Kenaf (*Hibiscus cannabinus* L.) fibre yield and quality as affected by water, nitrogen, plant population and row spacing

By

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DECLARATION

I, Polydor Kabeya Kayembe declare that the dissertation which, I hereby submit for the degree of Master of Science at the University of Pretoria, is my own and has not previously been submitted by me for a degree at this or any other University.

Signature:

Date:

DEDICATION

I wish to dedicate this piece of thesis to my parents, my wife and children for their sacrifices.

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ABSTRACT

Kenaf (*Hibiscus cannabinus* L.) is a highly productive crop that is cultivated worldwide for its fibre content which may be used to produce various commodities. The kenaf crop was commercially cultivated in South Africa in the 1950's, but production was discontinued from the 1960's up to the mid 2000's. Production commenced again and kenaf emreged as a "new" fibre crop with the first kenaf processing factory in the country going into production in 2006 in KwaZulu-Natal. Due to the importance of kenaf in manufacturing of various commodities, there was a need to investigate the agronomic practices thereof to ensure sustainable yield. Therefore a two year study (2008/09 and 2009/10 summers) was conducted in Pretoria to investigate the influence of nitrogen, plant population, row spacing and water treatments on kenaf growth, yield, chemical quality and microscopic analysis of the fibre. In total, four field trials were conducted at the Hatfield Experimental Farm of the University of Pretoria.

In 2008/09 a trial was conducted to investigate effects of plant population (200,000; 300,000 and 400,000 plants ha^{-1}), nitrogen level (0, 50, 100 and 150 kg

ha^{-1}) and row spacing (0.17, 0.34 and 0.50 m) under rainfed conditions. Sampling for growth parameters were done at 85, 113 and 126 days after planting (DAP). The biomass and chemical analysis of bark fibre were conducted only at or after the final harvest, at 126 DAP. In general, no clear effect of different treatment was observed on either parameter studied.

During 2009/10 three experiments were conducted. The first two had the same nitrogen levels as in the previous season, but were grown either under rainfed or irrigated conditions. The nitrogen was applied as two dressings of 0 and 50 kg ha^{-1} at planting and 0, 50 and 100 kg ha^{-1} at thinning (35 DAP). The third experiment investigated combinations of plant population (main plots) and row spacing (sub plots) under rainfed conditions. Due to increasing stem yield with increasing plant population during 2008/09, the lowest population of 200,000 plants ha^{-1} was left out and 500,000 and 600,000 plants ha^{-1} were added. The same three row spacings as in 2008/09 were used. Nitrogen was applied at 150 kg ha^{-1}, with 50 kg ha^{-1} at planting and 100 kg ha^{-1} at thinning. Growth and biomass parameters, water use efficiency (WUE) (nitrogen trial only) were subsequently measured up to the end of the growth cycle. The chemical characteristics of bark fibre and nutrient removal (nitrogen trial only), nutrient use efficiency as well as the nitrogen contents of leaves and stems were determined only once at final harvest. The number of fibre rings and fibre bundles were assessed only once during the growth cycle.

Growth and biomass parameters, WUE and both nutrient removal and nutrient use efficiency generally tended to increase with increase in nitrogen level under both rainfed and irrigated conditions. On the other hand, increasing plant population tended to result in a decrease in all growth parameters, while it increased biomass yield per hectare. Finally, the effect of row spacing was inconsistent for the same parameter from one sampling to another one, and from one parameter to another. The chemical characteristics of bark fibre showed inconsistent responses to all agronomic practices. The number of fibre rings and fibre bundles increased with increasing nitrogen level, decreased as plant population increased, but did not show clear trends with regard to row spacing. In general the plants grown under irrigated conditions performed better than those

grown under rainfed conditions. The results of this study revealed that under the environmental conditions of Pretoria, nitrogen levels above 100 kg ha^{-1} applied in two dressings should result in best plant performance, but most benefit could be obtained under irrigated conditions. A plant population of 500,000 plants ha^{-1} or higher and row spacing wider than 0.34 m proved to be most suitable for both growth and biomass parameters.

Key words: Kenaf, nitrogen, plant population, row spacing, irrigation water treatment, fibre, yield, chemical analysis

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CHAPTER 1.

INTRODUCTION

The Food and Agriculture organization (FAO) (2005) indicated that paper manufacturing accounts for about 14% of the total wood harvested over the world (including fuel wood), or about one-third of the world's total harvest of wood for industrial uses. South Africa is the only African producer of pulp and paper other than Swaziland, supplying in 15% of the World market demand (Anonymous, 2008). López-Belido *et al*. (2006) indicated that the use of non-woody faster growing species for papermaking may have a great advantage because they could provide a solution for environmental problems associated with the industrial use of soft and hard wood species. The potentiality of some of the fast growing plants for use as raw material for paper and cellulose industries has been studied intensively (Nelson *et al*., 1966; Cunningham *et al*., 1978; Kulkarni *et al*., 1985; Saikia *et al*., 1991&1997). According to López-Belido *et al*. (2006), the world production of cellulose from non-wood plants alone accounted for 10% of the total pulp production in 2000. Among the fast growing and non-wood species studied, kenaf (*Hibiscus cannabinus* L., Malvaceae) was found to be one of the most promising alternatives to supply cellulose to the paper and other industries. Kenaf has been reported to be three to five times more productive per unit area than pulpwood trees and produces a pulp that is equal or superior to many wood pulps (Theisen *et al*., 1978, LeMalieu *et al*., 2003). Kenaf is the third most economically important fibre crop after cotton and jute (United States Department of Agriculture: USDA, 1986). Furthermore, Alexopoulou *et al*. (2000) and Thi Batch *et al*. (2003) reported that kenaf has attracted increasing interest from the viewpoint of preserving the global environment and its significantly high rate of CO_2 accumulation. Another view from Bhangoo *et al*. (1994) stipulated that kenaf can lower soil salinity and make it more suitable for crop production due to its salt (boron and selenium) removal capacity.

Kenaf is a fast growing erect annual plant of tropical origin whose stem has traditionally been grown as a source of soft fibre and used as a substitute for jute (Crane, 1947). It is a herbaceous to woody plant, grown in many parts of the tropics and some sub-tropical and warm temperate areas (Abdul-Hamid *et al*., 2009). It is

adapted to a range of climate and soil conditions which is more extensive than that of many hard and soft wood species. The kenaf plant is composed of multiple useful components; e.g. stalks, leaves and seeds, and within each of these plant components there are various usable portions; e.g. fibres and fibre strands, proteins, oils and allelopathic chemicals (Webber *et al.*, 2002).

On the other hand, while being a key component in many countries' economy, agriculture is an ever-changing industry upon which everyone is dependent. Management practices to maintain yields while minimizing external input requirements is necessary in ensuring economic and environmental sustainability (Hill *et al*., 2006). However, productivity in agriculture ecosystem is severely reduced by various biotic and abiotic stresses (Boyer, 1982). Agricultural inputs such as nitrogen and water, and cultivation practices such as plant population and row spacing are among the key management processes in determining adaptability and biomass productivity for a crop under any given environment. Baldwin and Graham (2006) stated that due to the flexibility in the use of kenaf either for industrial applications or livestock feed, growers are challenged to modify agronomic practices to produce a crop in accordance with the demands of the consuming industry. It is also important to understand agronomical practices and cultivation in order to achieve high biomass at low production costs.

However, though considerable information on kenaf agronomy and biomass productivity has been reported worldwide, it is often conflicting as to the responses of the crop to different agronomic practices and cultivation. The yield and composition of kenaf plant components can be affected by many factors including cultivar, planting date, photosensitivity, length of growing season, plant maturity, plant population, row spacing and soil fertility (Webber *et al.*, 2002; Webber & Bledsoe, 2002 a & b; Archontoulis *et al*., 2005; Danalatos and Archontoulis, 2010; Hossain *et al*., 2011 a & b). Therefore, optimal agronomical practices for kenaf may vary according to production region, growing conditions, cultivar and the end use of the crop.

Furthermore, due to the scarcity of information on growth and productivity of kenaf planted in South Africa the commercial kenaf producers in the Winterton/Bergville

area implement a variety of cultivation and agronomical practices of plant population, row spacing and nitrogen application level. Using no scientific based practices can not only result in un-economical returns but also may have a negative impact on the environment, especially with respect to nitrogen fertilizers. Hence, research is needed to determine interactions among production practices for kenaf, and to determine the impact on growth components and yield composition through modifications of these practices.

The aim of the research was to:

- determine the sustainable yield potential of kenaf as a fibrous crop in Pretoria
- evaluate the effect of different agronomical practices on quantity and quality of kenaf raw material

Hypotheses

- Increased level of nitrogen and lower plant populations will have a positive effect on individual plant parameters in terms of growth, yield and fibre characteristics, while row spacing will have no effect on individual plant parameters
- Increased level of nitrogen and higher plant populations will have a positive effect on per hectare yield and water and nitrogen use efficiency, while row spacing will have no effect on the per area parameters
- Kenaf growth, yield and nitrogen use efficiency as affected by nitrogen will be lower under rainfed than irrigated conditions, while water use efficiency will be higher under rainfed conditions

CHAPTER 2.

LITTERATURE REVIEW

2.1 Overview on kenaf

2.1.1. Scientific classification

Kenaf (*Hibiscus cannabinus* L.) (Fig. 2.1.) is an important short-day annual plant with rapid growth and a single, straight and branchless stem, but if grown under wider spacings it may produce branches (Dempsey, 1975; Webber *et al.*, 2002). It is a warm season woody-herbaceous plant of the Malvaceae family (Danalatos & Archontoulis, 2010; Hossain *et al*., 2011a & b). Kenaf has a similarity to cotton (*Gosypium hirsutum* L.), okra (*Hibiscus esculentus*), hibiscus (*Hibiscus hibiscum* L.) and hollyhock (*Althaea rosea*) (Scott & Cook, 1988; Webber *et al*., 1999; Banũelos *et al*., 2002; Abdul-Khalil *et al*., 2010). The origin of the name kenaf is from Persian and is used to signify both the tall annual plant with large showy flowers, characteristic of the Mallow family, and the bark fibre obtained from the stem of that plant (Crane & Acuña, 1945; Dempsey, 1975). A list of over 120 common names which depend upon the linguistic area has been compiled for kenaf worldwide (Miyake & Suzuta, 1937; Sellers *et al*., 1993). As for example; kenaf or Deccan hemp (English); chanvre de Bombay, chanvre du Deccan (French); cânhamo rosella, juta de Java (Spanish); ambari, dekkanhanf (Germany), and stokroos (Afrikaans). This reflects the diversification and common uses of this fibrous species.

The scientific classification of kenaf can be presented as follows:

- Kingdom: Plantae (Planta, plants,)
- Division: Magnoliophyta (angiospermes, angiosperms, flowering plants)
- Class: Magnoliopsida (dicots, dicotyledons)
- Order: Malvales
- Family: Malvaceae (mallows)
- Genus: *Hibiscus* (hibiscus, rose mallow)
- Species: *cannabinus* (brown Indian hemp)

Fig. 2.1. Full grown kenaf plants under trial conditions (left) and kenaf flowers (right) at the Hatfield Experimental Farm, University of Pretoria (UP) (K.P. Kayembe, 2010)

2.1.2. Origin, environmental requirements and botany

Kenaf is reported to originate from east central Africa (LeMalieu *et al*., 1991), North Africa (Webber, 1999) or being endemic to Africa (El Bassam, 1998). It has been grown for several thousand years for food and fibre (LeMahieu *et al*., 1991), or cordage crop to produce twine, rope, and sackcloth (Wilson *et al*., 1965). According to Dempsey (1975) there is evidence of its domestication in the Sudan region since 4000 Before Christ (BC). However, other writers are of opinion that the plant is native to the East Indies (Dodge, 1897), Asia and Australia (Tobler, 1922).

