRES et al. 2007) (Table 7.3).

No herbicides, no insecticides, no weed control expenses appear on the table (unless some chemicals are included in the ground preparation phase). The “subsidy”

**Table 7.3** Production cost of kenaf in Italy (KEFI S.p.A 2009)

| Per hectare | Quantity | Price, € | Total cost, €/ha | % |
|---|---|---|---|---|
| *Direct costs* | | | | |
| Ground preparation | 1 | | 175 | 20 |
| Fertilisation | | | 108 | 12 |
| Seeds (kg/ha) | 13 | 13 | 169 | 19 |
| Sowing | 1 | 33 | 33 | 4 |
| Irrigation | 2 | 75 | 150 | 17 |
| Harvesting and chipping | | | 252 | 28 |
| Total cost | | | 887 | 100 |
| Sales tonnes/ha | 15 | 124 | 1,860 | |
| Profit margin per ha | | | 974 | |
| Profit margin per tonne | | | 65 | |
| Subsidy (€/ha) | | | 431 | |

Compiled from: KEFI S.p.A (2009)

figure recorded in the original KEFI publication refers to set aside subsidies of the early 2000s and has not been considered here. No land rent has been charged.

Today, KEFI is active in Malaysia, cultivating a 200 ha field for the production of kenaf and sale of the biocomposite products.

### 7.6.2 Economic Feasibility of Kenaf Production in Three Tennessee Counties (Bazen et al. 2007)

The authors are measuring the economic feasibility of cultivating kenaf in Tennessee. After experimentation on 30 different soils, they have estimated and applied optimal levels of fertilisation (especially nitrogen) and they used the University of Tennessee experience for the determination of the other inputs.

The study estimates all expenses with the exception of land rent and tillage.[15] There is no irrigation expense. Labour and fixed machinery costs[16] are estimated separately. At the bottom line "Return to Land and Management" is estimated and it is compared with corresponding figures for some of the most popular cultivations in the area.

The results of the study show that kenaf can be a viable alternative choice for the local farmer. If sold at a price of $55 per ton (48.51 €/tonne), it appears as the second best choice of the farmer, just behind cotton, but it appears more profitable than wheat, soybeans and even corn!

However, the authors admit the existence of uncertainty especially with regard to kenaf selling prices and yields. Indeed, if one assumes lower yield and price by a mere 15–20 %, the return to land and management falls to zero (Table 7.4)!

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[15] The cost of land (and tillage) is sometimes omitted when we make economic comparisons between alternative cultivations competing for the same piece of land, since it is eliminated from both calculations.

[16] Capital Service Costs (see also the Methodology of Economic Analysis above).

**Table 7.4** Kenaf feasibility in three Tennessee counties, 2007

| Item | Description | Unit | Quantity | Price | (€/ha) | % |
|---|---|---|---|---|---|---|
| Revenue | Kenaf stalks | tonnes/ha | 16.13 | 48.51 | 782.39 | |
| *Variable expenses* | | | | | | |
| Seed | 8.5 seed/ft | kg | 7.39 | 5.29 | 39.12 | 7 |
| Fertilizer | N, P, K | | | | 116.39 | 22 |
| Custom application | Tenn Farm Coop | ha | 1.00 | 7.90 | 7.90 | 1 |
| Herbicide | | | | | 92.09 | 17 |
| Machinery repair and fuel | | ha | | | 8.46 | 2 |
| Custom harvesting | | ha | 1.00 | 89.65 | 89.65 | 17 |
| Operating capital | @ 16 % ann.int rate | ha | 406.23 | 0.08 | 32.50 | 6 |
| Total variable expenses | | | | | 386.11 | 73 |
| *Machinery fixed expenses* | | | | | | |
| Production | | ha | 1.00 | 14.54 | 14.54 | 3 |
| Harvesting | | ha | 1.00 | 117.71 | 117.71 | 22 |
| Total machinery fixed | | | | | 132.25 | 25 |
| *Labour* | | | | | | |
| Production | | h | 0.27 | 6.40 | 1.74 | 0 |
| Harvesting | | h | 1.63 | 6.40 | 10.43 | 2 |
| Total labour | | | | | 12.17 | 2 |
| Total expenses | | | | | 530.54 | 100 |
| Return to land and management | | | | | 251.86 | |

Compiled from: Bazen et al. (2007), Tennessee

Note that in the table, the cost of land (rent) and the cost of tillage are not included in the calculation. Also, overheads expense and the cost of employed capital (interest) are not charged. The seed rate of 7.48 kg/ha is rather on the low side when compared with European current practices. In this case, the cost of harvesting is by far the most costly agricultural application, accounting for almost 40 % of total costs (excluding land, interest and tillage). The plantation is not irrigated.

### 7.6.3 *Kenaf, a Possible New Crop for Central Florida US (Stricker et al. 2006)*

This publication reports results from growing kenaf in two locations in Central Florida, Bartow and Gainesville with different soil types (phosphatic clay and sandy soil respectively).

A very detailed analysis of costs for the two distinct cases is shown in comprehensive tables. Here, we have summarised the information regarding the Gainesville plantation in less detail.

Although the authors admit that irrigation especially during the first weeks of the plant is very beneficial for securing good yields, they have no irrigated experiments to present.

**Table 7.5** Cost of growing 1 ha of kenaf on sandy soil in Florida US, 2006

| | Amount | Price, €/unit | Cost, €/ha | % |
|---|---|---|---|---|
| *Materials* | | | | |
| Fertiliser | | | 140.30 | |
| Herbicide | | | 15.63 | |
| Seeds (kg) | 11.20 | 4.41 | 49.40 | |
| Total materials | | | 205.33 | 39 |
| *Equipment (fixed and variable)* | | | 170.03 | 32 |
| Land rent | 1 ha | 39.52 | 39.52 | 7 |
| Interest | | 0.08 | 21.48 | 4 |
| Labour (h) | 6.03 | 5.20 | 31.34 | 6 |
| Supervision | | | 43.29 | 8 |
| Overhead | | | 21.64 | 4 |
| Total cost | | | 532.63 | 100 |
| Average yield (tonnes/ha) | | | 17.92 | |
| Selling price (€/tonne) | | | 44.10 | |
| Revenue (€/ha) | | | 790.30 | |
| Profit margin (€/ha) | | | 257.67 | |

Yield: Average 18 tonnes/ha depending upon cultivar and soil type
Compiled from: Stricker et al. (2006)

The list of expenses of the cultivation is complete, but does not include harvesting.[17] Total expense for growing only is equivalent to 539 €/ha, while harvesting cost could be anything between 100 and 200 €/ha.

In more detailed tables, the authors distinguish between fixed and variable costs (all materials are variable, the rest have a fixed and a variable component). We have estimated that the proportion of fixed expenses in total cost is around 40 % (Table 7.5).

The cost analysis refers to the expenses for *growing* kenaf and *does not* include the harvesting expense. Also note that there is no cost for irrigation.

### 7.6.4 *Economic Analysis of Kenaf in Mississippi (Rochelle et al. 2000)*

The authors have studied the experimental cultivation of kenaf in Mississippi. The plantation was irrigated (and fertilised) with dairy effluent, thus utilising the waste from another industry in order to achieve economic and environmental benefit.

Fixed and variable costs of machinery and equipment have been estimated in detail and are shown in appended tables. For the machinery cost allocation on

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[17] If for example a paper mill offers contracts to local farmers for growing the crop, it may seem much more reasonable to organise and perform harvesting and transport to the mill centrally, in order to achieve better timing and economy.

**Table 7.6** Kenaf production budget, Dairy Research Centre, Mississippi, 2000

| Item | Unit | Price | Quantity | Amount (€/ha ) | % |
|---|---|---|---|---|---|
| *Direct expenses* | | | | | |
| Custom harvesting | ha | 79.04 | 1.00 | 79.04 | 19 |
| Fertiliser | ha | 11.86 | 1.00 | 11.86 | 3 |
| Herbicide | ha | 8.06 | 1.00 | 8.06 | 2 |
| Seeds | ha | 39.52 | 1.00 | 39.52 | 9 |
| Other | ha | 69.16 | 1.00 | 69.16 | 16 |
| Operator labour | h | 6.00 | 2.19 | 13.12 | 3 |
| Hand labour | h | 4.70 | 1.31 | 6.15 | 1 |
| Irrigation labour | h | 4.70 | 1.58 | 7.42 | 2 |
| Unallocated labour | h | 6.00 | 1.97 | 11.80 | 3 |
| Diesel fuel | l | 0.17 | 75.87 | 13.13 | 3 |
| Repair and maintenance | ha | 29.19 | 1.00 | 29.19 | 7 |
| Interest on oper. capital | ha | 10.31 | 1.00 | 10.31 | 2 |
| Total direct expenses | | | | 299 | 70 |
| Total fixed expenses | | | | 126 | 30 |
| Total expenses | | | | 425 | 100 |
| Yield (tonnes/ha): | 17.38 | | Sales (€/ha) | 843 | |
| Selling price (€/tonne): | 48.51 | | Profit (€/ha) | 419 | |

Compiled from: Rochelle et al. (2000)
Based on 1998 input prices

kenaf, it is assumed that all equipment is owned and fully utilised (for example the purchase cost of the travelling gun, 54,000 US$, has been amortised for 20 years and has been assumed that it is used in a 100 acres plantation). Materials and labour are also detailed in the study. The proportion of fixed expenses on total cost is 30 %, although the cost of land is not included.

The income and expense table estimates total expenses and profits assuming a yield of 17.4 tonnes/ha and a sales price of 48.51 €/tonne of kenaf, very similar for example with the figures given by Bazen et al. (2007) and Kaldor and Hodges (1998) (Table 7.6).

All costs and values are expressed in 1998 prices. Irrigation costs 107 €/ha, of which 84 €/ha is fixed expense and the rest is variable.

### *7.6.5 The Economics of Introducing Kenaf Fibres as a Complementary Fibre Source in Existing Wood Pulp Mills in Georgia USA (Kaldor and Hodges 1998)*

The authors, professionally involved in the kenaf business chain in the US, describe their experiences after collaboration with farmers for the production of kenaf for paper pulp in Georgia, USA.

This is the only study which includes the cost of separating the two types of fibre of kenaf, which is just over 10 % of total cost. Harvesting and storage is

**Table 7.7** Cost of kenaf production in Georgia, 1998

| | €/ha | €/tonne | % |
|---|---|---|---|
| Seed | 55.33 | 3.09 | 8 |
| Lime | 9.88 | 0.55 | 1 |
| Fertiliser | 135.95 | 7.59 | 20 |
| Herbicide | 34.09 | 1.90 | 5 |
| Insecticide | | | 0 |
| Machinery | 23.71 | 1.32 | 3 |
| Irrigation | 71.73 | 4.00 | 10 |
| Interest | 16.54 | 0.92 | 2 |
| Growing | 347.22 | 19.38 | 50 |
| Harvesting | 152.51 | 8.51 | 22 |
| Storage | 121.41 | 6.77 | 17 |
| Harvesting and storage | 273.91 | 15.29 | 39 |
| Separation[a] | 74.14 | 4.14 | 11 |
| Total cost | 695.28 | 38.80 | 100 |
| Sales | 860.16 | 48.00 | |
| Gross margin | 164.88 | 9.20 | |

Compiled from: Kaldor and Hodges (1998)

Yield (tonnes/ha): 17.92 (at 10 % moister content)

[a] Total cost includes cost of separation. Overheads, management and recovery on capital invested are not included

again the most expensive operation accounting for 40 % of total cost, while fertilising being the second most expensive item, is only 20 % of total cost (Table 7.7).

The cost of land is *not* included in the calculation of expenses.

### *7.6.6 Kenaf Growing Costs in the Lower Rio Grande Valley, Texas (Scott and Taylor 1997)*

The authors have estimated the agricultural costs of growing kenaf (*excluding harvesting*) and selling it through contract to a facility that will harvest and collect the yield from the farm for further treatment for the production of paper pulp. The estimates are based on the experience gained from growing kenaf in the area.

It is assumed that for land preparation and planting, the existing equipment is used, i.e. there is no investment expense for purchasing this equipment. Probably, only machine operating costs are charged to the corresponding operations. It is, however, not quite clear from the text if capital service cost of machinery is also included in the cost figures. We have to assume that it is.

Although labour cost is explicit only under "Irrigation Costs", it is assumed that the cost of the required labour has been incorporated in all other operations too.

The selling price per tonne of kenaf has been calculated as 70 % above production cost per tonne, which is regarded as an appropriate mark-up for the farmer, in order to cultivate kenaf. For example, the selling price in the Irrigated Kenaf

**Table 7.8** Economics of kenaf production in the lower Rio Grande Valley, Texas

| | Irrigated kenaf budget | | | Non-irrigated kenaf budget | | |
|---|---|---|---|---|---|---|
| Cost category | €/ha | €/t | % | €/ha | €/t | % |
| Land preparation | 64.25 | 3.82 | 16 | 64.25 | 5.96 | 21 |
| Agri-chemical inputs | 75.12 | 4.47 | 19 | 75.12 | 6.97 | 24 |
| Seed and planting costs | 54.54 | 3.25 | 14 | 47.50 | 4.41 | 15 |
| Other operation costs | 14.82 | 0.88 | 4 | 14.82 | 1.37 | 5 |
| Irrigation costs | 43.50 | 2.59 | 11 | | | |
| Land charges | 138.38 | 8.24 | 35 | 108.73 | 8.08 | 35 |
| Total cost | 390.61 | 23.25 | 100 | 310.42 | 26.79 | 100 |
| Yield (tonnes/ha) | 16.80 | | | 13.50 | | |
| Sales[a] | 567.17 | 33.76 | | 451.60 | 39.89 | |
| Profit | 176.56 | 10.51 | | 141.18 | 13.10 | |

Compiled from: Scott and Taylor (1997)

[a] Profit margin (mark-up) assumed at 70 % of var. costs

Budget of the table (33.76 €/tonne) is the price that the farmer would aim if decisions are made based on cost of production. If the pulp and paper industry is willing to pay this price for its raw material, then there is scope for growing kenaf in Texas (Table 7.8).[18]

Harvesting cost is not included. *Land preparation* includes pre-plant fertilisation. *Agri-chemical inputs* include fertilising and herbicide/weed management. *Seed and Planting Costs* consist of 39 €/ha for seeds and 15 €/ha for planting. *Irrigation costs* consist of 24 €/ha for water and 20 €/ha for irrigation labour.

### 7.6.7 Cost of Production: BIOKENAF Project (CRES et al. 2007)

The BIOKENAF project has undertaken to cultivate 2 ha of kenaf in each of the selected countries and analyse the production of kenaf in southern Europe for several years. Yields and production costs have been recorded and summarised in the Kenaf Handbook (CRES et al. 2007) and other publications.

With regard to the Economic Analysis of the BIOKENAF project, the reader is notified that part of the cost is not included in the financial tables. The cost of machinery, land rent, permanent labour, financial expenses and overheads have not

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[18] However, the decision of the farmer is not really based on mark-ups or profit margin percentages, but on the opportunity cost of his land, which is compared with the expected profit from shifting from one crop to the other.

been included.[19] Therefore the reported margin is in effect the "Return above Variable Expenses" (Gerloff and McKinley 2012). In comparison with other studies, where fixed costs are roughly accounting for one-third of total costs, cost estimates in this study should be increased accordingly to approximate total fixed and variable costs of kenaf production (Table 7.9).

Harvesting, permanent labour, interest on capital employed and overheads costs are not included. Application cost of mechanical weeding is included in the weeding cost.

The Greek yield figure has been corrected according to additional information supplied by CRES (Alexopoulou et al. 2007).

In Italy, the plantation was not fertilised nor irrigated and as a result yields were much lower. The line "Variable cost per tonne" has been added in order to make comparable the total cost figures in the three countries. By comparison with market selling price, it also shows if an operation should or should not be undertaken on economic grounds. In the case of Italy, we observe that irrigation and fertilisation of the plantation would increase yield more than proportionately to the increase in agricultural expense and as a result the cost per tonne of kenaf would be lower. This has been the case with many energy crops.

**Table 7.9** BIOKENAF: revenues and costs of kenaf in South Europe (€/ha), 2007

| | Greece, €/ha | Spain, €/ha | Italy, €/ha |
|---|---|---|---|
| Seed and sowing | | | |
| Seed | 17 | 19 | 17 |
| Sowing | 55 | 25 | 40 |
| Cultivation | 255 | 111 | 200 |
| Fertiliser and application | | | |
| Base | 100 | 74 | |
| Top dressing | 54 | 54 | |
| Application | 60 | 5 | |
| Herbicides/mechanical weeding | | | |
| Herbicides | 19 | 7 | 7 |
| Weeding | | 8 | 43 |
| Application | 35 | 8 | |
| Irrigation | 175 | 360 | |
| Harvesting | 100 | 72 | 250 |
| Total variable costs | 870 | 743 | 557 |
| Variable costs/tonne | 48 | 39 | 76 |
| Selling price €/tonne | 80 | 80 | 80 |
| Yield dry tonnes/ha | 18 | 19 | 7 |
| Total revenues from sales | 1,440 | 1,520 | 584 |
| Gross margin | 570 | 777 | 27 |

Costs not included: Rent, salaries, machinery, interest and overheads
Compiled from: CRES et al. (2007), and Cook (2007), *Final Report*

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[19] The average land rent in Greece, Spain and Italy was 273, 119, 177 €/ha respectively (FADN 2011). Adding also an amount for permanent (imputed) labour, interest and overheads would increase much more the already high cost of production.

The economic results in Spain seem to be more promising with a variable cost of 39 €/tonne. This is due to lower cost of production and higher yields.

In contrast with commercial applications, one should be cautious with the interpretation of financial outcomes of scientific experiments, where researchers may not have the opportunity, the pressure or even the desire to explore all financial options in order to minimise the costs of production. A second point with experimental plantations is that they are usually small-scale activities with obvious diseconomies of scale.

## 7.7 Comparative Analysis

### *7.7.1 Net Profit*

Now one would probably be tempted to compare yields, sales and profits, which unfortunately were recorded at different times, in different countries with different currencies, etc.

In order to make comparisons more meaningful, we have (already) transformed all values into common units of the metric system. Acres were transformed into hectares, short tons into tonnes, pounds into kilogrammes, dollars into euros, etc., according to the Conversion Factors table, which is repeated here for convenience.

| Conversion factors |
|---|
| 1 € = 1.25 US$ |
| 1 ha = 2.47 acres (A) |
| 1 lb = 0.4536 kg |
| 1 gallon = 3.79 l |
| 1 ton = 2,000 lb |
| 1 ton/A = 2.24 tonnes/ha |

Having done this, we gather all cases together into a single table which shows the most important cost categories for each case as well as the overall economic results (Table 7.10).

However, even now values are not quite comparable. Costs, selling prices and all subsequent values reflect the price level of the year of the study, which is not the same for all. For example, is a profit of 177 €/ha (Scott and Taylor 1997) greater or lower than a profit of 252 €/ha (Bazen et al. 2007) 10 years later? Is total cost of 695 €/ha in Georgia (Kaldor and Hodges 1998) higher than 557 €/ha in Italy (CRES et al. 2007) if the accounts of the latter do not include the labour and machinery expenses?

One may appreciate the difficulties in interpreting such a table and make meaningful comparisons among the different cases. In order to reduce the incompatibilities, we have:

Applied general Retail Price Indices (national inflation rates in each of the countries involved) to transform (update) all costs to current values. Although some cost items might have been actually inflated at rates different from the general RPI, it is expected that on average the estimation is fair.

**Table 7.10** Cost comparison between reviewed cases

| | Biokenaf, Greece | Biokenaf, Spain | Biokenaf, Italy | KEFI, Italy | Bazen, Tennessee | Stricker, Florida[a] | Rochelle, Mississippi | Kaldor, Georgia[a] | Scott, Texas[b] | Average | % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Variable costs[c] | 595 | 311 | 307 | 485 | 296 | 319 | 86 | 251 | 194 | 316 | 51 |
| Harvesting | 100 | 72 | 250 | 252 | 90 | | 79 | 274 | | 159 | 25 |
| Irrigation (fixed + variable) | 175 | 360 | 0 | 150 | 0 | 0 | 107 | 72 | 44 | 101 | 16 |
| Labour (other than irrigtn) | | | | | 12 | 31 | 31 | | | 25 | 4 |
| Machinery (other fixed) | | | | | 132 | 57 | 42 | 8 | | 60 | 10 |
| Total variable, machinery and labour costs | 870 | 743 | 557 | 887 | 531 | 407 | 345 | 605 | 237 | 576 | 92 |
| Land rent | | | | | | 40 | | | 138 | 89 | 14 |
| Overheads, interest, etc. | | | | | | 86 | 79 | 91 | 15 | 68 | 11 |
| Total cost (€/ha) | 870 | 743 | 557 | 887 | 531 | 533 | 425 | 695 | 391 | 626 | 100 |
| Total cost (€/tonne) | 48 | 39 | 76 | 59 | 33 | 30 | 24 | 39 | 23 | 41 | |
| Yield (odt) | 18 | 19 | 7 | 15 | 16 | 18 | 17 | 18 | 17 | 16 | |
| Selling price(€/tonne) | 80 | 80 | 80 | 124 | 49 | 44 | 49 | 48 | 34 | 65 | |
| Revenue (€/ha) | 1,440 | 1,520 | 584 | 1,860 | 782 | 790 | 843 | 860 | 567 | 1027 | |
| Profit (€/ha) | 570 | 777 | 27 | 974 | 252 | 258 | 419 | 165 | 177 | 402 | |

[a] Assuming that one-third of equipment cost is fixed
[b] Irrigated
[c] Excluding Harvesting
Units transformation: ton/tonne = 0.907, €/$ = 1.25, gallon/lt = 3.79, lb/kg = 0.4536, ha/acre = 2.47, ton/lb = 2000

Approximated the selling price of kenaf in comparison to what is being paid today for wood. This is a modest approximation, because kenaf has obvious industrial and environmental advantages over wood, such as its applications versatility, generation of revenues from the first year of installation, preservation of forests, etc. One would probably be tempted to try even higher selling prices, as for example recorded by KEFI (124 €/tonne) which though includes the extra cost of 17 €/tonne for chipping the biomass and loading on the truck (KEFI 2009).

With regard to expenses that were made but not recorded in the examined cases, we have added the missing values (numbers in *italics*) by copying the average cost of the other cases (one before last column of the table). For example, the missing values for labour and machinery cost in the BIOKENAF experiments were assumed equal to the horizontal average of 29 and 66 €/ha, respectively. The reader is warned that this intervention to the table is introducing highly uncertain values, but otherwise, profit comparison among cases is practically impossible.[20]

We have added land rent (as in FADN 2011) to the cases where it was omitted (in *italics* too). In most cases, land rent is not added to total production cost (return to land and management), because comparisons are made among alternative land uses (of the same spot of land). However, the farmer also needs to know his farm total cost after land rent, paid or imputed.

Although the above approach is not very accurate, it rather improves the comparability and allows approximate comparisons among these very different cases.

The transformed data have been shown in Table 7.11.

All values have been transformed into 2009 prices using the retail price index of each country (European Commission 2012).

For the kenaf selling prices for Europe we adopt the price as estimated in the BIOKENAF Project. For the American cases, the price used (60 €/tonne) reflects the somewhat lower wood prices in the US and is closer to most of the inflated original US prices of the cases considered.

The entries in *italics* added in the empty cells are equal to the average of the existing figures for the same item. Some error may have been introduced in cases that the value of an entry had already been accounted for by the authors under other headings. For example, labour cost (or part of it) may have been included in variable expenses.