Kenaf is generally grown as an annual plant but can become perennial in certain environments (Crane, 1947). It is a fast growing plant and has a high potential in terms of fibre or lignocellulosic material (Dempsey, 1975; Manzanares *et al*., 1997; Alexopoulou *et al*., 2000; Hossain *et al*., 2011 a). For example, it grows to more than three meters within three months even in moderate ambient conditions with a stem diameter of 25-51 mm (Aji *et al*., 2009), but under good conditions kenaf will grow to a height of five to six meters in six to eight months and produce up to 30 t ha^{-1} of dry stem material (Wood, 2003). The stem color of most varieties is green, but there are several red and purple stemmed accessions (LeMalieu *et al*., 1991).

It is a dicotyledonous plant meaning that the stem has three layers; an outer cortical (‘bark”) tissue layer called phloem, an inner woody (“core”) tissue layer called xylem,

and a thin central pith layer which consists of sponge-like tissue with mostly non-ferrous cells (Ashori *et al*., 2005) as can be seen in Fig. 2.2. The first two layers or regions; bark and core can be distinguished by their anatomical characteristics, chemical composition, and chemo-physical properties, and are considered as two distinct types of raw material (Mambeli & Grandi, 1995; Ohtani *et al*., 2001; Banũelos *et al*., 2002; Kuroda *et al*., 2005; Edeerozey *et al*., 2007). For example, the bark lignin is different from the core lignin in respect not only to the content but also the chemical structure (Neto *et al*., 1996). The bark portion comprises roughly 40 % of the stem's dry weight, while the inner fibre or core including the pith comprises 60% of the stem's dry weight (Voulgaridis *et al*., 2000; Sullivan, 2003 a & b; Chiaise *et al*., 2011). According to Dempsey (1975) the ratio between the amount of core: bark fibres is about 3:1. However, Neill and Kurtz (1994) indicated that this ratio varies due to cultivar selection and the agronomic practices employed to produce the crop. The outer portion or the bark contains long fibrous strands that are composed of many individual smaller soft fibres, while the central core of the stem contains weakly disbursed pith cells surrounded by a thick cylinder of short woody fibres (Stricker *et al*., 2006). Fibres from the bark portion of the stem are about 2.5 m long similar in length than that of softwood fibres while those from the core are shorter, about 0.6 mm long and resemble hardwood fibres (Sabharual *et al*., 1994; Lin *et al*., 2004). The fibres of kenaf are ligno-cellulosic in nature, multi-cellular with single cells embedded in a matrix composed of non-cellulosic matter, with lignin constituting one of the primary components (Sen, 2009). The bark fibres are of better quality than the core fibres; both of which can be utilized in various blends for the production of pulp (Petrini *et al*., 1994). The bark produces a high-quality pulp comparable to that produced from softwoods, whereas the core, richer in lignin, gives pulps with poor strength characteristics (Watson & Gartside, 1976; Watson *et al*., 1976). According to Karnani *et al*. (1997) the kenaf bark fibre has high potential as a reinforcing fibre in thermoplastic composites because of its superior toughness and high aspect ratio in comparison with other fibres. The bark fibre can be extracted by retting (Burkett, *et al*., 1949), by mechanical methods (Guterma, 1952), or by the combination of these methods (Bryom, 1951).

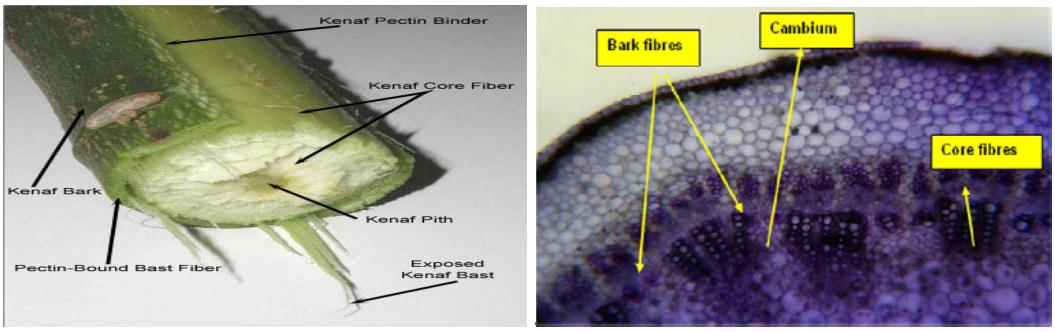


Fig. 2.2. Exposed physical appearance of a kenaf stem (Aji *et al*., 2009) (left) and a cross section through a kenaf stem (K.P. Kayembe, 2009) (right)

Kenaf plants have long effective taproot systems with relatively deep, wide-ranging lateral roots, which makes the plant drought tolerant (Grower's, 1989; LeMalieu *et al*., 1991).

Kenaf plants produce two general leaf types, divided (dominant characteristic) and entire (recessive characteristic) (Jones *et al*., 1955; Webber and Bledsoe, 2002 a & b; Stricker *et al.*, 2006) (Fig. 2.3.) which alternate on the stem. Stricker *et al.* (2006) indicated that the divided-shaped leaf closely resembles marijuana (*Cannabis sativa*) and can be mistaken for the illegal weed, while the entire-leaf type looks much like okra, and cotton. Divided leaf cultivars can produce three to ten entire juvenile leaves prior to producing the first divided leaf (Webber *et al*., 2002). Since cultivar and age of the plant affect the leaf shape, the juvenile or young leaves on all kenaf seedlings are simple, entire and cordate (Webber & Bledsoe, 2002 a). As a kenaf plant matures additional leaves are produced, and the newer leaves start to differentiate into the leaf shape characteristics of that particular cultivar (Webber & Bledsoe, 2002 a; Stricker *et al.*, 2006). The divided (split-leaf) cultivars have deeply lobed leaves with three, five, or seven lobes per leaf, for example "Everglades 71", "Tainung 1", "Tainung 2". The entire leaf cultivars produce leaves that are shallowly lobed, and basically cordate (heart-shaped) for example "Everglades 41", "Guatemala 4", "Cuba 108", and "Cuba 2032" (Webber *et al*., 2002). Each leaf also contains a nectar gland on the mid-vein on the underside of the leaf (Dempsey 1975).

Fig. 2.3. Kenaf leaf types; divided leaf (left) and entire leaf (right) (Annymous, 1963; http://www. Davesgarden.com)

Kenaf cultivars differ in their sensitivity and response to day length (Webber *et al*., 2002). The influence of latitude (day length) is fundamental in selecting the ideal cultivar for the production location and the intended use of the crop (Webber & Bledsoe, 2002 a & b; Webber *et al*., 2002). Furthermore, it has been indicated that to avoid reduced growth associated with flowering and fruit formation, it is recommended that the day length be greater than 12.5 hours during the growing season (Rehm & Espig, 1991).

Based on their photosensitivity, kenaf varieties are divided into two major groups; photosensitive and photo-insensitive cultivars;

- Photosensitive varieties, classified as short-day plants are referred to as early to medium maturity cultivars, and are typically preferred for use in the production of fibre in the United States (Webber *et al*., 2002). According to Scott (1982) and Stricker *et al*. (2006) photosensitive cultivars initiate flowering when day length decreases to approximately 12.5 hours. Three of these varieties are: “Tainung 2”, ‘Everglades 41’ and ‘Everglades 71’.

- Photo-insensitive varieties or late maturing (also referred to as day-neutral) cultivars are ideally suited for the latitudes surrounding the equator, 0° to 10° N or S may be suited for use as forage or livestock feed crops within USA (Webber & Bledsoe, 2002 a). Dempsey (1975) indicated that although these cultivars are considered as photo-insensitive, they may still be responsive (semi-sensitive) to day length for flowering initiation. Some photo-insensitive cultivars are “Guatemala 4”,

"Guatemala 45", "Guatemala 48", "Guatemala 51" and "Cuba 2032" (Webber & Bledsoe, 2002 b).

Kenaf plants produce large showy light yellow to creamy-colored flowers that are bell-shaped and open widely, only after day length reaches approximately 12.5 hours in the fall (Webber *et al*., 2002; Coetzee, 2004) (Fig. 2.4). The flowering period of all the cultivars can last three to four weeks or longer. The flowers have a deep red or maroon colored centre, and they open and close within a single day (Webber & Bledsoe, 2002 a & b; Webber *et al*., 2002; Sullivan, 2003 a). Once pollinated, the seeds require four to five weeks to mature (Crane & Acunã, 1945). The plants are generally considered self-fertile, cross-pollinated crops (LeMahieu, 1991; Webber *et al*., 2002). Following pollination, a pointed, ovoid, seed capsule (Fig. 2.5. left) is formed that is about 1.9 to 2.5 cm long and 1.3 to 1.9 cm in diameter. The seed capsules are covered with many small, fine, loosely held, hairy structures that are very irritating to the human skin (Webber *et al*., 2002). Each capsule (fruit) contains five segments with a total of 20 to 26 seeds per capsule (Dempsey, 1975). The seeds are brown, glabrous, wedge-shaped, approximately 6 mm long and 4 mm wide (Fig. 2.5 right) (Webber *et al*., 2002). The average 1000-seed weight range between 25 to 27 g, with 1 to 28 g of seed per plant.

It has been reported that kenaf seed has a high oil content of 21.4 to 26.4%, averaging at 23.7% (Mohamed *et al*., 1995). Freshly harvested kenaf seed have a germination percentage of about 98 % (Coetzee, 2004). However, as with other crop seeds containing high oil percentages, seed viability decreases over time when stored at high relative humidity and temperatures (Webber *et al*., 2002). Kenaf seed should be stored in airtight containers, under refrigeration or at least in an area of low humidity (Dempsey, 1975). It is also important to properly clean and condition the seeds after harvest to maintain high seed viability (Scott & Cook, 1995).

Fig. 2.4. Flowers of kenaf (Courtesy of Tolibaev *et al*., 1986)

Fig. 2.5. Kenaf fruits (left) and seeds (right) (Courtesy of Tolibaev *et al*., 1986)

The kenaf plant is said to have a wider range of adaptation to climate and soil than any commercial produced fibre plant (Caldwell, 1936; Dempsey, 1975; LeMalieu *et al*., 1991; Meints & Smith, 2003; Aji *et al*., 2009). Dempsey (1975) indicated that kenaf can be grown at latitudes from 16ºS to 41ºN with a mean relative humidity range of 68-82% and temperatures during the growing season from 23 to 30ºC. Another writer stated that kenaf is grown between 45ºN and 30ºS, which consists mainly of the warm temperature zone of the Equator, with a maximum elevation of approximately 500 m (El Bassam, 1998). However, kenaf is also found growing wild in Africa from the Equator to a latitude of 30ºN and 30ºS at altitudes up to 1250 m (Coetzee, 2004). This wider adaptability of kenaf in comparison to jute, explains the interest that this crop has arosed in countries where jute cultivation has proved difficult (Geus, 1967).

According to Villar *et al*. (2009), under appropriate temperature, irrigation and fertilization conditions, kenaf can grow in warm temperate regions (e.g. Mediterranean countries), as well as in the more favorable tropical and subtropical

areas, some of which can result in two harvests in one year. Kenaf yields are the highest in regions with high temperatures, a long growing season and abundant soil moisture (LeMalieu *et al*., 1991). Crane (1947) pointed out that 500-625 mm of rainfall over a period of 5-6 months is essential for a successful production of kenaf fibre. This view is strengthened by Dempsey (1975) who indicated that during the growing season, a well-distributed rainfall of 100-125 mm per month is necessary for proper kenaf growth. According to Bhangoo *et al.* (1994) under low-rainfall conditions adequately and timely irrigation should be applied.

Killinger (1969) pointed out that the growth of kenaf is limited by the number of frost-free days, fertility, moisture, and sunshine, length of growing season, and the average day and night temperatures. In regard to frost, LeMalieu *et al*. (1991) found kenaf plants to be quite sensitive to cool temperatures and grow slowly when temperatures are below 10°C. According to Ramaswamy *et al*. (1999) frost kill is often associated with fungal growth or rot, so its effect on fibre quality is a major concern. Hence, due to the fact that kenaf is frost sensitive, the crop management must be planned in such way that the growth cycle can end before the first frost.