Land rent has been added in all cases with data from FADN 2012.

The cost of separation in the case of Georgia, USA (Kaldor and Hodges 1998), has been deducted.

The results of the BIOKENAF experiments must be treated with caution; because their costs were increased by serious diseconomies of scale (only 2 ha were cultivated in each case). Low yields in the case of Italy are the consequence of lack of irrigation. In many similar cases, it has been found in the past that irrigation improves yields (and consequent benefits) more than proportionally, increasing bottom line results.

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[20] The reader is encouraged to substitute more accurate values for the missing items to refine and improve bottom line results.

**Table 7.11** Cost comparison of reviewed cases—adjusted for inflation and missing values

| | Biokenaf, Greece | Biokenaf, Spain | Biokenaf, Italy | KEFI, Italy | Bazen, Tennessee | Stricker, Florida[a] | Rochelle, Mississippi | Kaldor, Georgia[a] | Scott, Texas[b] | Average | % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Variable costs[c] | 628 | 323 | 320 | 485 | 306 | 339 | 114 | 330 | 259 | 345 | 37 |
| Harvesting | 106 | 75 | 261 | 252 | 93 | 139 | 104 | 360 | 139 | 170 | 18 |
| Irrigation | 185 | 374 | 0 | 150 | 0 | 0 | 141 | 94 | 58 | 111 | 12 |
| Labour | 29 | 29 | 29 | 29 | 13 | 33 | 41 | 29 | 29 | 29 | 3 |
| Machinery (fixed) | 66 | 66 | 66 | 66 | 137 | 60 | 55 | 10 | 66 | 66 | 7 |
| Total variable, machinery and labour costs | 1,013 | 866 | 676 | 981 | 548 | 571 | 454 | 824 | 551 | 720 | 76 |
| Land rent | 273 | 119 | 177 | 177 | 114 | 42 | 114 | 114 | 185 | 146 | 16 |
| Overheads, interest, etc | 84 | 84 | 84 | 84 | 84 | 92 | 105 | 45 | 20 | 76 | 8 |
| Total cost (€/ha) | 1,370 | 1,069 | 937 | 1,242 | 746 | 705 | 672 | 983 | 755 | 942 | 100 |
| Total cost (€/tonne) | 76 | 56 | 128 | 83 | 46 | 39 | 39 | 55 | 45 | 63 | |
| Yield (odt) | 18 | 19 | 7 | 15 | 16 | 18 | 17 | 18 | 17 | 16 | |
| Selling price(€/tonne) | 80 | 80 | 80 | 130 | 60 | 60 | 60 | 60 | 60 | 74 | |
| Revenue (€/ha) | 1,440 | 1,520 | 584 | 1,950 | 968 | 1,075 | 1,043 | 1,075 | 1,008 | 1185 | |
| Profit (€/ha) | 70 | 451 | −353 | 708 | 221 | 370 | 371 | 92 | 253 | 243 | |

[a] Assuming that one-third of equipment cost is fixed
[b] Irrigated
[c] Excluding Harvesting
Units transformation: ton/tonne = 0.907, €/$ = 1.25, gallon/lt = 3.79, lb/kg = 0.4536, ha/acre = 2.47, ton/lb = 2000

The table shows that kenaf in general could be profitable if sold at prices around 60–80 €/tonne, similar to or a little higher than the price of wood. KEFI, calculations at higher chips prices, estimates a clearly positive bottom line profit.

It clearly seems from all the cases that have been analysed that kenaf profitability can only be achieved after very strict management of expenses and aggressive sales policies and effort for increasing both volume and price. Since it is costly to transport kenaf stalks, one expects a local industrial investor (fibre extraction and sale or paper pulp industry) to manage the kenaf agro-industrial chain. Today, kenaf is produced in areas with more suitable climate and much lower labour cost, which makes it more economic than using machinery (Southeast Asia). It is expected though, that improvements in the cultivars, machinery and methods of production and handling in combination with further development of demand for various industrial uses, will drastically reduce costs and make kenaf a very competitive fibre plant of South Europe.

### *7.7.2 Gross Margin Comparisons*

Viewed from the farmer's standpoint, there is a need to compare the financial return per hectare of his land from kenaf with the return achieved by whatever the farmer is currently cultivating. This exercise has been undertaken by the BIOKENAF Project (CRES et al. 2007).

Such comparisons are useful, because they reveal the willingness of the farmers to allocate part of their land to a new cultivation. Naturally, among the considerations in exploring such a change, is whether the new crop is more profitable than the currently cultivated crop.

The comparisons ideally should be made at the *Return to Land and Management* level in order to include all costs and revenues. However, due to lack of detailed information, the Gross MarginGross Margin[21] of kenaf cultivation has been compared with the corresponding margins of the most popular conventional crops produced in Southern European countries. In the BIOKENAF Project the Gross Margin has been approximated as:

Sales Revenues–Variable Costs

As an indicative average margin for kenaf for the whole of South Europe, the BIOKENAF Project assumes 464 €/ha.

Using the table of comparative analysis above, we have found the Gross Margin in each of the three countries studied as the difference between "Revenues" *minus* "Total Direct Costs" (i.e. variable, machinery and labour costs). The Gross Margin for Greece is 427 €/ha (=1,440 − 1,013), for Spain 654 €/ha and for Italy−92 €/ha. For Italy the figure is not very useful, because as said before, it was a non-irrigated, non-fertilised cultivation which has only proved the need for more inputs.

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[21] Gross Marginis equal to *Sales Revenues* minus *Cost of Goods Sold.* CGS includes all expenses directly attributable to the product.

The Gross Margins of Greece and Spain can now be compared with margins of usually cultivated crops in these countries, in order to approximate the amount of land which is likely to be made available for kenaf cultivation if the price paid to the contracted farmer is 80 €/tonne of dry biomass (Table 7.12).

## 7.8 Conclusions

Kenaf is a fast growing fibrous crop which can grow successfully in warm and wet climates. However, it may also be cultivated with adequate yields in south Europe. Only a handful of large experimental plantations have been established in the last 20 years in the US, and much less have been reported for Europe. Even in the Far

**Table 7.12** Gross margins of popular crops in South Europe

| Country | Crop | Area grown, 000 ha (% of arable cropping) | Price (€/tonne) | Gross margin (€/ha) |
|---|---|---|---|---|
| France | Wheat | 4826 (42) | 90 | 661 |
| | Maize | 1796 (16) | 86 | 419 |
| | Feed barley | 1626 (5) | 80 | 518 |
| | Sunflower | 616 (5) | 221 | 609 |
| | Durum wheat | 405 (4) | 120 | 636 |
| Greece | Durum wheat | 650 (40) | 153 | 562 |
| | Cotton | 370 (23) | 838 | 1432 |
| | Maize | 180 (11) | 136 | 1116 |
| | Wheat | 155 (10) | 135 | 349 |
| | Spring barley | 370 (23) | 136 | 153 |
| Italy | Durum wheat | 1870 (40) | 149 | 195 |
| | Maize | 1194 (26) | 110 | 751 |
| | Wheat | 490 (10) | 119 | 468 |
| | Rice | 227 (5) | 179 | 1126 |
| | Soya beans | 138 (3) | 228 | 85 |
| Portugal | Durum wheat | 145 (15) | 126 | 462 |
| | Maize | 120 (12) | 115 | 816 |
| | Sunflower | 75 (8) | 236 | 255 |
| | Rice | 26 (3) | 152 | 1066 |
| | Wheat | 30 (3) | 118 | 254 |
| Spain | Spring barley | 3150 (31) | 236 | 566 |
| | Wheat | 1408 (14) | 116 | 291 |
| | Durum wheat | 850 (8) | 124 | 459 |
| | Sunflowers | 780 (8) | 236 | 156 |
| | Maize | 484 (5) | 114 | 315 |

Source: BIOKENAF Project, CRES et al. (2007)

East, where the climate is more suitable and costs are lower, kenaf mills are not always profitable (Kaldor and Hodges 1998) and its commercial uses are restricted to only a few of its possible applications.

Currently, kenaf is commercially cultivated only in Southeast Asia. Its volume of production has been falling sharply due to fierce competition from man made and other natural fibres. However, research has identified many new markets where kenaf could play a very important role due to its physical characteristics and moderate requirements of agricultural inputs which are harmful to the environment. It remains to be seen if economic and environmental conditions will allow wider adoption and increased market shares of kenaf in the West.

The economics of kenaf have to be treated very carefully. Published material is confusing rather than clarifying the true financial position of kenaf, mainly due to the lack of a common basis for comparisons. According to the findings of the BIOKENAF project and related material, the kenaf agro-industrial chain seems to offer under circumstances a marginally profitable opportunity for European farmers (CRES et al. 2007; Lips and van Dam 2007), which does not guarantee sufficient incentive for significant commercial exploitation of the plant. At this stage, industrial initiatives offering risk-free long-term contracts must provide the floor for commercialising kenaf cultivation, which in turn will undoubtedly lead to the benefits of the learning curve in two directions: (a) Increasing yields, (b) Cost reductions along the agro-industrial kenaf chains.

The two most decisive figures in the economic analysis of kenaf, yield and selling price, are also the two most uncertain items in the list. Because of the minimal and very small-scale experimentation in South Europe, expected yields are considerably uncertain. The current experimental range from about 6 to 20 tonnes per hectare is too wide for a deterministic financial examination. On the other hand, selling prices of kenaf in Europe will be very much case specific, depending upon the industrial chain it will serve. Prices around or above 100 €/tonne are not improbable (Tahir et al. 2011; British Forestry Commission 2012). At this level, some kenaf applications seem to appear profitable with respect to approximate opportunity cost of land.

Today, research on kenaf has not reached maturity. Specific cases need to be individually examined in detail under the conditions at the location and the distinctive characteristics of each kenaf agro-industrial application. Since kenaf markets are not yet quite established, sufficient pre-contracted sales quantities should exist before undertaking a substantial investment in kenaf cultivation. State intervention for the support of this environmentally superior fibre crop may be decisive for the future kenaf.

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# Chapter 8
# New Insights from the BIOKENAF Project

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**Abstract** This chapter summarizes the most important achievements of the European research project entitled "BIOKENAF—Biomass Production Chain and Growth Simulation Model for Kenaf" (www.cres.gr/biokenaf) that carried out for 2003–2007. The overall objective of the BIOKENAF project was to introduce and evaluate kenaf as a non-food crop through an integrated approach for alternative land use in South EU that will provide diversified opportunities for farmers and biological materials for the "bio-based industries" of the future. Several fields' trials were carried out in South EU aiming to identify the appropriate crop management for yields maximization (sowing dates, plant densities, best varieties, irrigation and fertilization needs, harvesting time). A dynamic crop-growth simulation model was developed to produce quantitative estimates of the yielding potential of kenaf at regional level. The model was based on the detailed crop data that were collected from the field trials and were included in photosynthetic capacity, respiratory losses, phenology, dry matter distribution, and data on leaf area. The

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appropriate harvesting time for south EU countries that ensure the highest possible yields with the lowest possible moisture content investigated as well as best storage method in order to the minimum losses in the quality and quantity of the feedstock to be achieved. The suitability of kenaf for both selected industrial products (composites, building materials, nonwovens, paper, and board and absorption particles) and for thermo-chemical energy applications (combustion, gasification, and pyrolysis) was investigated. Following an environmental/economic assessment and market studies insight in the feasibility of kenaf for industrial and energy applications was provided that was used not only for comparison of the crop with other conventional crops with similar cultural practices but also for the development of scenarios for alternative land use and diversified opportunities for farmers in order to produce industrial bio-products that will supply the "bio-based industries" of the future.

**Keywords** BIOKENAF project • Kenaf • *Hibiscus cannabinus L* • Kenaf adaptation • Productivity • Varieties • Irrigation • Nitrogen • Sowing dates • Plant populations • Growth simulation model • Harvesting • Storage • Industrial applications • Insulation mats • Composites • Absorption materials • Ash behavior • Ash melting point • Combustion • Gasification • Pyrolysis • Environmental impact assessment • Life cycle analysis • Economic analysis • Market opportunities

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## 8.1 Introduction

Kenaf is an important fiber crop cultivated long (3500–4000 BC) but still considered as an old-new crop. During the Second World War, as foreign fiber supplies were interrupted, kenaf research and production was started in the U.S. to supply cordage material for the war effort (Dempsey 1975). Soon after its introduction in USA (in 1940s) efforts to bring kenaf from experimental crop status to an accepted alternative in established cropping systems were started and are still on progress More than 500 plant species were evaluated in USA in 1950s in order to cover the increasing future fiber demands in the USA. Kenaf was evaluated as an excellent cellulose fiber source for a large range of paper products (Nelson et al. 1962).

Currently, many countries pay more attention to kenaf research and cultivation because of its high biological efficiency and wide ecological adaptability. Kenaf has been called "the future crop" (Mazumder 2000; Cheng 2001). Nowadays, kenaf is commercially cultivated in more than 20 countries, particularly in China, India, Thailand, and Vietnam (FAO 2003) but still the knowledge on dissemination of the crop worldwide is still limited. Although kenaf originated from Africa, its production in Africa is very low. In 2010, the total production of Africa was just 3 % of the world production (FAO 2010).

Kenaf has been accepted by the European Community as a "non-food" crop with high production of biomass, which is composed primarily of cellulose-rich stalk (Venturi 1990; Webber 1993). It has designated for utilization in the production of industrial fiber (EC Reg. 1765/92 of the Committee of 30th April 1992 amended by EC Reg. 334/93 of the Committee of 15th February 1993). The research at European level on kenaf started in the early 1990s and the developments on the crop have been concentrated on the Mediterranean region with subtropical climates and have been focused mainly on the primary production in the framework of a European demonstration project that was aimed at testing kenaf as raw material for paper pulp production.

In the view of this project (EUROKENAF) demonstrative fields were carried out in all the Mediterranean countries to produce the raw material for the paper pulp tests. According to the results derived from the cultivation of kenaf in the demonstrative fields it has been reported that the dry matter yields strongly which depend on the maturity type of the cultivated variety and was ranged from 8 to 18 t/ha in Greece, from 12 to 17 t/ha in Italy, from 13 to 24 t/ha in Spain, and from 12 to 20 t/ha in Portugal (Paschalidis et al. 1997). In the view of this project the research on kenaf focused strictly on its use as a raw material for the paper/pulp industry. Hardly any research has been directed toward the other industrial uses of the crop as well as the energy exploitation of it, in spite of the favorable characteristics of kenaf feedstock and its high biomass yields.

The BIOKENAF project (www.cres.gr/biokenaf) offered an integrated approach for kenaf covering the whole production chain (production, harvesting, and storage) testing the suitability of the crop for industrial products and energy. This integrated approach was carried out taking into consideration the environmental and the economic aspects of the crop and a market feasibility study was led to the production of industrial bioproducts and biofuels with respect to security of supply and the sustainable land management.

## 8.2 Adaptation of the Crop in Europe

Although kenaf is capable of adapting itself to a large variety of climatic conditions, it grows up best in tropical and subtropical regions since it is sensitive to frost. It is grown at latitudes from 45° N to 30° S (Mc Gregor 1976) and at altitudes from the sea level to 1000 m above the sea level. It is reported that any field that belongs to the cultivation zone and that is capable of producing corn, cotton, sugar, beans, or vegetables can be used for kenaf cultivation. Any of these mentioned crops can be used in rotation with kenaf. Areas where the plant is to be cultivated should be free or protected from strong winds, since the growth is rapid and the plants get so tall that they cannot withstand much wind.

In the BIOKENAF project field trials were established in 11 sites in Europe (Greece, Italy, Spain, Portugal, and France). The achieved yields varied a lot among the sites and came up to 28 t/ha. Two field trials were established in areas that were outside the cultivation area of kenaf (the latitude in these areas were above 45° N); in Trieste–Italy (Latitude: 45° 51′ N) and in Estree Mons–France (Latitude: 49°52′44") (Fig. 8.1).

**Fig. 8.1** Sites that the kenaf fields were established in the BIOKENAF project

In all sites kenaf showed good adaptability apart from the case of the north France and in this case both low yields and diseases were recorded. The yields of the varieties tested (Everglades 41 and Tainung) in north France were 11.5 and 10.5 t/ha, respectively (with 75 % moisture content. Additionally, fungi attacks (Anthracnose and gray mold) were recorded in the trial since the crops is sensible on that (Campbell and O'Brien 1981). Between the two varieties Tainung 2 was more sensitive (30 % of the plants had been infested in the Tainung 2 plots and 11 % in the Everglades 41 plots).

## 8.3 Kenaf Productivity in Europe

For a period of three subsequent years (2003–2005) kenaf trials (Table 8.1) were established in Aliartos-GR, Palamas-GR, Komotini-GR, Catania-IT, Trieste-IT, Bologna-IT, Madrid-ES, Extremadura-ES, Lisbon-PT, Estree Mons-FR, and Flamarens-FR. Several sowing times were tested from the middle of March until

**Table 8.1** Description of the kenaf field trials (sites, factors, experimental design)

| Field trials | Sites | Factors under study | Experimental design |
|---|---|---|---|
| Screening trial | Aliartos-GR | Six kenaf varieties (Tainung 2, Everglades 41, Gregg, Dowling, SF 459 and G4) | Randomized complete block design in three replications |
| Sowing times, varieties and plant populations | Aliartos-GR, Palamas-GR, Catania-IT, Madrid-ES, Lisbon-PT, Bologna-IT, INIA, University of Lisbon, Paris-FR | 2 varieties (Tainung 2, Everglades 41)<br>2 sowing times (middle of May, early of June)<br>2 plant populations (200,000 and 400,000 plants/ha) | A $2^3$ factorial in three blocks |
| Irrigation and nitrogen fertilization trial | Aliartos-GR, Palamas-GR, Catania-IT, Madrid-ES, Lisbon-PT, Bologna-IT, INIA, University of Lisbon, Paris-FR | In Aliartos-GR, Catania-IT, Lisbon-PT, Madrid-ES the tested factors were:<br>3 nitrogen levels (0, 75 and 150 kg N/ha)<br>4 irrigation levels (0, 25, 50 and 100 % of PET)<br>In Palamas-GR, Paris-FR, Bologna-IT the tested factors were:<br>4 nitrogen levels (0, 50, 100 and 150 kg N/ha)<br>3 irrigation levels (0, 50 and 100 % of PET) | A split-split plot design in three blocks |
| Kenaf field trial with size 2 ha | Trieste-IT, Komotini-GR | Everglades 41 was used in a plant density of 200,000 plants/ha | |

the middle of July. Two were the applied plant densities: 200,000 and 400,000 plants/ha. In all sites two were the cultivated varieties: Everglades 41 and Tainung 2, while in Aliartos-GR the tested varieties were six (Tainung 2, Everglades 41, Gregg, Dowling, SF 459, and G4). Regarding the irrigation rates they were applied 0, 25, 50, and 100 % of PET and for nitrogen rates 0, 50, 75, 100, 150 kg N/ha. A large number of subsequent harvests were carried out in all trials for dry matter yield estimations. It was also investigated the appropriate harvesting time for the crop in relation to its final end use.

### *8.3.1 Varieties*

Six kenaf varieties were cultivated and evaluated which categorized in three groups: (a) the most common late-maturity varieties (Tainung 2 and Everglades 41) (b) new released late-maturity varieties in USA (Gregg, Dowling, SF 459) and (c) an early variety when it is cultivated in the climatic conditions of Europe (G4). The two traditional late varieties (Tainung 2 and Everglades 41) were cultivated and evaluated in seven sites in Europe, while the rest four varieties were tested only in central Greece (Aliartos, Greece).

In Fig. 8.2 the final dry stem yields Tainung 2 and Everglades 41 in seven sites are presented. In three sites (Aliartos, Catania, and Madrid) Tainung 2 was more productive than Everglades 41, in two sites (Palamas and Bologna) Everglades 41 was the most productive, while in two sites (Palamas and Paris) the yields were almost the same for both varieties. Quite large variations in dry stem yields both varieties among the 3 years were recorded in Lisbon and in Paris, while in Palamas-GR the variations among the years (2003–2005) were quite small.

In Fig. 8.3 the final dry stem yields the six tested varieties for a period of four subsequent years are presented. From 2003 to 2006 the dry stem yields were gradually declined. It should be noted that in all years the screening trial was conducted in exactly the same place in Aliartos (GR). In 2004 the reduction was 11 % (compared to 2003), in 2005 the reduction was bigger 15 % (compared to 2004), and finally in 2006 the reduction was 16 % (compared to 2005). A comparison among the 4 years showed that the achieved yields in 2006 was 37 % lower compared to the recorded yields in 2003 (10 t/ha versus 16 t/ha).

In all years the lowest yields were recorded from the early variety G4, while as a mean of all years the best yields were recorded from the new realized variety SF 459 (14.5 t/ha). It is very important to point out that the three realized varieties (Gregg, Dowling, and SF 459) have at least equal or higher yields compared to the traditional late varieties (Tainung 2 and Everglades 41). In 2003 the most productive variety was Tainung 2, in the following year the variety was Everglades 41, while in 2005 and 2006 the most productive was SF 459. The mean dry stems yields of the six tested varieties (2003–2006) by descending order were 14.55 t/ha (SF 459), 14.38 t/ha (Everglades 41), 13.98 t/ha (Gregg), 13.32 t/ha (Tainung 2), 13.3 t/ha (Dowling), and 9.68 t/ha (Dowling).

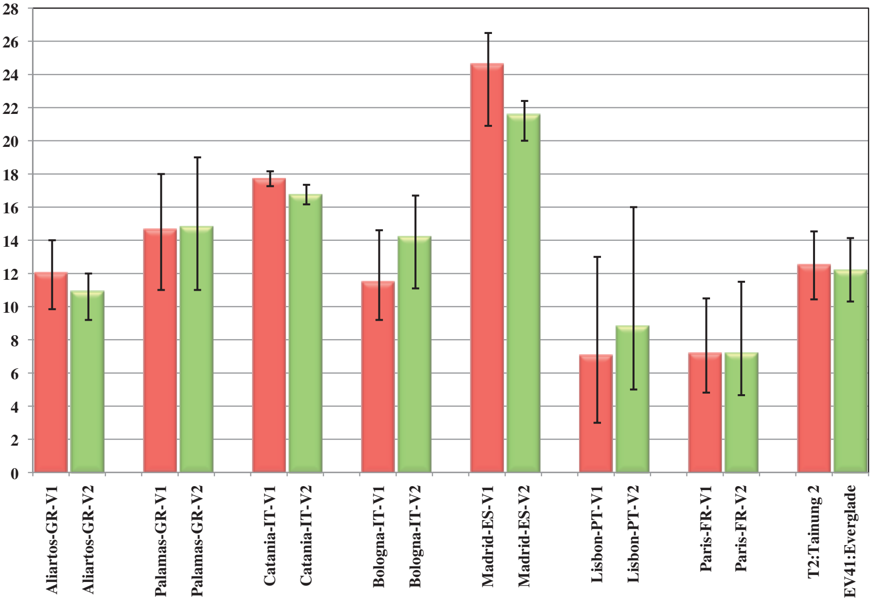

**Fig. 8.2** Variety effect (Tainung 2, Everglades 41) on final dry stem yields (t/ha, 2003–2005) in seven kenaf field trails (Aliartos-GR, Palamas-GR, Catania-IT, Bologna-IT, Madrid-ES, Lisbon-PT, Paris-FR)