Despite the fact that kenaf can be grown successfully in a wide range of soil types, from high organic peat soils to sandy desert soils (Dempsey, 1975), it grows best in well drained, light sandy loam soils or sandy clay loam soils with pH of 6.0-6.8, good organic matter content and good water-holding capacity (Geus, 1967). It does not perform well in soils with severe drainage problems, and prolonged periods of standing water, particularly during the seedling stage (LeMahieu *et al.*, 1991). However, the crop can withstand late season flooding (Dempsey, 1975). Kenaf has also been shown to respond in a manner that is typical of a moderately salt tolerant non-halophyte (Francois *et al*., 1992).

2.1.3. History

Crane (1947) reported that although an interest in kenaf as a source of soft fibre has developed in the western hemisphere mainly within the last five years, fibre from this plant has been used in other parts of the world for many years. For example, kenaf has been used for centuries as a source of fibre (similar to hemp, jute or sisal) for manufacturing twine, cloth and other similar products in India and Africa (Killinger, 1967). It is reported that India has produced and used kenaf for only the last 200 years, while Russia started producing it in 1902 and introduced the crop to China in 1935 (Dempsey, 1975). In Russia considerable attention to kenaf has been directed towards determining the cultural requirements, developing of methods of extracting the fibre and adapting processes for spinning and weaving the fibre (Crane, 1947).

In the United States, kenaf research and production began during World War II to supply cordage material for the war effort (Wilson *et al*., 1965). Webber *et al*. (2002) stated that the war not only interrupted foreign fibre supplies from countries such as the Philippines, but the US involvement in the war also increased the use of these fibres by the US army. This lead to a program started in 1943 by the USDA and the Cooperative Fiber Commission (CFC) in Southern Florida to determine the feasibility of growing, harvesting and processing kenaf for cordage fibres for making rope, matting, and bags (Stricker *et al*., 2006). Their effort resulted in the development of high yielding cultivars with resistance to anthracnose (*Colletotrichum hibisci*) (Taylor, 1984). In the mid 1950's and early 1960's the USDA, after evaluating 506 plant species to fulfill future US fibre demands, determined that kenaf was an excellent source of cellulose fibres for a large range of paper products (newsprint, bond paper, and corrugated liner board) (Mayberry, 1988; Webber & Bledsoe, 2002 a). Printing and writing paper made from kenaf fibres has been up for offer in the United States since 1992 (Webber & Bledsoe, 2002 a & b). The view from Nieschlag *et al*. (1960) and Miller (1965) indicated that kenaf has showed promise as an annual pulp crop for production of paper in the United States. In the same line Abdul-Khalil *et al.* (2010) reported that due to the fast growth and good fibre quality, there has been increasing interest in kenaf, primarily for its potential use as a commercial fibre crop for the manufacture of newsprint and other pulp and paper products.

The kenaf crop was commercially cultivated in South Africa in the 1950's, but production was discontinued from the 1960's up to the mid 2000's. Production commenced again as a new fibre crop with the first kenaf processing factory in the country going into production in 2006 in KwaZulu-Natal. The kenaf fibre bales from this factory were mostly exported to the automotive industry in Europe (Liu & Labuschagne, 2009). According to Coetzee (2004) the Sustainable Projects Development Group (SPDG) (Ltd) of the Coach House Group of the United Kingdom chose South Africa for the establishment of a bio-composites project due to the excellent cultivating conditions of the crop in KwaZulu-Natal. Accordingly Kwazulu-Natal (Winterton) and "Tainung 2" were chosen as the suitable area and cultivar by the Agriculture Research Council (ARC) (Malan, 2011).

Although kenaf originated from Africa its production in this continent is very low. For example in 2002, the total production in Africa was only 2.9% of the total global production (FAO, 2003). As pointed out by the FAO (1998) kenaf is now commercially cultivated in more than 20 countries, particularly in China, India, and Thailand which represent 90% of the sown area and more than 95% of the total production in the World (Table 2.1) (FAO, 2003).

Table. 2.1. Global production of kenaf (10^3 tonnes) (Adapted from FAO, 2003)

Region	1996	1997	1998	1999	2000	2001	2002
Far East	703.9	763	500.3	409.1	372.1	393.8	383.7
China	364.9	429.5	248	164	126	136	130
India	210.4	198.7	182.2	196.2	198	203.4	202.1
Thailand	109.3	106.4	47.2	29.7	29.6	29.5	30.0
America	31.0	28.8	27.1	25.4	24.1	23.7	26.7
Vietnam	15.0	22.3	14.6	9.4	11.3	14.6	14.6
Africa	13.9	14.2	13.8	14.3	12.7	12.5	12.4
Near East	5.1	5.2	4.2	3.7	3.6	3.6	3.6

2.1.4. Potential uses of kenaf fibres

Kenaf, as a high yielding plant is generally known for its bark (outer) and core (inner) fibres (Dempsey, 1975). Because of its rapid growth and elevated fibre content, kenaf is considered as a new choice of natural fibre for industrial use (Woolf, 1993). Kenaf bark and core fibres each have desirable qualities; as a result, separate markets have been developed for the two types of fibre (Stricker *et al*., 2006). Kenaf can, amongst be used as; fibre, food (Dempsey, 1975), medicine (Cheng, 2001), food additive (Hossomi, 2000), medium for mushroom cultivation (Cheng, 2001; Liu, 2003), environmental cleaning agent (Lam, 2000), and oil and chemical absorbent (Sameshima, 2000). Kobaisy *et al*. (2001) and Agbor *et al*. (2005) noted that the kenaf plant is composed of various active chemical components including tannins, saponins, polyphenolics, alkaloids, essential oils and steroids, and has long been prescribed in traditional folk medicine in Africa and India. Kenaf seeds contain various bioactive constituents such as fatty acids, phenolic acids, phytosterols and tocopherols (Coetzee *et al*., 2008 a & b) with numerous industrial applications. The residues from different industrial processes can, as well, be utilized as energy sources (El Bassam, 1998). The whole kenaf plant can also be used as biomass for energy and as a substitute for non-renewable resources (Alexopoulou *et al*., 2000). Additional potential uses in manufactured products include automobile dashboards, carpet padding, and corrugated medium (Kugler, 1988). Kenaf can also be used as fibreglass substitute, blended with cotton and other synthetic fibres (Scott & Taylor, 1988), textiles (Ramaswamy & Boyd, 1994), and as fibres for injected molded plastics (Webber & Bledsoe, 1993). More recent research and development work in the 1990's has demonstrated the plant's suitability for use in building materials (Francois *et al.* 1992).

However, the end use of kenaf fibres primarily depends on their physical, structural and chemical properties, and the fibre portion used (Sullivan, 2003 a). For example, the morphology of the fibre cells ultimately indicates their suitability of utilization in the manufacture of different types of paper (Maiti, 1973). The bark is processed into high quality paper pulp due to the low content of both woody impurities and pectins (Manzanares *et al*., 1997; Webber & Bledsoe, 2002 a & b), while lower quality paper can be made from the short wood fibres of the inner core (Manzanares *et al*., 1997).

The bark fibres are used for specialty papers, tea bags, and grass mats (biodegradable mats impregnated with grass and/or flower seeds) (Striker *et al*., 2006), newsprint and multiple tissue paper grades (Bowyer, 1999). Because of the limited range and low value of products produced from core material and its high lignocellulose content, core fibres have the potential as a biomass conversion feedstock (Murphy *et al*., 2007) and as a replacement for vermiculite and Styrofoam packaging material (Young, 1992). Researchers have investigated the use of kenaf core as an absorbent material (Goforth, 1994), as well as poultry litter and animal bedding (Shi & Pill. 1993). The entire kenaf plant, stem and leaves can be used as a livestock feed (Stricker *et al*., 2006), bulking agent for sewage sludge composting (Webber, 1994), as a potting soil amendment (Laiche & Newman, 1994), and for anti-erosion mats (Fisher, 1994 a & b). Phillips *et al*. (1996 & 1999) pointed out that mature plants are harvested for use in the fibre industry, but immature plants have been used as a high-quality feed for livestock. The protein in immature kenaf are more soluble than the protein found in alfalfa (Suriyajantratong *et al*., 1973), which may alter ruminal dry matter (DM) digestion and DM indigestion (Koster *et al*., 1996).

Kenaf leaves are rich in calcium and phosphorus and have appreciable amounts of Vitamin C (Kobaisy *et al.,* 2001) and crude protein (Killinger, 1969). Suriyajantratong *et al* (1973) found that kenaf leaf meal compared favorably with dehydrated alfalfa meal as a supplement to rice straw for sheep. The seeds are rich in essential fatty acids and calories (Kobaisy *et al.,* 2001), and can be used for cooking (flour) and lubrication, soap manufacture, linoleum, paints, and varnishes (LeMahieu *et al*., 2003). The content of edible oil of kenaf seeds compares favorably with cotton seed oil and can be used for making margarine and protein stock feed (Berger, 1969). The cake obtained after oil extraction can be used for compounding animal feed (Echekwu & Showemimo, 2004). The vegetable oil contents of some crops including that of kenaf are given in Table 2.2.

Table 2.2. Production of vegetable oil of some crops (Adapted from Addison, 2013: http://www.journeyforever.org/biodiesel_yield.htm)

Crop	Liter oil per ha	Crop	Liter oil per ha
Maize	172	Soybean	446
Oats	217	Coffee	459
Kenaf	273	Rice	828
Cotton	325	Sunflower	952
Hemp	363	Cocoa	1059
Soybean	446	Olive	1212

2.1.5. Advantages of kenaf fibres

The advantages of kenaf as a source of pulp and paper making include; short growing cycle (120 to 130 days) as compared to thirteen to sixteen years for trees; and it lends itself to two crops a year under certain conditions (FAO, 1968). Kenaf has also attracted increasing interest from the viewpoint of preserving the global environment because of its high rate of CO_2 accumulation as compared to forests (Thi Bach *et al*., 2003). It also plays an important role as an alternative to wood fibre in the pulp and paper industry to avoid destruction of forest habitats while being considerably less polluting and environmentally destructive (Maiti, 1973; Sabharual *et al*., 1994; Kuroda *et al*., 2005). It can easily be grown even under severe conditions such as low water supply and little fertilizer availability (Kuroda *et al*., 2005).

In paper and pulp production lignin is an undesirable polymer and its removal during pulping requires high amounts of energy and chemicals. From this point of view kenaf offers the advantage of having a low lignin content resulting in reduced energy and chemical use during pulping (Hurter & Riccio, 1998; Webber *et al.,* 2002). The success of kenaf in papermaking is as a result of its high yield per hectare (about 20 t DM ha^{-1} $year^{-1}$) and low lignin content of its bark fibres, which provide paper with a strength exceeding that of paper from conifer fibres (Villar *et al*., 2001; Khristova *et al*., 2002; Ashori *et al*., 2005). Studies in the USA have shown that the stems of kenaf can be used to produce a pulp superior in strength characteristics to hardwood pulp and, except for resistance to tear, comparable with softwood pulps (Clark *et al.*,

1962). Francois *et al.* (1992) reported that the economic potential of kenaf is related to a gradual diminishing supply of hardwoods and softwoods in the world, and the increasing per capita consumption of paper and paperboard material. Kenaf can either be pulped alone or blended with recycled paper or used as virgin pulp (Liu, 2003). Finally, paper made from kenaf fibre is stronger, whiter, longer lasting, and more resistant to yellowing and has ink adherence better than that of wood paper (Liu, 2003).

Regarding the agricultural community, kenaf provides an additional option in crop rotation (Rymsza, 2004). Kenaf can be grown successfully in rotation with other crops such as soybean (Webber, 1999; Joordan *et al*., 2005); maize, cotton, peanut, and tobacco (Joordan *et al*., 2005). The advantage of such rotations is that it could have a major impact on pest development and yield of crops in the rotation (Joordan *et al*., 2005). Kenaf can also be intercropped with cowpea and sorghum (Raji, 2007); maize (Adeniyan *et al*., 2007), or alley cropped with leucaena (Gutteridge, 1988). Finally, kenaf plants can be a source of natural occurring allelopathic chemicals that prevent or inhibit weed seed germination and weed growth, and therefore could provide safe and economic means of inhibiting weed competition in vegetable and agronomic crops (Webber & Bledsoe, 2002 a & b).