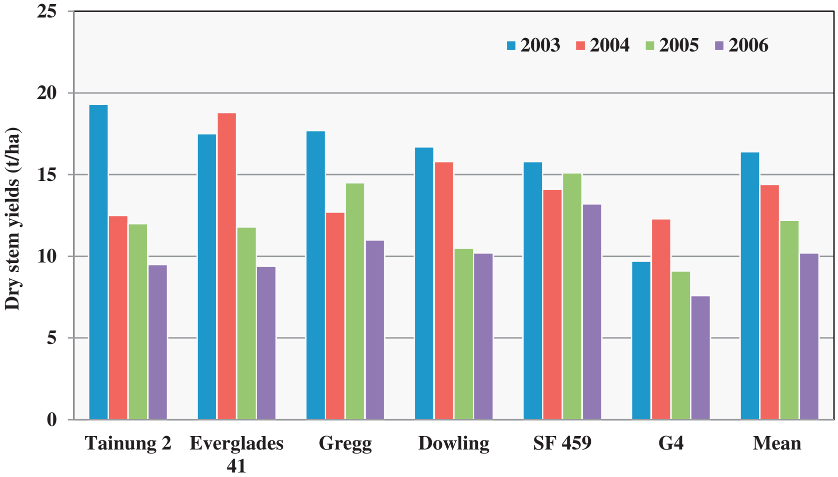

**Fig. 8.3** Effect of variety (Tainung 2, Everglades 41, Gregg, Dowling, SF 459, G4) on final dry stem yields (t/ha) in Aliartos-GR for a period of four subsequent years (2003–2006)

The result of cultivating kenaf in the same site for a period of four subsequent years was the decline of the maximum yields from year to year (37.8 % from 2003 to 2006). Not only the yields were reduced but also the nematodes populations were also increased. It should be pointed out that the smallest yields reduction was recorded in the plots of the variety SF 459 due to its high resistance to nematodes. On the contrary, the traditional kenaf varieties were the ones with the highest reduction in yields when these two varieties were cultivated in the same site for four subsequent years. The insertion of kenaf in an appropriate rotation scheme is necessary in order to secure high yields of the crop and to control the nematodes populations in the area of cultivation, especially when the soil type allow the increase of the nematodes populations.

### *8.3.2 Sowing Dates*

In BIOKENAF project several sowing dates were tested started from the end of March (Palamas-GR) to the beginning of July (Lisbon-PT). In each year and in each site two sowing times were applied (an early one from March to April and a late one from May to early July). It was found that in all sites (Fig. 8.4) the early sowings resulted in higher dry stem yields (2003–2005). The most profound superiority of the early over the late sowing in terms of yields was recorded in Palamas-GR (23 %), in Bologna-IT (32 %), and in Lisbon-PT (34 %). In the first case a quite early sowing time was tested (March), in the second case the late sowing took place in June, while in the third the late sowing took place in the beginning of July.

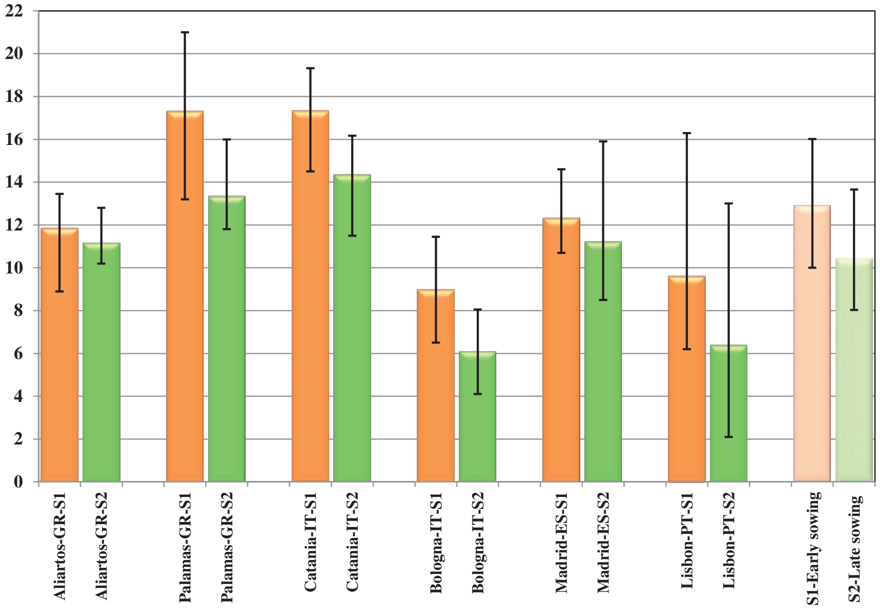

**Fig. 8.4** Effect of sowing time (early and late) on final dry stem yields (t/ha, 2003–2005) in six sites (Aliartos-GR, Palamas-GR, Catania-IT, Bologna-IT, Madrid-ES, Lisbon-PT

Averaged overall sites and 3 years the early sowing resulted in dry yields around 13 t/ha, while the yields in the late sowing plots did not exceed 10.5 t/ha. The largest variations among the years were recorded in the field trials that had been conducted in Portugal. The worst yields were recorded in Bologna with dry matter yields of the early sowing around 9 t/ha and the late around 6 t/ha.

It is reported that (Danalatos and Archontoulis 2010) the yields results recorded in Palamas-GR demonstrated a paramount effect of sowing time on crop growth and biomass yields and delayed sowings after the middle of May could reduce the yields by 38 %. In the specific climatic conditions of central Greece the proper time sowing of kenaf is from middle of April to the middle of May, when the temperature exceed 15 °C. In Catania-IT early sowing of kenaf (May) are suggested for both seed and biomass production (Patane and Cosentino 2010). These results are in accordance with previous studies in the Mediterranean region (Manzanares et al. 1993; Sortino et al. 2005).

### *8.3.3 Plant Densities*

There is no clear picture regarding the effect of plant population on yields (Fig. 8.5). In cases like Aliartos-GR, Catania-IT, and Madrid-ES a clear superiority of the low density (200,000 plants/ha) over the high one (400,000 plants/ha) was recorded, while in Bologna-IT and Lisbon-PT the opposite was happened. In Palamas-GR and Paris-FR both densities gave almost the same yields. The mean yields of low density, averaged overall sites, were 12.5 t/ha, while high density was 12.2 t/ha. It is reported that the plant population had a minimal effect on growth and yields of both kenaf varieties, despite the slight superiority in LAI in the denser populations at the advanced development stages (Danalatos and Archontoulis 2010).

However, it should be reported that in the plots with the high plant populations lower branching is reported and the basal stem diameter was smaller and the plants were more sensitive to lodging after the flowering initiation. Plant densities from 200,000 to 400,000 are quite acceptable for achieving high kenaf yields and unbranched stems. When the plant density is closer to 200,000 plants per ha the stems have larger stems with high resistance to lodging and when the plant density is increasing and approaching 400,000 plants/ha the stems have smaller stem diameter and are more sensitivity to lodging but at this high density higher bark yields can be achieved.

### *8.3.4 Irrigation Rates*

The kenaf trials carried out in five sites (Aliartos-GR, Palamas-GR, Catania-IT, Mardid-ES, and Lisbon-PT) for three subsequent years (2003–2005) proved that

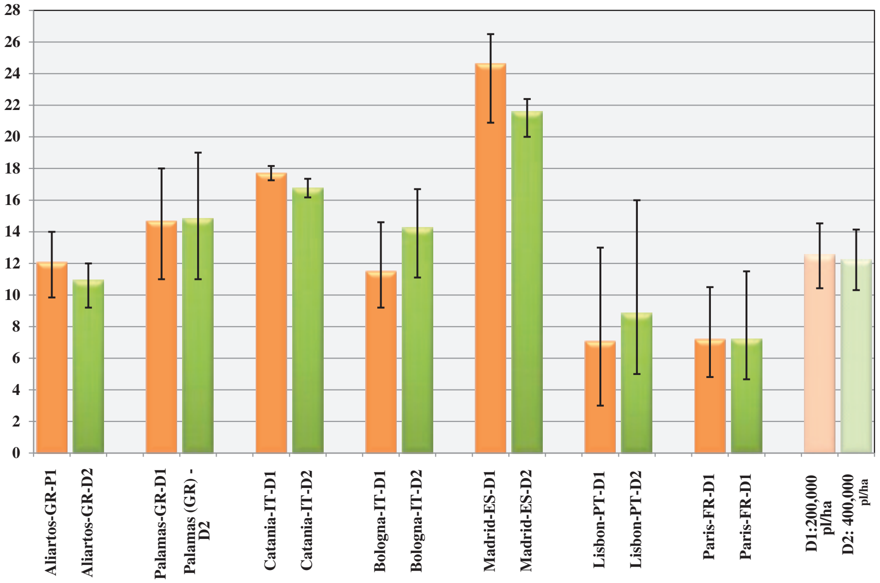

**Fig. 8.5** Effect of plant density (P1-200,000 and P2-400,000 plants/ha) on final dry stem yields (2003–2005) in seven sites (Aliartos-GR, Palamas-GR, Catania-IT, Bologna-IT, Madrid-ES, Lisbon-PT, Paris-FR)

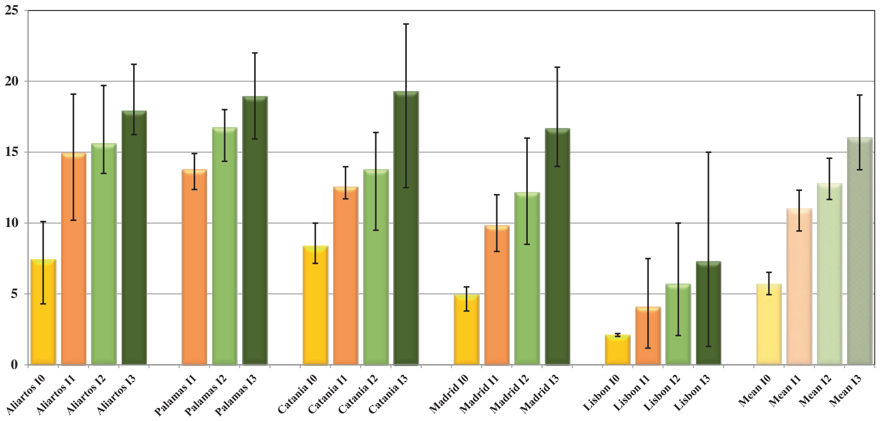

**Fig. 8.6** Effect of the applied irrigation (0, 25, 50 and 100 % of PET) on final dry matter yields (t/ha) in five sites (Aliartos-GR, Palamas-GR, Catania-IT, Madrid-ES, Lisbon-PT) for the period 2003–2005

when the irrigation rate was increased the growth and yields were also increased and in most of the cases statistical significant differences were recorded (Fig. 8.6). It should be pointed out that the clearest effect of the irrigation on growth and yields was recorded in Madrid trial.

The mean maximum dry yields (averaged over the five trials and the three years) were 5.7 t/ha (no irrigation), 11 t/ha (25 % of PET), 12.8 (50 % of PET), and 18 t/ha (100 % of PET). The corresponding values for the final dry yields were 4.7, 9, 11, and 13 t/ha. The fully irrigated plots gave 57 % (Catania-IT) to 71 % (Lisbon-PT) higher yields.

In Palamas-GR it was found that in the case of water applications from 90 to 130 mm a no modest total biomass of 13–17 t/ha can be produced (Danalatos and Archontoulis 2010). The relatively low effect of water to kenaf yields in Palamas-GR is due to the high moisture content of the subsoil. On the contrary in dry areas like Catania-IT and Madrid-ES the effect of water on growth and yields was quite clear, especially in the years that during the hot summer months the precipitation was quite low and the air temperatures were quite high.