2.2. Production of kenaf

2.2.1. Establishment

Soil fertility is one of the important aspects in kenaf production as it can significantly affect all plant components (stems, leaves, and seeds) (Webber & Bledsoe, 2002 a & b). Warm, moist soil, after the danger of a killing frost has passed, are ideal planting conditions (Webber *et al*., 1999). According to LeMalieu *et al*. (1991) recommended planting dates for kenaf are similar to those for soybeans. Planting too early often results in poor emergence and slow, non-competitive growth, while planting too late will often result in reduced yield potential due to reduced solar radiation availability (LeMalieu *et al*., 1991). Crane (1947) indicated that due to the fact that some kenaf varieties are extremely sensitive to changes in day length, an ideal planting date at a location of given latitude might result in poor yields if used in

another location of different latitude. He also added that the most suitable time of planting for fibre production in one location might possibly be the most ideal time of planting for seed production in another location depending on the latitude (Crane, 1947).

Kenaf responds well to good soil preparation and therefore a well-prepared seedbed is needed (Stricker *et al*., 2006). If there is heavy vegetation it should be mowed or treated with a herbicide or burned (Stricker *et al*., 2006). Another writer is of view that the soil should be deeply and thoroughly worked in order to provide a good medium for seed germination and to insure proper soil aeration for the seedlings that follow, which also best suits the root system (Crane, 1947). Kenaf is most commonly propagated by seeds. Planting can be accomplished by using standard equipment in a wide range of row spacings, and can be planted on raised beds or on flat ground (Webber *et al*., 1999). Webber *et al*. (2002) reported that kenaf and grain sorghum (*Soghum bicolour* L.) seeds are similar in size, and therefore kenaf is often planted using grain sorghum planting plates in commercial planters. Planting depth should be in the range of two to four centimeters (Webber *et al*., 2002; Stricker *et al*., 2006). LeMalieu *et al*. (1991) and Stricker *et al*. (2006) indicated that when planting, efforts should be made to get good seed-soil contact. Plants will emerge within two to six days if optimal conditions (temperature and moisture) are available in the soil (Webber *et al*., 1999; Stricker *et al*., 2006).

Kenaf's response to added fertilizer depends on initial soil nutrient levels, cropping history and other environmental and management factors (LeMalieu *et al*., 1991). For fibre production the stems are harvested after the leaves have dropped off the plant (Stricker *et al*., 2006). The leaves, rich in nitrogen, could return about 27 kg to 54 kg nitrogen to the soil (Bhangoo *et al*., 1986) depending on agronomic input and management.

Stricker *et al*. (2006) indicated that in phosphatic clay, a kenaf crop will need nitrogen at the rate of 109 kg to 127kg ha^{-1}, while they propose 127 kg to 145 kg nitrogen ha^{-1} for sandy soils. In both cases nitrogen fertilization must be applied in a split application as follows 36 kg nitrogen ha^{-1} pre-planting and the rest applied before the plants become too large for field access.

2.2.2. Weed control

Kenaf is a vigorous growing plant and under optimum growing conditions the canopy can cover the soil in as little as five weeks (Neill & Kurtz, 1994), shading low growing weeds and grasses and reducing the need for additional weed control (Stricker *et al*., 2006). However, initial weed control is often required in order to obtain optimum kenaf yields (Webber *et al*., 2002). According to Williams (1966) weed competition, with moderate weed pressure, reduced stem yields during one season by an average of 1.0 t ha^{-1}.

With respect to herbicides, it has been reported that many herbicides originally evaluated for use in kenaf production are either no longer available, phytotoxic to kenaf, or reduced kenaf plant populations (Orsenigo, 1964; Sparkes, 2005). According to Sparkes (2005) Fusilade is registered for post-emergent control of grasses in the USA. Webber *et al*. (2002) and Sparkes (2005) also pointed out that there are a number of efficacious pre-emergence herbicides that have registration potential for kenaf, including metolachlor, trifluralin and pendimethalin. Yet, in the absence of herbicide registration for kenaf, and particularly in cooler climates which inhibit rapid early plant growth, mechanical weed control should be used (LeMalieu *et al*., 1991).

Furthermore, to the best of our knowledge so far no chemical is registered for weed control in kenaf production in South Africa. However, Malan (2011) conducted pot trials to screen the available herbicides in South Africa in order to determine the sensitivity of kenaf to them. From these results (Malan, 2011), It was showed that kenaf exhibits least sensisitivity for the pre-emergence herbicides such as imazethapyr, pendimethalin, S-methachlor, and the combination of imazethapyr and S-methachlor.

2.2.3. Pest control: Nematodes, insects and diseases

One of the greatest problems affecting kenaf production is plant parasitic nematodes, particularly root-knot nematodes (*Meloidogyne* spp) (LeMalieu *et al*., 1991; Striker *et al*., 2006). In cotton growing areas, the root-knot nematode/fusarium wilt complex is expected to limit yield potential for both cotton and kenaf, and will create crop rotation challenges due to the common susceptibility of the two crops (LeMalieu *et al*., 1991). The degree of infestation will largely depend on the nematode population at planting, susceptibility of cultivar grown, and the standard of management (Crane, 1947). The Grower's handbook for kenaf production (1989) indicated that at the present time, no kenaf varieties are considered resistant to nematodes. According to Striker *et al*. (2006) Telone II, a soil fumigant is registered for use on kenaf but it may be too expensive to use. However, kenaf is a poor host for nematode species found in sugarcane, particularly root lesion nematodes (*Pratylenhus zeae*), and therefore may have a net positive effect in improving the 'health' of sugarcane soils if introduced in such a rotation system (Sparkes, 2005).

There has been little economic damage to kenaf by insects in experimental production fields. However, main insects causing defoliation in kenaf are the red-shouldered leaf beetle and a number of looper caterpillar species (Sparkes, 2005).

Though kenaf is resistant to most plant diseases (LeMalieu *et al*., 1991) anthrachnose is one of the serious diseases occurring in the crop. Fortunately USDA plant breeders were successful in breeding and selecting kenaf cultivars and accessions for resistance against anthrachnose (Stricker *et al*., 2006). Damping-off is of moderate concern during the seedling stage and seed treatments should be considered (LeMalieu *et al*., 1991). The Grower's handbook for kenaf production (1989) stipulated that both Everglades 71 and 41 are highly resistant, as are Tainung varieties, and lines developed in Cuba and Guatemala. Other diseases that attack kenaf are foot-rots which generally result in the death of the plant (Crane, 1947). According to Sparkes (2005) there appears to be considerable variation between kenaf varieties in their susceptibility to diseases. Good crop management as well as crop rotations play an important role in the incidence and severity of many diseases affecting kenaf.

2.2.4. Methods and time of harvesting of kenaf fibre

The evaluation of field equipment for harvesting kenaf continues to be an important aspect of commercialization (Webber *et al*., 2002). The harvest method depends on the production area, equipment availability, processing method, and final product use (Webber *et al*., 1999). In hand harvesting, the plants can be cut at ground level or uprooted (Caldwell, 1936). It has been demonstrated that standard forage cutting, chopping, and baling equipment can be used for harvesting kenaf as either forage or fibre crop (Webber & Bledsoe, 1993). Sugarcane harvesters, with and without modification, have also been successfully used to harvest kenaf (Webber *et al*., 1999). In cotton growing regions, cotton modules have been used for field-side storage of chopped kenaf (Fuller & Doler, 1994). According to Webber *et al*. (1999) when harvesting kenaf for fibre use, consideration of the moisture content is also of importance.

Kenaf can be harvested for fibre when it is dead, due to a killing frost or herbicides, or when it is still growing. Actively growing kenaf can be cut, and then allowed to dry in-field. Once dried, the kenaf can be chopped, baled with forage equipment (Broadway, 1990), or transported as full length stems (Webber *et al*., 1999). Crane and Acunã (1945) pointed out that the percentage of fibre in the stem increases until the time of flowering and then remains approximately the same. So the highest quality fibre is obtained when kenaf is harvested at the onset of flowering. This will lead to best results as far as yield and separation of the fibre from the stem is concerned (Crane, 1947; Webber *et al*., 2002; Sparkes, 2005). If done before flowering, lower fibre yields are obtained, and if done after flowering, the fibre is of poorer quality (Webber *et al*., 2002). In addition, Crane (1947) indicated that with the first formation of seed capsules on the stem, the fibre adheres to the pith more firmly than fibre in plants harvested earlier (Crane, 1947). In conclusion it is strongly recommended that kenaf harvested for fibre should be made during the early onset of flowering.

2.2.5. Kenaf fibre extraction

According to Crane (1947) there are various ways to extract the fibre from kenaf stems, all of which involve retting in water, except, of course, when power-driven decorticating machines are used. In the process of fibre extraction, kenaf leaves are separated from the stems, and the stems are sun dried; then submerged in a retting tank. The length of the retting period varies from five to 22 days (Caldwell, 1936). According to Crane (1947) the variation in retting period length is caused by the greatly divergent environmental conditions under which the plants are grown, the stage of maturity, temperature of the retting water, and many other interrelationships that are not always considered or controlled. The retting process is considered complete when the bark can be separated easily from the core. The fibre bundles can be removed manually from the core and dried in the sun. With the use of machines, bundles of kenaf are brought directly from the field when harvested and put into the decorticator. The central woody part, water and waste material from the plants are scraped away, leaving the clean fibre which is then sun dried (Crane, 1947). A study with hemp indicated that water retting produces fibre of greater uniformity and higher quality than can be produced by field retting (Fuller *et al*., 1946 a & b). Hessler (1945) pointed out that the control of the factors affecting field retting is very difficult, and fibre quality from field retted stems can vary greatly with prevailing environmental conditions during retting.

CHAPTER 3.
EFFECT OF PLANT POPULATION, NITROGEN APPLICATION LEVEL AND ROW SPACING ON KENAF GROWTH COMPONENTS AND YIELD

3.1. Introduction

Although kenaf is adapted to a range of climate and soil conditions, Boyer (1982) indicated that productivity in agriculture ecosystem itself is severely reduced by various biotic and abiotic stresses. Individual plants are facing different levels of competition in their environment. The competition may be for space, light, soil nutrients or water. Competition among individual plants occurs when two or more plants need a particular factor necessary for growth, or when the immediate supply of that factor is below the combined demand of the plants (Milthorpe & Moorby, 1974, Morrison *et al*., 1990).

Furthermore, the competition may be increased by using inappropriate management practices, such as increasing plant population, inadequate supplying of nutrients and to some extent by using unsuitable row spacings. For example, too little nitrogen retards leaf growth (Milford *et al*., 1985), accelerates leaf senescence (Burkcy & Biscoe, 1983) and thereby reduces the amount of solar radiation intercepted and thus yield (Werker & Jaggard, 1998). Conversely, too much nitrogen causes over production of leaves (Milford *et al*., 1988), with little benefit in terms of additional radiation interception (Scott *et al*., 1994), imposing a decrease in the proportion of assimilates stored as sugar (Milford & Watson, 1971).

However, due to the fact that agriculture itself is an ever-changing industry over time and across different environments, Grosbach (2008) indicated that producers are always looking to improve their production practices to make the most efficient use of inputs and resources in order to increase production and maximize profit. According to Hill *et al*. (2006) management practices to maintain yields while minimizing external input requirements is necessary in ensuring economic and environmental sustainability. Furthermore, agricultural inputs such as nitrogen fertilizers and

cultivation practices such as plant population and row spacing are among the key management practices in determining adaptability and biomass productivity for a crop under any given environment. Nevertheless, the optimal agronomical practices for any crop may vary widely according to the production region, growing conditions, cultivar used, and the end use of the crop.

In many natural environments, the availability of nitrogen is the primary factor limiting plant growth (Chapin, 1980; Berendse & Aerts, 1987). According to Pate (1973) plants depend almost entirely on the dissolved forms of inorganic nitrogen in their immediate environment for supply of this essential element. Evans (1980) indicated that the relationship between crop productivity and nitrogen supply is commonly used for fertilizer management scheduling.

However, due to the diversity in the form, timing and method of the application of nitrogen on kenaf, there are numerous and often conflicting reports on the effect of nitrogen on its agronomical aspects and productivity. For example, some reports indicated no responses of kenaf to nitrogen (Manzanares *et al*., 1997; Fernando *et al*., 2004; Danalatos & Archontoulis, 2010), while others pointed out its positive effects (Bhangoo *et al*., 1986; Muchow, 1992; Webber, 1996; Kuchinda *et al*., 2001; FAO, 2002).

As indicated above, besides nitrogen inputs, plant population and row spacing are also key factors in determining crop growth and productivity. Baldwin and Graham (2006) noted that in kenaf production, plant population and row spacing are very important factors since they can affect stem diameter and plant height which is correlated to whole stem yield. However, for any crop, optimum plant population as well as row spacing varies greatly between areas according to climatic and soil conditions, sowing time, varieties, and equipment used. Danalatos and Archontoulis (2004 a & b) and Fernando *et al*. (2004) indicated that the desired plant population and row spacing will vary among kenaf-producing regions due to crops generally grown in those areas and the equipment used to cultivate those crops.

Radosevich (1988) pointed out that the yield or biomass of a crop can dramatically respond to even a small change in plant population. Working in kenaf, Acrèche *et al*.

(2005) noticed that there is an inconvenience of defining a single optimum plant population for the crop, emphasizing that attention should be given to the suspected intraspecific competition and compensatory mechanisms involving diameter, height and dry bark weight. Webber and Bledsoe (2002 a & b) stated that plants in stands that are too dense for the cultivar or seasonal growing conditions tend to be short, spindly and weak-stemmed, while plants in stands that are too sparse produce lateral branches that are too heavy. Thus, the plant population should be selected after considering both the whole stem yield and the dimensional requirement, which affects whole stem pulp qualities (Ghumary & Bisen, 1967). Nevertheless, because of variations in growth conditions various plant populations have been suggested for kenaf production, for example a final plant count of 20 to 30 plants m^{-2} in Florida (Seale *et al*., 1952); 19.7 and 24.7 plants m^{-2} in Mississippi (Neill & Kurtz, 1994); and 20 to 25 plants m^{-2} under Mediterranean conditions (Danalatos & Archontoulis, 2004 a & b; Fernando *et al*., 2004). Other researchers suggested that a plant population of 18-37 plants per m^2 may be desirable for maximizing stem yield (Alexopoulou *et al*., 2000; Webber & Bledsoe, 2002 a; Webber *et al*., 2002). In other instances, Muchow (1979 a & b) stabilized the stem yield at a plant population of 50 plants m^{-2} in an Australian wet season.

Crop row spacing also plays important roles by influencing canopy architecture, which is a distinguishing characteristic that affects the utilization of light, water, and nutrients (Sharratt & McWilliams, 2005). Row spacing influences also the plant structure and yield (Eberbach & Pala, 2005; and Zhou *et al*., 2010). Furthermore, LeMalieu *et al*. (1991) suggested that decisions for row spacing selection in kenaf should probably consider weed problems and control measures, harvest method and plant population goals. Consequently, numerous studies conducted using various row spacing in kenaf production showed various and conflicting results. For example, when Williams (1966) established kenaf at a constant seedling rate with decreasing row spacing the total biomass production for the wider row spacing was less than for the narrow-row spacing. White *et al*. (1970) suggested a row spacing of less than 50.8 cm. In other conditions, Bitzer and Bruerning (1997) used 25, 53, 79, and 91 cm row spacings in their investigation, resulting in higher total biomass yields in 25 cm rows as compared to the 91 cm rows. According to Neill and Kurtz (1994) and Baldwin and Graham (2006) row spacings of 50.8-76.2 cm had produced maximum

stem yields on the alluvial plain of western Mississippi, whereas 20.3 cm rows were optimal for southern Mississippi. In South Africa, 30 to 35 cm row spacing are recommended for irrigated and dryland conditions respectively, which tended to be good for all major yield aspects (Pretorius *et al*., 2002 a & b).

However, the commercial kenaf producers in the Winterton/Bergville area of South Africa are making use of different cultivation practices; plant population, row spacing and nitrogen application levels sometimes resulting in an uneconomical return and environmental concerns.

Therefore, due to the conflicting reports worldwide and the limited available information in South Africa on the responses of kenaf growth, productivity and yield quality to nitrogen, plant population and row spacing, an investigation was conducted to quantify and qualify the suitable nitrogen fertilizer level, plant population and row spacing at Pretoria (South Africa).

The present chapter aimed to determine;

- the responses of kenaf growth components (stem diameter and plant height) to plant population, row spacing and nitrogen fertilization and their interaction effects
- quantitatively and qualitatively kenaf yield across the three mentioned agronomical inputs as well as their interaction effects

Hypothesess

- Increasing plant population will decrease plant height and stem diameter and consequently the yield per plant but will increase the yield per hectare,
- Increasing nitrogen level will increase plant height, stem diameter, stem yield per plant as well as per hectare,
- Increasing row spacing will not have an effect on plant height, stem diameter as well as yield per plant and per hectare,

- Increasing plant population will increase the acid detergent fibre (ADF), neutral detergent fibre (NDF), dry matter (DMt), cellulose, hemicelluloses, lignin and ash content,
- Increasing N level will increase ADF, NDF, DMt, cellulose, hemicelluloses content, while decreasing lignin and ash content,
- Increasing row spacing will not affect the ADF, NDF, DMt, cellulose, hemicelluloses content, while decreasing lignin and ash content.

3.2. Materials and Methods

A field study was undertaken to investigate the effects of plant population, row spacing and nitrogen application on growth components and yield composition of kenaf. The field trial was established at the Hatfield Experimental Farm of the University of Pretoria (25º 45' S; 28 º16' E and 1372 masl) on the 1st of December 2008 and harvested on the 6th of April 2009. The experiment was conducted using the photosensitive kenaf cultivar "Tainung 2". The soil of the experimental site was a sandy clay soil of the Hutton form. The site is situated in a summer rainfall region with an average annual rainfall of 670 mm, and monthly average maximum and minimum temperatures of about 30 ºC in (January) and 1.5ºC in (July) respectively (Annandale *et al*., 1999). The treatments consisted out of three plant populations (200 000 plants ha^{-1},300 000 plants ha^{-1}, and 400 000 plants ha^{-1}), four nitrogen application levels (0 kg ha^{-1}, 50 kg ha^{-1}, 100 kg ha^{-1} and 150 kg ha^{-1}) and three row spacings (0.17 m, 0.34 m and 0.50 m). The main plot (108 m^2), subplot (36 m^2) and sub-subplot (9 m^2) factors were respectively plant population, nitrogen application level and row spacing. The trial was laid out as a completely randomized split-split plot design. Each treatment combination was replicated four times.

The experimental site was ploughed one month before planting and the soil was loosened a day before the planting date to ensure maximize soil seed contact. In order to ensure optimum growth conditions 30 kg ha^{-1} of phosphorus as super phosphate (8.3%) and 100 kg ha^{-1} of potassium as potassium chloride (KCl) (50%) were applied to each experimental unit, based on a soil analysis. Nitrogen was

applied in the form of LAN 28%. All fertilizers were broadcasted at sowing. Due to good canopy closure, hand weeding was done only once at 60 days after planting (DAP) with no additional weed control after that. Furthermore, no problems in terms of insects or diseases were experienced during the growing season.

A seed germination test was performed at phytotron D on the Hatfield Experimental Farm using moistened cellulose paper (Fig.3.1). The seeds were incubated at 25ºC for nine days and the information was used to calculate the amount of seed needed for each experimental unit. The calculated number of seeds was planted by hand into a soil irrigated with 20 mm of water before planting. After planting the plots received three irrigations (once a week), each of 20 mm, to ensure good germination and establishment. Appart from this, the crop was reliant on rainfall for the rest of the season.

Fig. 3.1. Kenaf seed germination test after nine days of incubation at 25ºC in the 2008/09 season

Five inner plants (permanently marked) from each sub-subplot were selected at random and used for growth characterizing (stem diameter and plant height) at 85, 113 and 126 DAP. Plant height from the soil surface to the tip of the stem was taken using a meter stick. Stem diameter was taken using a digital caliper starting at a height of 10 cm above ground level in 50 cm increments up to the terminal meristem. Kenaf bark fibres develop from the base upward, therefore the lower stem diameters at 10, 60 and 110 cm above soil level will be of utmost importance to the producers and only those diameters will be discussed.

Dry mass production (stems, leaves) were analyzed only at the final harvest using the same five plants used for growth characterization at126 DAP. The harvest was done by hand and commenced as soon as 25% of plants showed one or more flowers (Agbaje *et al*., 2008). The plants were cut at ground level and the leaves and reproductive parts removed from the stems and weighed separately before and after oven drying at 67ºC until a constant dry weight was obtained (≈48 hours). Dry mass of stem and leaves of five plants were divided by five to obtain the dry mass per individual plant. The values obtained were then multiplied by the estimated number of plants per sub-sub plot at the final harvest to obtain dry mass per hectare. The total dry mass (total DM) per plant as well as per hectare were obtained by adding the weights of stems, leaves and reproductive parts per plant and per hectare.

In addition, at harvest, three one square meter samples from each sub-sub plot were cut at ground level and used to separate the plants in different categories according to the thickness of stem diameter at 10 cm soil level as follows: thick (> 20 mm), medium (< 20 mm > 15 mm), and thin plants (< 15 mm). Material from one of the three $1m^2$ samples was selected at random and used for chemical analysis of the bark fibre. It has to be noted that for this study, all stem tissues outside the vascular cambium will represent the bark (fibre) as indicated by Esau (1965), and Adamson and Bagby (1975), while the term core will indicate all tissues inside the vascular cambium (Bossia, 1975). For the purpose of analysis of bark fibre, the stems were retted in water for two weeks (Fig. 3.2. A & B) until the bark separated easily from the rest of the stem. Afterwards, the bark was manually extracted from the stems and then both the bark and core were sun dried for approximately two weeks (Fig. 3.2. C & D).The bark fibre was then analysed in the Nutri-Lab of the University of Pretoria. Neutral detergent fibre (NDF), acid detergent fibre (ADF), acid detergent lignin (ADL), dry matter, crude fibre, hemicellulose and cellulose contents were determined.

Fig. 3.2.(A) Container in which kenaf material was retted, (B) crates at the bottom of the container to allow water movement, (C) material being sun dried and (D) workers assisting in separating the bark and core during the 2008/09 season at Phytotron D at the Hatfield Experimental Farm, UP.

The bark material was ground to mm sized particles. NDF and ADF were determined by the procedure described by Ankom Technology using an Ankom 200 Fibre analyzer (Macedon, NY, USA) (Fig. 3.3. A, B, C, & D). The procedures are based on the sequential extraction methods proposed by Robertson and Van Soest (1981) for NDF and Goering and Van Soest (1988) for ADF. Hemicellulose concentration was expressed as the difference between NDF and ADF, while cellulose concentration was obtained by subtracting Acid detergent lignin (ADL) from ADF. The lignin content was obtained from the ADL procedure (Goering and Van Soest, 1988) using a Fiberteck 2010 (Foss tecator, HÖGANÖS, SWEDEN) (Fig. 3.3. C). Dry matter and crude fibre determination were carried out by using the methodology provided by the Association of Official Analytical Chemists (AOAC, 2000).