### *8.3.5 Nitrogen Rates*

In Fig. 8.7 the effect of applied nitrogen fertilization (0, 75, and 150 kg N/ha) on kenaf productivity is presented. In most sites it was found that when the nitrogen application was increasing the dry stem yields were also slightly increased. The clearest picture of this trend was recorded in Lisbon (Fig. 8.7). It should be pointed out that only in very few cases the differences among the nitrogen rates differed statistically significant. Averaged all trials, it was found that the dry stem yields were 7.6 t/ha (0 kg N/ha), 8.1 t/ha (75 kg N/ha), and 8.8 t/ha (150 kg N/ha).

Two sites in Europe (Palamas-GR and Bologna-IT) four nitrogen rates (0, 50, 100, and 150 kg N/ha) were tested. The results at the final harvest are presented in Fig. 8.8. The increasing of the applied nitrogen fertilization (from 0 to 150 kg N/ha) did not result in increasing of dry yields in both sites (Palamas and Bologna). The mean dry yields were 13.6 t/ha (0 kg N/ha), 15.5 t/ha (50 kg N/ha), 13.6 t/ha (100 kg N/ha), and 15 t/ha (150 kg N/ha).

It is worth mentioning that in the case of the Palamas trial the plots that received the high nitrogen fertilization rate resulted in the lowest yields (Fig. 8.8). In Palamas trial (mean of 3 years) the highest yields were recorded in the plots that fertilized with 50 kg N/ha. In the same site, the plots that did not fertilize and the ones that received 100 kg N/ha gave exactly the same dry stem yields (17.5 t/ha), while the highly fertilized plots were the ones with the poorest yields of the four rates.

In the other site (Bologna-IT) the highest yields measured the plots that was fertilized with 150 kg N/ha. As it is presented in Fig. 8.8 in Bologna the no fertilized plots and the ones that received 100 kg N/ha resulted in exactly the same productivity. A comparison between the plots that fertilized with the low and the high nitrogen rate showed that the yields were higher in the highly fertilized plots but the superiority of the high over the low nitrogen rate was relatively small to justify the need for this additional fertilization.

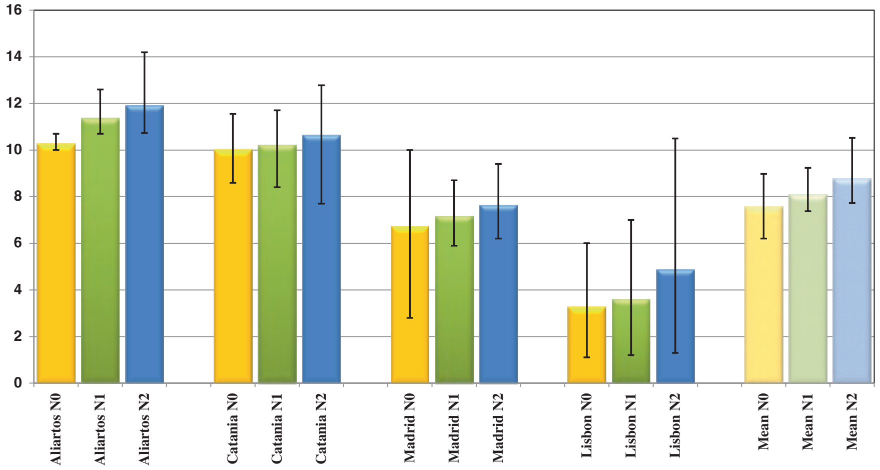

**Fig. 8.7** Effect of nitrogen rate (0, 75 and 150 kg/ha) on final dry matter yields (t/ha) in four sites (Aliartos-GR, Catania-IT, Madrid-ES, Lisbon-PT) for the period 2003–2005

The results recorded in the six sites for a period of 6 years cannot give a clear picture regarding the effect of the nitrogen fertilization of kenaf growth and yields and thus additional research is needed. It should be also pointed out that in the international literature quite contradictive results have been reported with clear and no effects of nitrogen fertilization of yields.

## 8.4 Development of a Growth Simulation Model

A new dynamic crop growth simulation model named "BIOKENAF" was developed and it is able to predict kenaf phenology, growth characteristics (leaf area index, soil water balance, etc.), and biomass yields (stems, leaves, petioles) under a wide range of soil climatic environments in Europe. This model was based on the Wageningen photosynthesis modeling approach and it can simulate biomass production under two production situations: potential and water-limited.

After the development of the BIOKENAF model the validation was carried out using data that were provided by all BIOKENAF partners from kenaf fields that were established in several sites in Southern Europe for the period of 2003–2005. In these trials, the growth and development of two important kenaf varieties (Tainung 2 and Everglades 41) were studied under two plant populations, two sowing dates, three irrigation and four nitrogen fertilization rates.

The results on BIOKENAF model validation were quite encouraging, showing a good agreement between the measured and simulated data on dry biomass production per plant organ of kenaf (evolution throughout the growing period and final yields).

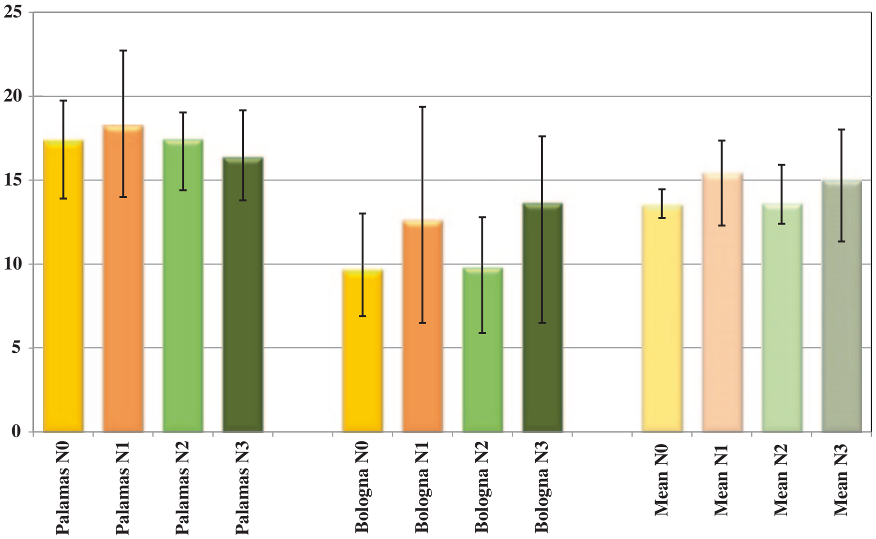

**Fig. 8.8** Effect of nitrogen application (0, 50, 100 and 150 kg N/ha) on final dry matter yields (t/ha) in two sites in South Europe (Palamas-GR, Bologna-IT) for the period 2003–2005

Figure 8.9 demonstrates the good fit between measured and predicted values of dry biomass of kenaf throughout the growing period of years 2003–2005 in central Greece. It is noticeable that the model assesses well the negative growth rates of leaves and total dry weight due to leaf senescence and to the low assimilation-respiration rate recorded at advanced development stages. The measured data of years 2003–2004 were used for model calibration whereas the data of 2005 were used for model validation. It should be noticed that model calibration is a difficult exercise since it is not sure that the field experimental data are always correct due to the experimental error involved, and therefore the slight variation between measured and calibrated values should not be attributed to model weakness. Surely, during model calibration, an effort was made toward better prediction of the dry matter yields during advanced development stages and of course of the final yields. Based on these considerations, the result of model validation for Greece was on 2005 (Fig. 8.10) shows a very good fit (coefficient of determination equals to 95.5 %) between measured and simulated total dry biomass yields of kenaf. The same holds for the examples of Italy (2003) and France (2005) for which model validation gives encouraging results. Note that the model may successfully predict dry matter variation from over 22 t/ha to lower than 8 t/ha in different European environments, performing a substantial sensitivity required in such broad predictions.

Particularly, the model may predict quite successfully final biomass yields production as this is reflected by the high values of the relevant indexes: viz. r2 = 95 %, RMSE < 15, and ME ~0.8).

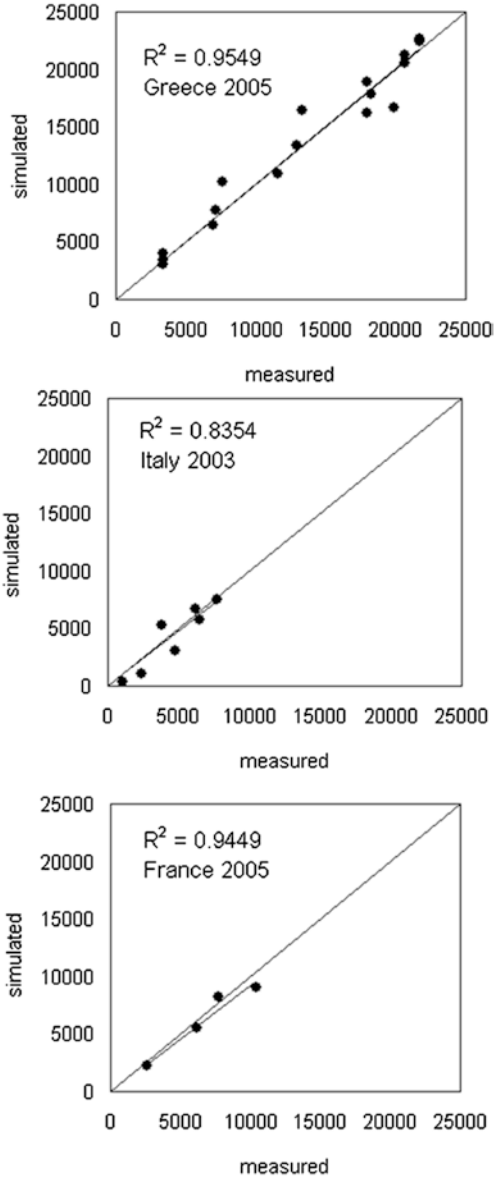

**Fig. 8.9** Measured versus estimated total dry biomass (kg/ha) throughout the growing period of kenaf in selected European sites and years

## 8.5 Harvesting and Storage

The determination of the appropriate harvesting time and methods and the storage techniques as well as the techno-economic evaluation of storage methods for the feedstock (indoors and outdoors) was one of the main objectives of the BIOKENAF project.

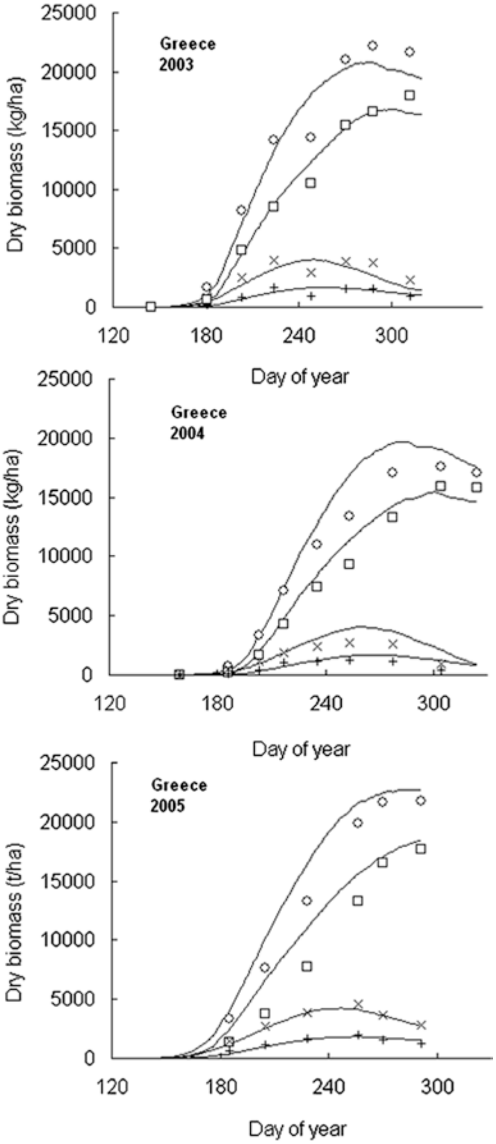

**Fig. 8.10** Measured (○, □, ×, +) and simulated (line) dry mater production in Palamas, central Greece (2003–2005). Predictions refer to potential production situation. (○): total, (□): stem, (×): leaf and (+): petiole dry weight. *Note* Data 2003, 2004 used for model calibration and data 2005 used for model validation

In order to carry out the harvesting trial a kenaf field trial with size 2 ha was established in Cervignano del Friuli, in the North East of Italy, for a period of 2 years. In both years harvest trials of the kenaf biomass as well as storage in building were carried out. Additionally, in the second year the collected biomass was processed to produce insulation mats. The kenaf variety used for these trials was “Everglades 41”.