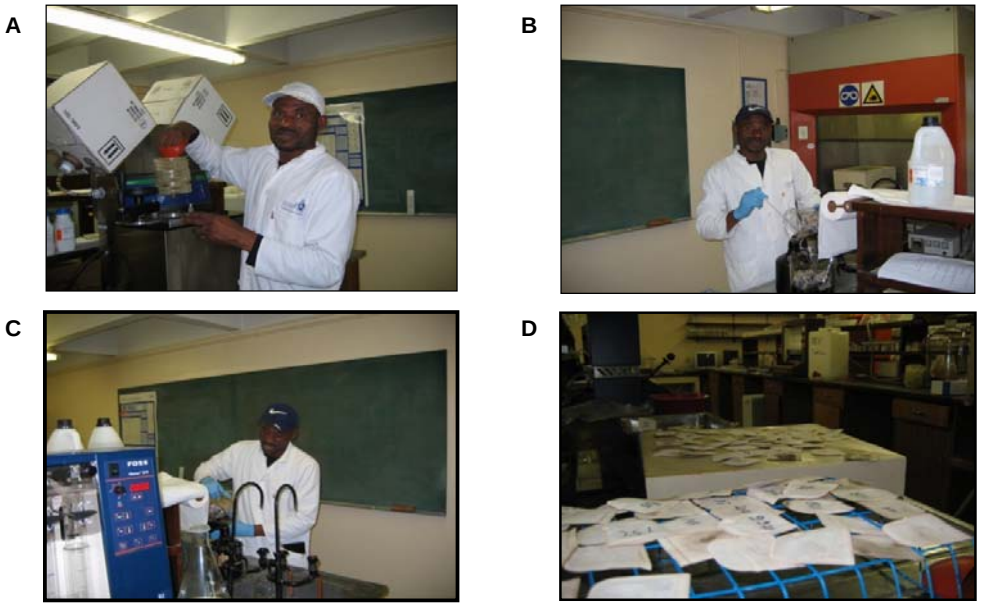


Fig. 3.3. Chemical analysis of bark fibres of kenaf conducted at the Nutri Lab, Department of Animal and Wildlife Sciences, UP. (A) Equipment for extraction of ADF, NDF, and crude fibre, (B) removing samples from acetone, (C) Lignin extraction, (D) samples being air dried at room temperature before oven drying.

All the data were analysed using analysis of variance (ANOVA) with the GLM procedures of SAS (SAS® Institute, inc., 2002-2010, 9.3 Software) to estimate treatment variations. The measured trait was considered significantly affected if Pr < 0.05, or highly significant affected if Pr < 0.01 and not significant if Pr > 0.05. Mean separation was done using Tukey's Honnestly Significant Difference (HSD) test at Pr = 0.05. Because of the missing plots, the statistical analyses were done using the procedures of unbalanced design with Type IV sum of square as advised by Freund *et al*. (1986) and Shaw and Olds (1993).The results regarding different parameters studied in this chapter are presented in the tables under each section regarding each parameter, but the complete ANOVAs can be found in Appendix A, Tables 3.1 to 3.8.

3.3. Results and discussion

An automatic Weather Station (Fig. 3.4) adjacent to the experimental site was used to record the daily climatic parameters (Figs. 3.5 to 3.7) during the growth cycle. The

average temperature fluctuated between 20 and 25ºC across the growing season. In general all three temperature components started to decline from the end of February up until the end of the growing season. A lot of rain fell at the beginning of January (40 mm), but the highest amount (50 mm) was recorded at the end of February/beginning of March. For most of the season, solar radiation did not drop below 15 Mj m^{-2}. The total amount of precipitation recorded during the growing season was 590 mm. This amount was enough to sustain good kenaf crop growth (Crane, 1947, Dempsey, 1975). The average solar radiation and temperatures during the growing season were also suitable for the kenaf crop (Cosentino *et al*., 2004; Archontoulis *et al*., 2005).

Fig. 3.4. Automatic Weather Station at the Hatfield Experimental Farm, UP situated about 50 m from the kenaf trial

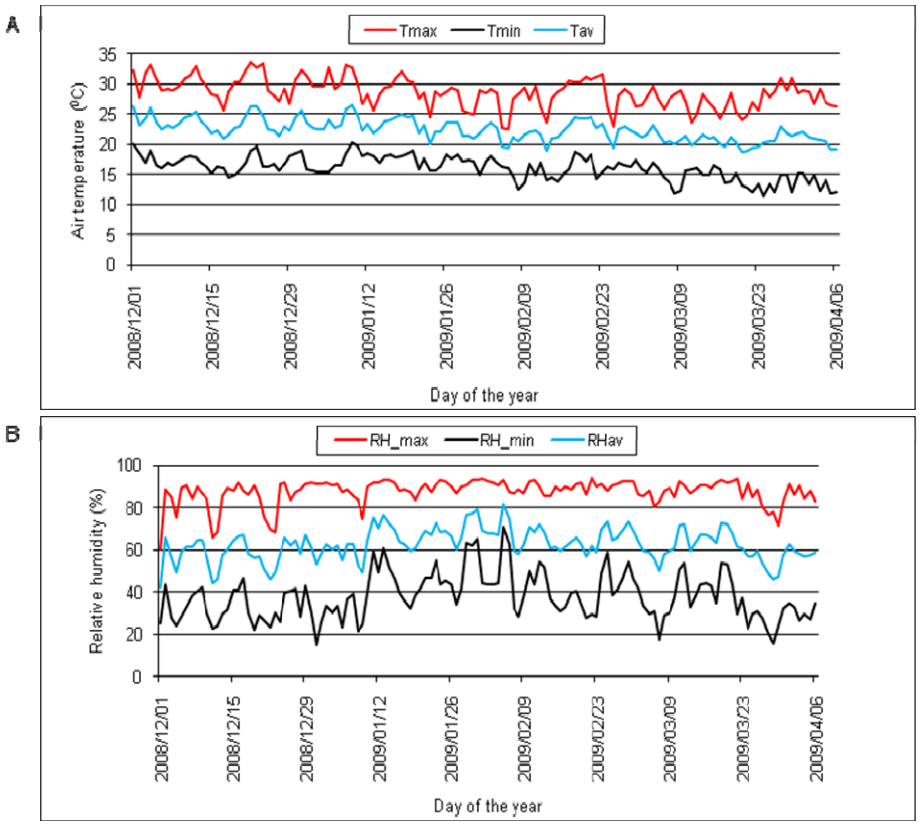


Fig. 3.5. Air temperature (A) and relative humidity (B) over the growth cycle in the 2008/09 season

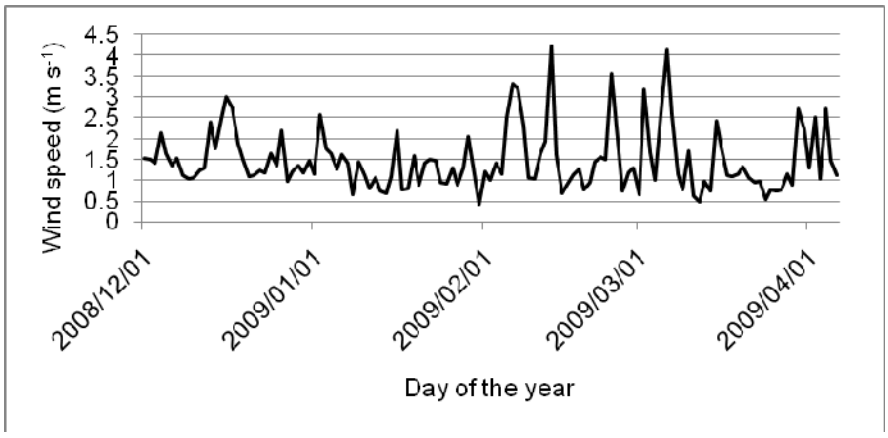


Fig. 3.6. Wind speed over the growth cycle in the 2008/09 season

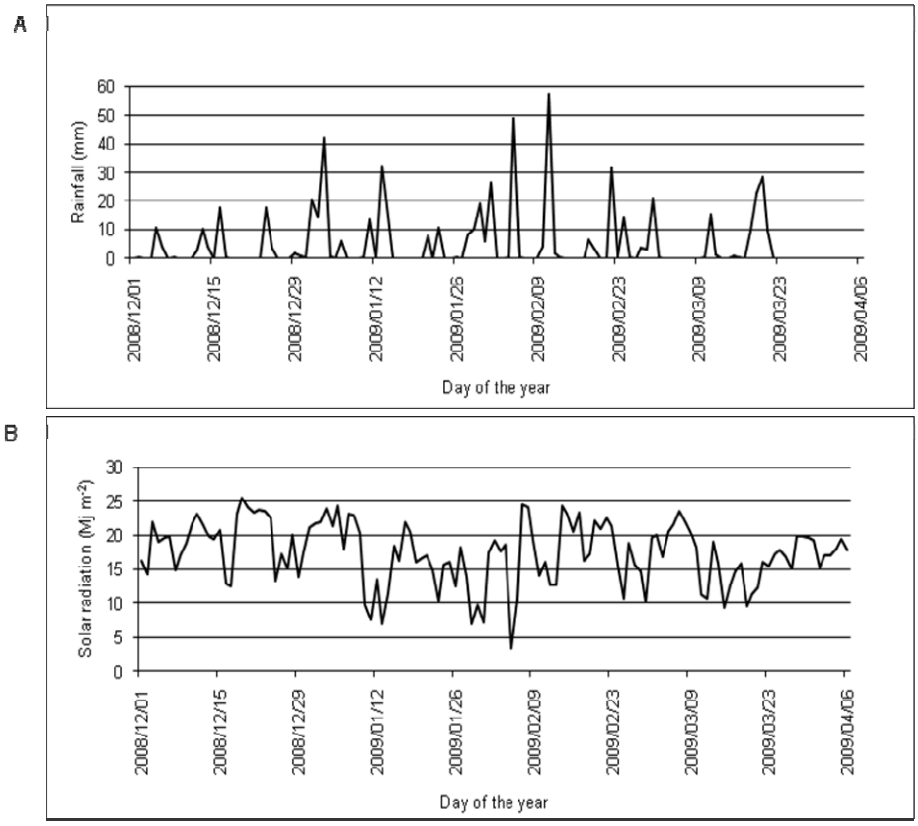


Fig. 3.7. Rainfall (A) and solar radiation (B) over the growth cycle in the 2008/09 season

The appearance of 50% seedlings above the soil surface and the first flower buds were recorded respectively at 4 (5th of December) and 112 DAP (23rd of March). However, although the seed germination was taken into account to ensure target plant population being met, poor germination was experienced in the field resulting in 21.5% missing sub-sub plots. Furthermore, the number of missing sub-sub plots was much higher for the 0.17 m row spacing (±56%), therefore none of the treatment combinations containing 0.17 m were included for data analysis. No thinning was done during this season as a result of bad germination. More plants than was desired were available at the two higher plant populations. The stand counts were done in each sub sub plot on three randomly selected areas of 1 m^2 and the material harvested on this area was used for chemical analysis including the five plants harvested for biomass accumulation.

3.3.1. Growth parameters

Plant height

At 85 DAP, none of the treatment factors or their interactions had significant effect on plant height (Table 3.1, Fig. 3.8). At this stage, there was a slight decrease in plant height in response to increase in plant population. Regarding nitrogen level, the plant height tended to increase up to 100 kg ha^{-1} where it reached the maximum value (204 cm) followed by a decrease (198 cm) at 150 kg ha^{-1}. No significant effect of row spacing was observed at any of the sampling dates (Fig. 3.8). Also no consistent trend of plant height was observed in response to row spacing. Interaction effects were observed between plant population and nitrogen level at 113 and 126 DAP (Tables 3.2-3.3). Generally, the plant height tended to decrease as plant population increased for each nitrogen level. Furthermore, both at 113 and 126 DAP the maximum and minimum plant height was found at 0 kg ha^{-1} with the former being detected under 200,000 plants ha^{-1} and the later at 400,000 plants ha^{-1}. This indicates that as the competition between plants increased the plant height decreased. However, no clear trend of plant height was observed in response to nitrogen level at any of the plant populations as well as at any of the sampling dates.

The lack in response of plant height to plant population observed at the first sampling may be attributed to the absence of competition for available resources such as radiation, soil moisture, and nutrients at the beginning of the growing season. Thereafter, the competition became severe due to the age of the plants which in turn affected canopy development in such a way that the plant height difference became distinguishable for different plant populations. The reduction in plant height due to increase in plant population were previously found by other researchers (Muchow, 1979 a & b; Manzanares *et al*., 1997; Zhou *et al*., 1998; Alexopoulou *et al*., 2000; Danalatos and Archontoulis, 2004 a; Acrèche *et al*., 2005). In other instances, however, no effect of plant populations on plant height was observed (Danalatos & Archontoulis, 2004 b). In the same line of comparison Manzanares *et al*. (1997) found both decrease and increase in plant height with different cultivars of kenaf due to plant population.

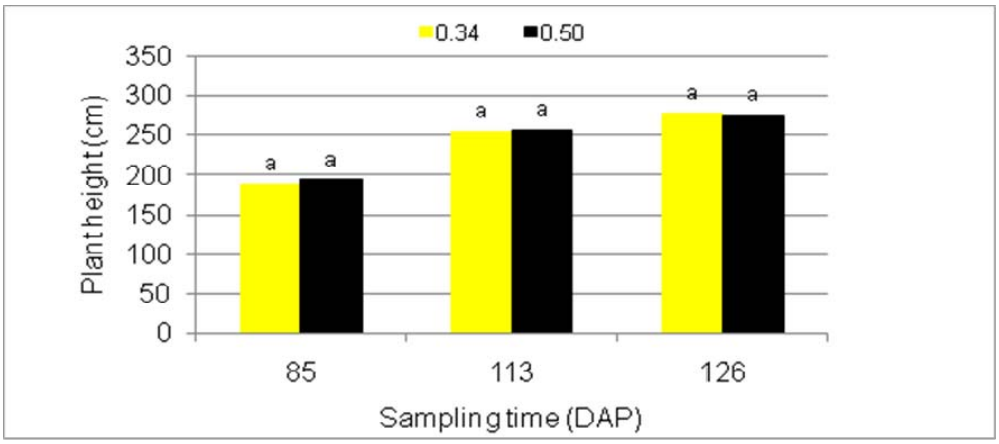
The lack of responses of plant height to nitrogen level or to row spacing may not be explained at this stage and are attributed to unknown factors.

Table 3.1. Effect of plant population and nitrogen level on plant height at 85 DAP

Plant population (plants ha^{-1})	Plant height (cm)	Nitrogen level (kg ha^{-1})	Plant height (cm)
200.000	194.9 a	0	182.8 a
300.000	192.4 a	50	187.3 a
400.000	191.6 a	100	203.7 a
		150	197.7 a
Mean	192.9		192.9
Pr	NS		NS
HSD	-		-

Means within the same column with the same letter are not significantly different from each other

NS: not significant



Bars of the same sampling date with the same letter are not significantly different from each other

Fig. 3.8. Effect of row spacing on plant height over the growing season

Table 3.2. The interaction effect between plant population and nitrogen level on plant height at 113 DAP

Nitrogen level (kg ha^{-1})	Plant population (plants ha^{-1})			Mean
	200,000	300,000	400,000	
0 kg ha^{-1}	289.2 a	261.8 ab	217.5 b	256.2
50 kg ha^{-1}	255.7 ab	250.1 ab	243.6 ab	249.8
100 kg ha^{-1}	271.50 a	250.2 ab	261.9 ab	261.2
150 kg ha^{-1}	275.7 a	267.2 ab	244.4 ab	262.4
Mean	273.0	257.3	241.9	257.3
Pr		*		
HSD		52.782		

Means with the same letter are not significantly different from each other

*: significant at 5% level of probability

Table 3.3. The interaction effect between plant population and nitrogen level on plant height at 126 DAP

Nitrogen level (kg ha^{-1})	Plant population (plants ha^{-1})			Mean
	200,000	300,000	400,000	
0 kg ha^{-1}	314.9 a	270.0 ab	236.7 b	273.9
50 kg ha^{-1}	273.7 ab	269.8 ab	261.9 ab	268.5
100 kg ha^{-1}	284.3 ab	281.4 ab	278.3 ab	281.3
150 kg ha^{-1}	308.2 a	287.4 ab	258.4 ab	284.7
Mean	295.3	277.2	258.8	277.0
Pr		*		
HSD		56.957		

Means with the same letter are not significantly different from each other

*: significant at 5% level of probability

Stem diameter at different positions

None of the main factors or their interactions had significant effect on the stem diameters (Figs.3.9-3.13). However, a tendency of decrease in stem diameter as plant population increased at the three levels from the soil surface was observed at each sampling date (Figs.3.9-3.10.A). As in the case of plant height, no clear response of stem diameter either to nitrogen level (Figs.3.10.B-3.11) or to row spacing (Figs.3.12-3.13) was observed.

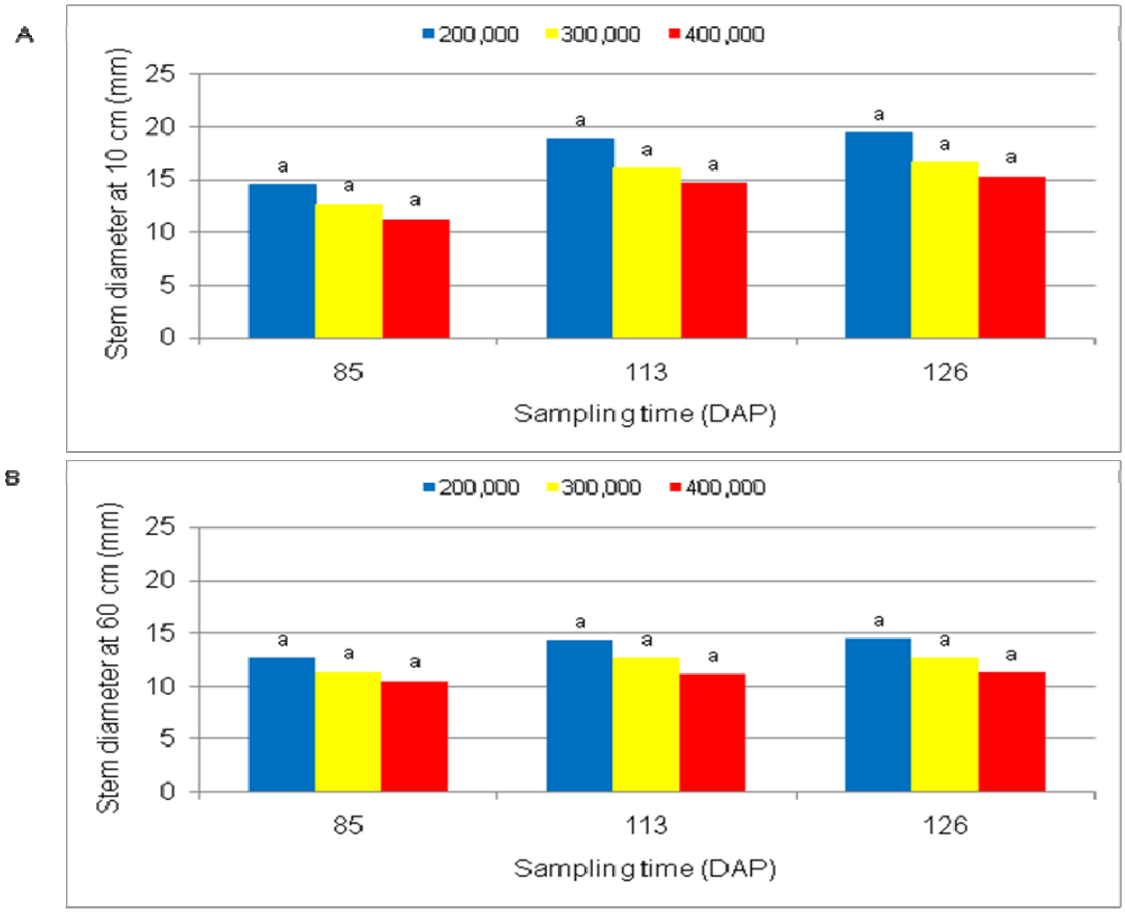


Fig. 3.9. Effect of plant population on stem diameter at 10 cm (A) and 60 cm (B) above soil level over the growing season

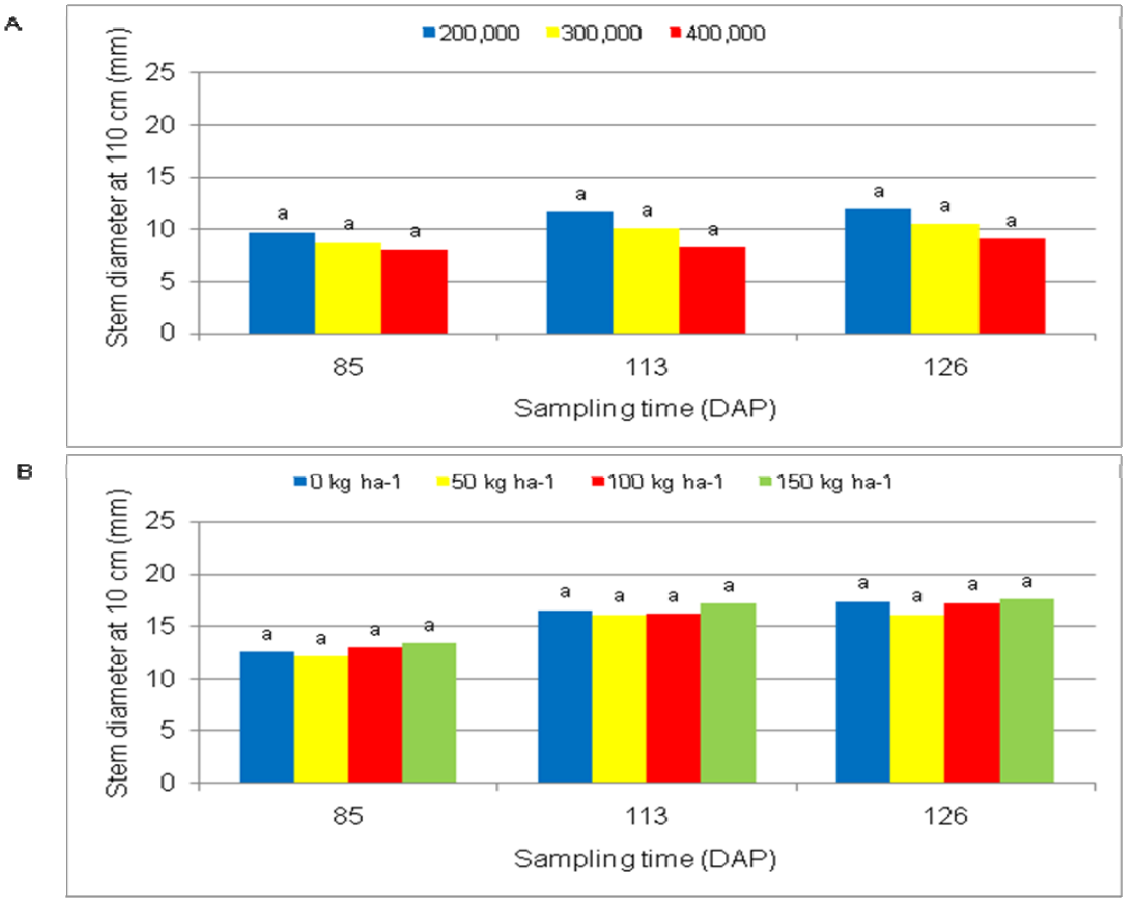
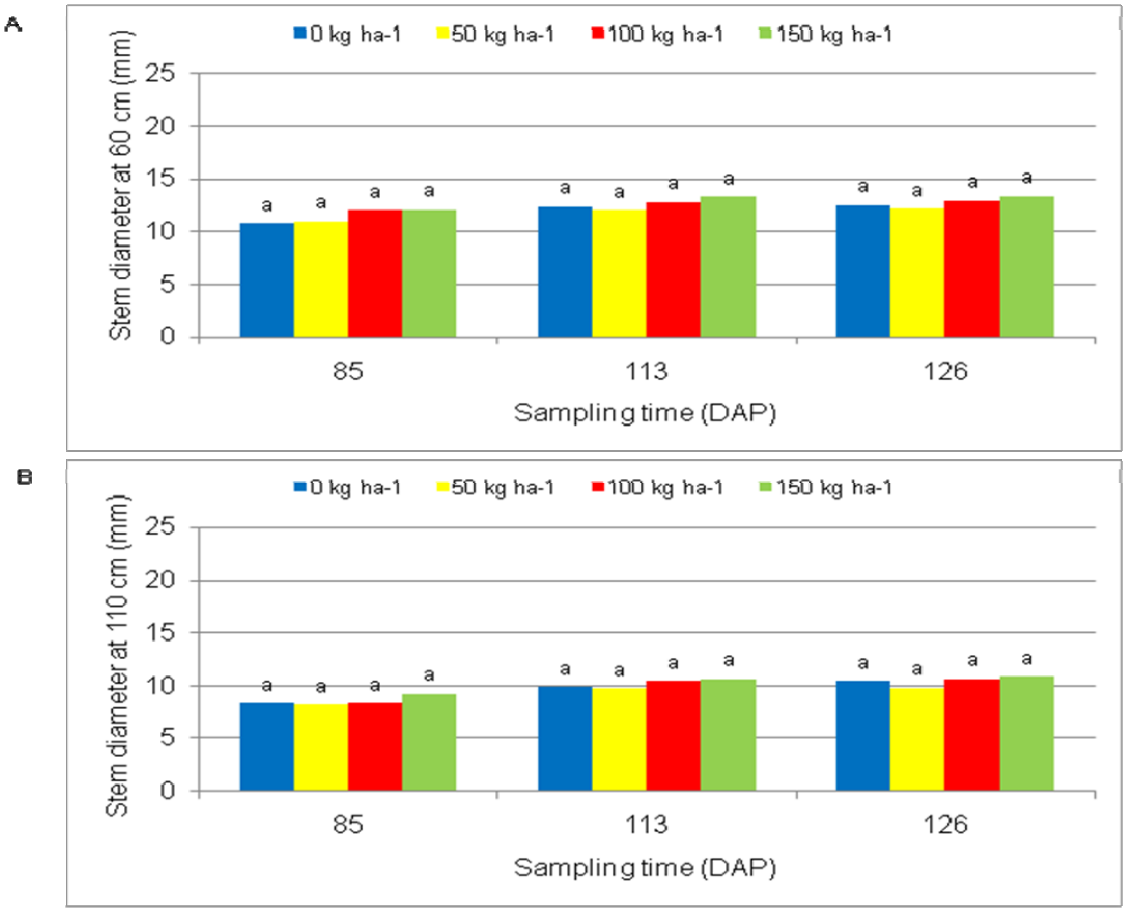