In the first year the harvesting operations have been carried out in February, 2004 and the planned activities were including mowing-chopping harvesting with sheltered storage of the product. A Jaguar 870 (Claas) was used to mow and chop the material. This kind of harvesting chain has been working very efficiently. The weak point of the chain is represented by the low bulk density (less than 30 kg/m$^3$ for 34 mm chopped biomass) that does not make long transport economically convenient (it can be considered that only 30 % of the working time has been allocated to chopping while the rest for transport-unload operations, even if the storage place was closed to the field). The chopped kenaf was piled up on beds in sheltered storehouse. The low chopped kenaf bulk density involves the necessity of large volume buildings for storage. No fermentation process inside the pile was started during the storage due to the low content of moisture of the biomass (about 17 %).

In the second year, the aim was to harvest the kenaf stems according to the quality parameters required by a natural fiber transformation factory and finally to produce some panels or boards from the kenaf fiber harvested. This prompted to study and to characterize a right harvesting method with the aim to optimize the conveyance of the product to the processing firm. An Italian factory processing natural fibers was contacted (KEFI—Kenaf Eco Fibers Italia S.p.A.). For KEFI fiber processing it was necessary to supply chopped material (sized between 2.5 and 5 cm), unbaled. For the kenaf harvesting it was possible to use the same harvesting yard tested in the first year of project, with a chopper and a series of trailer. The harvesting was carried out in March, 2005. The chopped kenaf moisture content was 12.2 %, while the bulk density was about 32 kg/m$^3$. The chopped kenaf was piled up near the field border and covered with a plastic sheet, waiting for loading up on a big trailer (model “walking floor”) and transporting it to KEFI. On April 2005, a visit of KEFI firm was planned, and it was possible to see the kenaf processing in two times: first the separation plant, in which the fiber is separated from the core, and second the fiber processing plant, in which the fiber is added to the polyester fiber and processing to obtain panels (Fig. 8.11).

## 8.6 Industrial Applications

According to the literature kenaf is being used for composites, building materials, paper and pulp production, absorbent materials, and animal bedding. In the framework of the BIOKENAF project a limited number of promising applications were selected for further research and testing. The choice of these applied topics was based on the market needs and the literature review. The under study topics were: (a) the quality of the fibers, (b) the use of kenaf fibers in insulation materials, and (c) kenaf core as absorption particles in animal bedding and oil spills.

### *8.6.1 Fiber Extraction and Fiber Quality*

It was shown that kenaf fibers could be extracted easily from kenaf stems that were harvested after winter without additional retting. Both on laboratory and

**Fig. 8.11** View of the harvesting (mowing-chopping) and storage trial in Trieste (Italy) and transportation to KEFI ITALIA premises (Source: CETA, BIOKENAF project)

industrial scale fiber extraction was carried out without any problems. After decortication the fibers still contained about 11 % (w/w) of core particles.

When stem retting is applied, fibers are affected by microorganisms during the winter period in the field, resulting in weaker fiber bundles with much heterogeneity. In tensile tests, the cell wall of the elementary fibers breaks apart because they are weaker than the bonds between the elementary fibers. No difference in fiber strength was found by additional warm water retting.

To ensure sustainable kenaf fiber business a broader range of applications must be developed by improving the quality of the fibers. Higher quality fibers can be achieved by developing improved retting and extraction processes.

### *8.6.2 Insulation Mats*

No problems were met in producing dry laid insulation mats made of kenaf fibers containing still 11 % (w/w) core particles. These kenaf fiber mats show a thermal conductivity close to commercial products made of other fibers. In spite of the quite high amount of core particles, the kenaf mats satisfy insulation properties.

In insulation mats made from natural fibres, the moisture absorption under humid conditions depends more on the applied additives like fire retardants than on the origin of the natural fibers.

Test shows that especially when application of fire retardants is required good ventilation on the outside of the mat is a necessity to avoid accumulation of moisture in the mat, resulting in microbiological growth and decay of the material.

### *8.6.3 Composites*

Test with kenaf fibers in PP compounds show acceptable strength properties. No differences were found in strength properties of kenaf/PP composites between kenaf fibers harvested before and after winter. However, because of the limited amount of kenaf fiber samples and tests performed, these experiments need to be confirmed. The tested composites of polypropylene with kenaf fibers can compete with other natural fibers on flexural strength properties.

### *8.6.4 Absorption*

Absorption experiments show that kenaf core particles have water absorption and water retention characteristics in the range of those of commercial animal bedding materials. The large kenaf core particles show higher water retention values, but this product contains still too much bast fibers and it is too coarse to be used as animal bedding. These large particles should be reduced in size at the beginning of the separation process.

Absorption experiments show that kenaf core particles can be used as oil spill absorber, but they need a size reduction to below 2 mm to be as efficient as other natural absorbers like straw, wood shavings, flax core, and hemp core. Kenaf/polyester mats show high absorption capacity for oil. They can be pressed out and reused at least six times without losing their absorption capacity.

## 8.7 Thermochemical Conversion and Ash Behavior of Kenaf

In BIOKENAF project the suitability of Kenaf feedstock for thermal conversion processes was investigated. Kenaf stem samples and core fiber produced after bast fiber removal have been tested for various thermal conversion applications. The thermal conversion experiments that were conducted are: (a) ash content and melting tests (b) combustion tests (c) gasification tests and (d) pyrolysis tests.

### 8.7.1 Ash Content and Ash Melting Tests

The behavior of ash derived from biomass can be a critical factor in all thermochemical conversion processes. An ash which fuses easily into a viscous liquid can form clinkers in the reactor or block the system. Additionally, part of the inorganics may appear in the gas phase causing an emission problem. Herbaceous energy crops like kenaf may contain relatively high amounts of ash, and its composition is quite different from woody biomass. The behavior of the ash under reactor conditions will strongly influence the selection of a conversion technology.

For the analysis of the ash melting behavior the standard Seger cone method (ASTM D2013–D3174) has been used. Ash melting tests have been performed in air and in a nitrogen atmosphere (inert). With the current set-up it was not allowed (safety reasons) to use a reducing atmosphere.

The measured ash content for Kenaf core material and whole plant material was 2.0 and 2.4 wt%, respectively, which is relatively low. This is favorable for energy applications. The ash content of the core material is close to that of the whole stem. This indicates that there was hardly any soil material in the samples.

For the technologies considered in this project the most important parameter is the IDT (Initial Deformation Temperature: start of melting range). The IDT of Kenaf is well above 1270 °C, which is high for an herbaceous energy crop. Both the Kenaf core and the fiber material show this high IDT. Other crops like *Miscanthus*, switchgrass, and giant reed have clearly lower IDT's. This means that for energy purposes Kenaf has a clear advantage for thermal conversion.

In literature there is quite some discussion on the relevance of the Seger cone method however. A sufficient high IDT is not a guarantee that conversion is trouble-free and actual conversion tests will therefore still be needed.

### 8.7.2 Combustion Tests

A fluidized bed combustion system has been used for the combustion tests. Biomass was stored in a hopper system, and fed into the combustor by a feeding screw and a transport screw. The combustor was a fluidized bed reactor containing an internal cyclone. Due to this internal cyclone the combustor could be operated over a wide capacity range (5–25 kg/h). The internal diameter of the bottom section was 0.2 m; the ID of the top section was 0.3 m. The height of the fluidized bed was about 0.8 m. The combustion experiments had been carried out at a relative low biomass feeding rate of about 4 kg/h to enable a sufficiently high air-to-biomass ratio.

With whole plant material the feeding was extremely irregular and the material frequently bridged in the hopper system. Appropriate data could not be obtained. Based on the composition of the whole plant material, it was expected that the high nitrogen content in the whole plant material might cause quite high NOx levels even in a commercial, optimized installation.

A series of experiments had been carried out with core material at varying air-to-biomass ratio (change in lambda). As expected the amount of NOx will increase with increasing air flow rate to about 200 ppm $NO_x$ for $\lambda = 1.3$. Under the combustion conditions used in the tests no thermal $NO_x$ is expected because the temperature is far too low (~750 °C). Based on the composition of Kenaf and assuming that all fuel bound nitrogen is converted into $NO_x$ a maximum content of 300 ppm $NO_x$ is expected.

### *8.7.3 Gasification Tests*

A fluidized bed gasification system was used for the combustion tests. The same fluidized bed system had been used for gasification as for the combustion tests; the only difference in operation was the biomass to air ratio. For the whole plant material it was difficult to maintain stable operation, because very often bridges were formed between the feed screw conveyor and the transport screw conveyor. The operation temperature was rather low (650–700 °C), due to the unstable operation because of feeding problems.

Roughly half of the energy ended up as chemical energy in the producer gas, which was rather low. About 10 % was found in the ash/carbon and tar, which can be reduced by optimizing the process at the benefit of the energy in the product gas. Part of the remaining energy will be left the reactor as sensible heat in the product gas (as in a real case) and via heat losses (which is typical for small-scale installations). Further improvement of the energetic efficiency could be realized by preheating the incoming air.

Chlorine could not be detected in the product gas. One explanation might be that chlorine was captured by calcium and/or magnesium. The measured sulfur and ammonia content might be rather high for direct use of the product gas in, e.g., a gas engine and further cleaning will be required.

With core material a very similar gasification experiment has been carried out. The operation was less interrupted than with whole plant material. It seems that the energetic efficiency was higher for core material, but might be due to experimental errors.

Whole plant material was considered as a difficult material to feed in the gasifier/combustor. For an industrial installation further pre-treatment might be desired. Core material could be used as such and no further pre-treatment was needed. The core material behaved very much the same as other energy crops like giant reed, switchgrass, and *Miscanthus*. Compared to wood it was more difficult to maintain a high temperature in the system due to its low bulk density. This could be overcome by a redesign of the feeding system.

### *8.7.4 Pyrolysis Tests*

A 5 kg/h test unit had been used for the pyrolysis tests. Fast pyrolysis technology was based on the rotating cone reactor. Biomass particles at room temperature and hot sand particles were introduced near the bottom of the cone where the solids were mixed and transported upwards by the rotating action of the cone. In the process bio-oil, char and gas were produced as primary products. Since no “inert” carrier gas was used the pyrolysis products were undiluted. This undiluted and hence small vapor flow resulted in downstream equipment of minimum size. In only a few seconds the biomass was transformed into bio-oil. Charcoal and sand are recycled to a combustor, where charcoal was burned to reheat the sand.

The water content in the bio-oil was rather high (~38 wt%), and strong phase separation was occurred. Water in the bio-oil came from water in the feedstock and water formed upon pyrolysis. Water—originating from the feedstock—could be further reduced by drying the feedstock. Water formed during the reaction was difficult to control. It is known that minerals in the feedstock might catalyze the pyrolysis reactions, and in general oil produced from grasses and agricultural residues contain more water than oil from woody biomass. The high water content of the oil caused the phase separation.

The oil had not been analyzed in detail, but based on the analysis of the kenaf quite some fuel nitrogen could be expected in the oil. Combustion of the kenaf oil might result in high $NO_x$ emissions.

The total oil yield was 49 wt%, which is relatively high compared to other energy crops (like *Miscanthus*, *Arundo*, Switch grass, straw ~45–55 wt%), but low compared to wood (~70 wt%).

## 8.8 Environmental Impact Assessment and Life Cycle Analysis of Kenaf Production and Use

The evaluation of the environmental sustainability of kenaf as a non-food crop through an integrated approach for alternative land use in the Mediterranean Region was carried out in the BIOKENAF project. The work aimed at addressing the sustainable yielding potential of kenaf, the alternative industrial bio-products as well as the fuel quality of kenaf as a non-food crop, under certain cultivation techniques, in South Europe.

In order to compare the ecological sustainability of production and use of kenaf among different sites in southern European regions and to compare the ecological sustainability of kenaf in southern European regions with the sustainability of other crops and of other conventional counterparts (e.g., fossil fuel), some ecological criteria were studied: replacement/conservation of fossil energy sources, emission of greenhouse gases and acidifying gases, effects on the quality of soil and water, use of resources, waste production and utilization, biodiversity and landscape.

In relation to the energy balance, for crop growth and utilization, this is assessed on the basis of a life cycle approach, considering the crop management and the several energy and industrial uses of the biomass. In the works of Fernando et al. (2008) and Correia (2011), based on the Biokenaf pilot field’s results, the utilization of biomass from kenaf plants to produce solid fuel as well as thermal insulation materials was analyzed. In those studies, a simple indicative scenario assumed that kenaf was grown on set-aside or on surplus agricultural land following CAP reforms (like grassland and tobacco cultivation). The outcomes suggest that the use of kenaf fibers for the production of energy or for the production of insulation boards are superior to their fossil or conventional equivalents in terms of energy saving. Several authors also indicate that by means of the same energy generating technologies, kenaf grants similar or higher energy savings to those reported for wood chips and wood pellets, hemp and cardoon but lower than those reported for herbaceous perennials, such as *Miscanthus*, or fiber and sweet sorghum (Venturi and Monti 2005; Cherubini et al. 2009). It was also stated that kenaf requires less energy and chemicals to process as pulp for paper than wood fibers (Webber 1993).

A further deep analysis on the Biokenaf results revealed that the energy balance is highly sensitive to biomass productivity (Correia 2011). The higher the yield of the crop, the higher is the energy efficiency of the system and the amount of fossil energy saved. Consequently, overall energy balance results are linked to the geographical position in the Mediterranean region, once a significant variation in yield was registered among the Biokenaf established sites in Europe. As the degree of mechanization of the various cultivation systems may also differ strongly in the Mediterranean region, the input energy can diverge substantially. Besides, although the energy balance is relatively insensitive to variation in cultivation, some crop management options, especially those that influence directly and significantly the productivity, may affect considerably the overall energy budget. The time of sowing and the level of irrigation are the main crop management factors that affect biomass yields and consequently the energy balance. So, these factors should be addressed particularly in the production phase. Accordingly, the best sowing date should be defined for each location in order to achieve positive and high energy savings (if this is the most important category to be considered). By opposition, irrigation of the fields is a highly energy demanding process. Thus, lowering the level of irrigation, to circa 50 % of potential evapotranspiration, despite the yields reduction observed with lower addition of water, increases the energy efficiency (Correia 2011). Several other factors may affect the amount of fossil energy sources replaced/conserved, such as the transportation distance, the conversion technologies, and its use for bioenergy or bioproducts.

In addition, on the basis of a life cycle approach, the magnitude of the greenhouse gas emission reductions from utilizing kenaf fibers as a source of electricity and heat or as thermal insulation boards was quantified based on the Biokenaf pilot fields results (Fernando et al. 2009). The study focused on processes and input materials which cause the main greenhouse gas emissions, and pointed out critical issues and steps with the highest improvement potentials. Results indicated that the use of kenaf natural fibers involves a significant reduction of the GWP when compared to the employment of their fossil or conventional counterparts and appears to represent an efficient land-use option for this purpose. The incidences of yields and irrigation on the eco-profile have been evaluated.

Net avoided emissions were relatively insensitive to variation in irrigation, but highly sensitive to stem yields. Transportation distance, processing and use, also affect the magnitude of the avoided emissions. The highest share of $CO_2$ emissions is caused by the fibers drying process (either as solid fuel and insulation mat) and by the manufacture of input materials and, in particular, of the polyester fibers (when kenaf fiber is used as a thermal insulation board). Net avoided emissions can be magnified if plants and residues are left in the field until moisture content is about 40 % (Fernando et al. 2009). In contrast, substitution of fossil fuels and materials through the use of kenaf is negatively associated with the acidification potential, especially due to the $NO_x$ emissions (Ardente et al. 2008). When used as a solid fuel, the acidification potential of kenaf is equivalent to that obtained with perennials due to its chemical composition. Nevertheless, the intensive management associated with kenaf as annual crop increments the acidifying emissions associated with its cultivation by comparison with perennials.

Benefits of this crop relies not only on the possibility of its use as a renewable raw material for energy and industrial purposes but also on the possibility to make good use of set aside land or even derelict land, limiting erosion risks. But, due to the short permanence period in the ground, it stands out to be as burdening as other annual crops regarding erodibility and biodiversity. Risks associated with losing soil quality and use of water, nutrients, and land are also comparable to most annual energy crops. Yet, kenaf can be considered as a more environmentally acceptable crop than other annual energy crops, since it requires fewer inputs (fertilizers, pesticides). Impact reduction strategies are limited to crop management options which can influence emissions, nutrient status, and resources depletion, as it was closely enlightened in Chap. 5. All other impacts are site-specific dependent, knotted with the crop traits. Therefore, the implementation of an environmental sustainable kenaf system should also be based on the fittingness between crop and setting.

## 8.9 Economic Analysis for the Crop Production Chain

The economics of production has a significant impact on the future potential of the crop. The costs of production, harvesting, transportation, storage, and separation determine the cost of Kenaf to the end-users. Although it may be technically possible to grow and utilize Kenaf, the products made from the fiber must be sold at an economic price compared to those based on other raw materials, and also give an economic return to farmers in comparison with other crops. In BIOKENAF project the production cost of kenaf cultivated in southern EU was investigated. The production cost of kenaf can vary greatly depending on where the crop is grown (need for fertilization, irrigation, etc.), farming practices (degree of mechanization) and the labor costs.

Although kenaf can be adapted to a wide range of soils, but obviously some soils will produce higher yields than others will. In some areas it may also require fertilization and irrigation to produce economic yields. The yield produced per hectare will affect the overall returns from the crop against which these costs are offset. As the production methods and costs influence yield, a cost benefit analysis of various treatments being studied was done.

Baseline costs of land preparation and crop establishment for Kenaf have been determined based on data produced from the BIOKENAF project and other Kenaf studies in the southern EU. In the economic analyses that have been carried most of the data were taken from four large kenaf fields with size 2 ha each that contacted in Greece (Komotini and Thessaloniki), Italy (Trieste), and Spain (Madrid).

The total production (from sowing to the harvest) in the four large fields is presented in Fig. 8.12. The total production costs varied from 558 euros/ha (Trieste-Italy) to 896 euros/ha (Komotini-Greece). The gross margin (without subsidies) was taken under consideration the production cost and the total revenues were presented in Table 8.2 for four sites in South Europe.

Market opportunities have been identified for Kenaf as a fuel, in the manufacture of paper, tea bags, and as a fiberglass substitute. Kenaf is also a viable

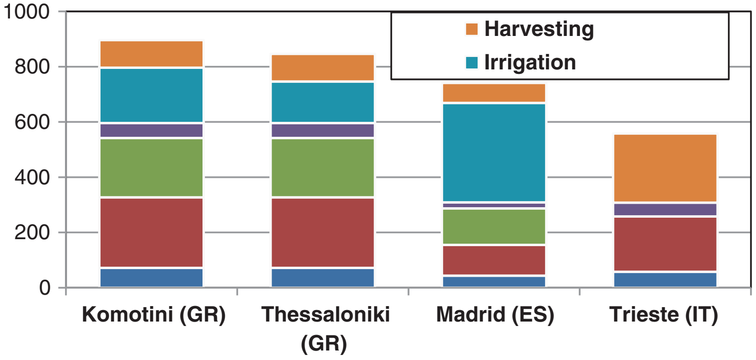

**Fig. 8.12** Production cost of kenaf (€/ha) in four different sites of south Europe (*Source* BIOKENAF project)

**Table 8.2** Gross margin for Kenaf (€/ha) (figures taken from actual inputs made to 2 ha areas of Kenaf grown within the project)

| Activity | Orestiada (GR) | Thessalonika (GR) | Madrid (ES) | Trieste (ES) |
|---|---|---|---|---|
| Production cost (euro/ha) | 895 | 845 | 741 | 558 |
| Revenue | | | | |
| Price (euro/tn) | 80 | 80 | 80 | 80 |
| Yield (t/ha) | 12.0 | 14.0 | 19.0 | 7.3 |
| Total revenues from sales (euros/ha) | 960 | 1120 | 1520 | 581 |
| Gross margin (euro/ha) (without subsidies) | 65 | 275 | 787 | 67 |

feedstock for chemical pulp mills for the production of specialty paper. High yields of 18 t/ha and above may be economically viable for Kenaf as an energy crop on large farms. Moderate yields of 14 t/ha will be economically viable for Kenaf if the product price is €80/odt. There is an opportunity to increase gross margins/ha by optimizing the seed, fertilization, and irrigation.

## 8.10 Conclusions

The recorded yields had great variation among the sites (from 6 in Paris to 24 t/ha in Madrid, mean yields around 12 t/ha). The achieved yields were recorded in harvests that carried out between end of November and beginning of January in order to have the lowest possible moisture content. Among the tested factors (varieties, plant density, sowing dates, irrigation, and fertilization) the most profound effect on yields and growth was recorded among the irrigation rates (in all sites) and the sowing dates (in most of the sites). The clearest effect of water to yields was recorded in Madrid.

A new dynamic crop growth simulation model named “BIOKENAF” was developed and it is able to predict kenaf phenology, growth characteristics (leaf area index, soil water balance, etc.), and biomass yields (stems, leaves, petioles) under a wide range of soil climatic environments in Europe. The model may successfully predict dry matter variation from over 22 t/ha to lower than 8 t/ha in the different European environments, performing a substantial sensitivity required in such broad predictions.

Harvesting kenaf in January by a machine used for maize it was easy and the chopped material was separated and insulation mats from the bark fibers were produced. The low density of the chopped material requires large volume buildings for storage. No fermentation process inside the pile was recorded during the storage period.

Kenaf can be used for many industrial uses but the question is which of them are economic viable. Separation of the stems is worthwhile if both stem fractions (bark and core) can be sold (bast fibers for insulation mats, core as absorber). It was found that kenaf pith has very high absorption absorbing 6 g water/1 g of pith. Kenaf pith absorbs 200 % more oil than kenaf core.

Kenaf core is a good material for combustion, while the whole plant has problems with feeding systems. Combustion of the whole plant gives high NOx emissions. The initial deformation temperature is higher (>1270° C) compared to other energy crops *Miscanthus*, switchgrass, giant reed) and this prevent ash melting problems at thermal conversion. Further optimization gasification to obtain higher efficiency. Additional drying and/or post treatment is needed to obtain a one-phase oil (pyrolysis as such is no problem).

Environmental benefits of this crop relies not only on the possibility of its use as a renewable raw material for energy and industrial purposes but also on the possibility to make good use of set aside land or even derelict land, limiting erosion risks. Kenaf can be considered as a more environmentally acceptable crop than other annual energy crops (such as sweet sorghum), since it requires fewer inputs (fertilizers, pesticides). Impact reduction strategies are limited to crop management options which can influence emissions, nutrient status, and resources depletion.

Market opportunities have been identified for Kenaf as a fuel, in the manufacture of paper, tea bags, and as a fiberglass substitute. Kenaf is also a viable feedstock for chemical pulp mills for the production of specialty paper. High yields of 18 t/ha and above may be economically viable for Kenaf as an energy crop on large farms. Moderate yields of 14 t/ha will be economically viable for Kenaf if the product price is €80/odt. There is an opportunity to increase gross margins/ha by optimizing the seed, fertilization, and irrigation.

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