Fig. 3.10. Effect of plant population on stem diameter at 110 cm (A) and and effect of nitrogen level on stem diameter at 10 cm (B) above soil level over the growing season



Bars of the sampling date with the same letter are not significantly different from each other

Fig. 3.11. Effect of nitrogen level on stem diameter at 60 cm (A), and at 110 cm (B) above soil level over the growing season

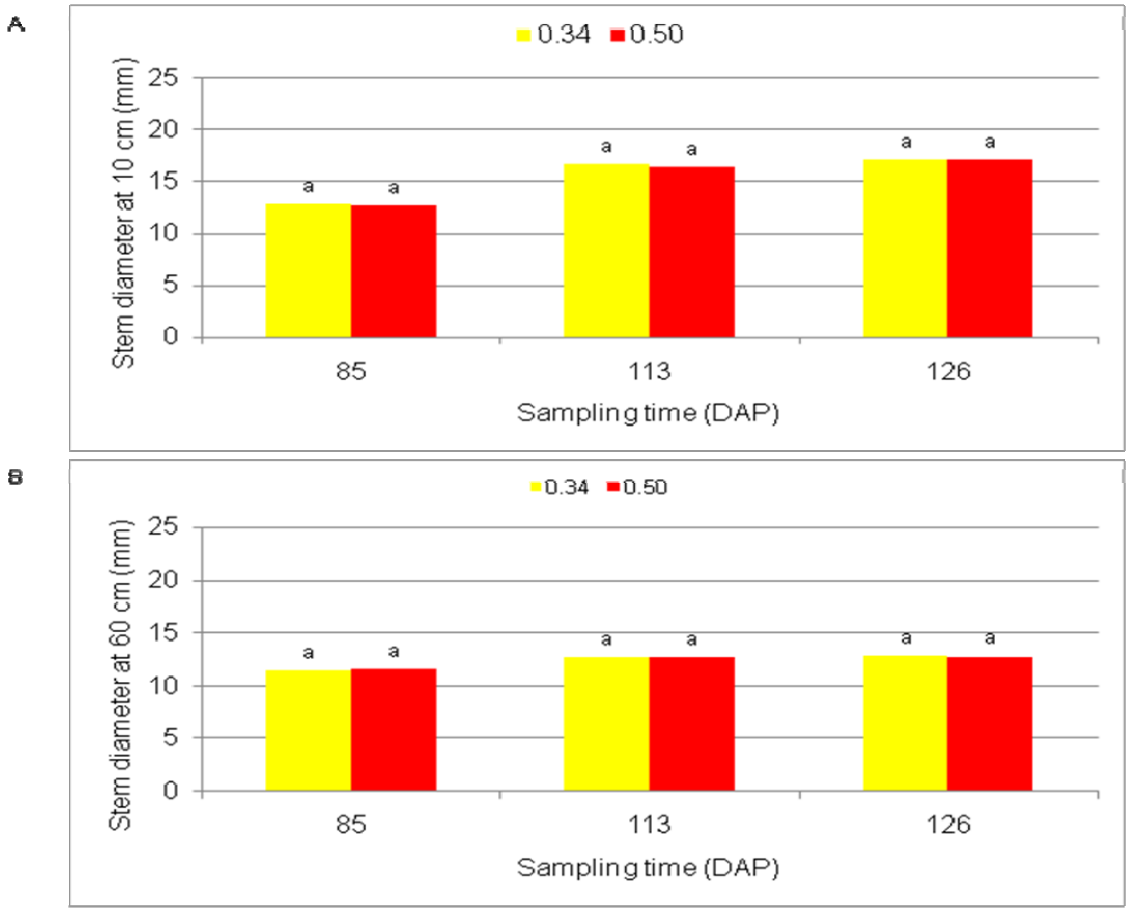


Fig. 3.12. Effect of row spacing on stem diameter at 10 cm (A), and at 60 cm (B) above soil level over the growing season

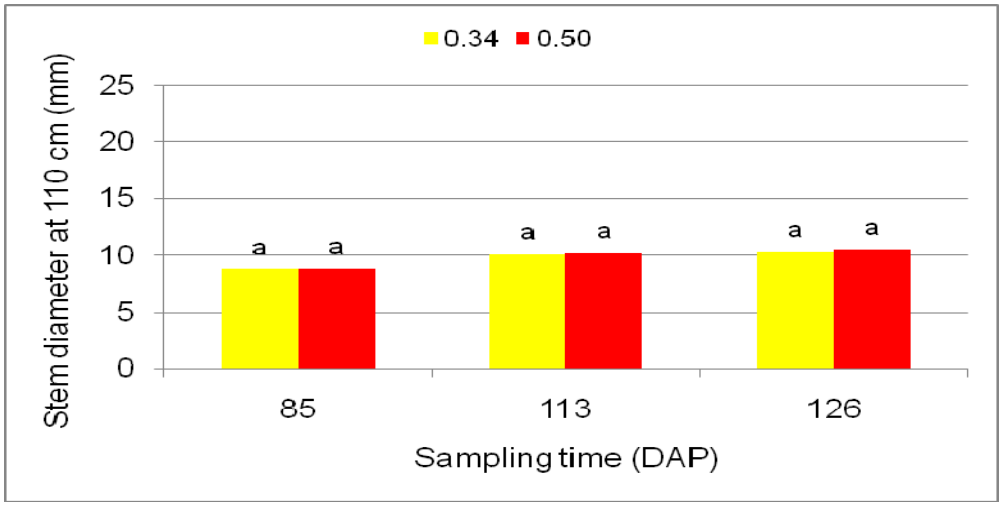


Fig. 3.13. Effect of row spacing on stem diameter at 110 cm above soil level over the growing season

3.3.2. Biomass production

Stem and leaf dry mass per plant and per hectare

Significant effect of plant population was found only on leaf dry mass per plant, which showed a decreased trend as plant population increased (Tables 3.4-3.5). Generally, the stem and leaf dry mass per plant and leaf percentage decreased as plant population increased, although the former and the latter are without significant effect (Tables 3.4-3.5). However, reversed trends were observed with regard to stem and leaf dry mass per hectare (Tables 3.4-3.5). The stem percentage did not show a consistent trend. The decrease in stem and leaf dry mass per plant with increase in plant population may be due to the increase in pressure as the plant population increased. The increase in plant part yield per hectare with increase in plant population might be attributed to the increase in the number of plants per hectare.

Table 3.4. Effect of plant population on stem percentage, stem dry mass per plant and per hectare

Plant population (plants ha^{-1})	Stem (%)	Stem dm per plant (x10^{-3} kg)	Stem dm per hectare (t ha^{-1})
200,000	67.7 a	101.9 a	17.6 a
300,000	68.5 a	75.6 a	23.2 a
400,000	68.0 a	59.4 a	28.10 a
Mean	68.0	78.4	23.1
Pr	NS	NS	NS
HSD	-	-	-

Means within the same column with the same letter are significantly different from each other

NS: not significant

Table 3.5. Effect of plant population on leaf percentage, leaf dry mass per plant and per hectare

Plant population (plants ha^{-1})	Leaf (%)	Leaf dm per plant (x10^{-3} kg)	Leaf dm per hectare (t ha^{-1})
200,000	22.1 a	32.3 a	5.6 a
300,000	20.9 a	22.8 b	6.3 a
400,000	19.4 a	15.8 c	7.6 a
Mean	20.8	23.4	6.5
Pr	NS	0.0437	NS
HSD	-	6.2607	-

Means within the same column with the same letter are significantly different from each other

NS: not significant

No significant effect of nitrogen level was found on stem and leaf dry mass per plant, and per hectare as well as on stem and leaf percentages (Tables 3.6-3.7). Furthermore, no clear trends were observed with regards to those parameters in response to nitrogen level. The lack of clear response of stem dry mass to nitrogen

level may be linked to the conflict behaviours of the plant height and stem diameter at different plant heights. Abdul-Hamid *et al.* (2009) found a positive response, while, Danalatos & Archontoulis (2005) and Gonzalez-Moreno *et al*. (2004) found no response of stem dry mass per hectare to nitrogen level. Abdul-Hamid *et al*. (2009), reported no, as well as a positive response of kenaf leaf dry mass per hectare to nitrogen in a dry and wet season respectively.

Table 3.6. Effect of nitrogen level on stem percentage, stem dry mass per plant and per hectare

Nitrogen level (kg ha^{-1})	Stem (%)	Stem dm per plant (x10^{-3} kg)	Stem dm per hectare (t ha^{-1})
0	68.5 a	84.9 a	22.2 ab
50	66.5 a	63.1 a	18.0 b
100	69.7 a	79.3 a	26.3 a
150	64.5 a	85.7 a	25.8 ab
Mean	68.0	78.4	23.1
Pr	NS	NS	NS
HSD	-	-	-

Means within the same column with the same letter are significantly different from each other

NS: not significant

Table 3.7. Effect of nitrogen level on leaf percentage, leaf dry mass per plant and per hectare

Nitrogen level (kg ha^{-1})	Leaf (%)	Leaf dm per plant (x10^{-3} kg)	Leaf dm per hectare (t ha^{-1})
0	20.9 a	25.2 a	6.6 a
50	21.1 a	19.4 a	5.5 a
100	19.5 a	21.5 a	7.1 a
150	21.6 a	27.2 a	6.9 a
Mean	20.8	23.4	6.5
Pr	NS	NS	NS
HSD	-	-	-

Means within the same column with the same letter are significantly different from each other

NS: not significant

Similarly to nitrogen level, no significant effect of row spacing was observed on stem and leaf dry mass, and on their percentages (Tables 3.8-3.9). However, there was tendency of increase in stem and leaf dry mass per hectare as well as in their percentages in response to increase in row spacing. The leaf and stem dry mass per plant showed reversed trends.

Table 3.8. Effect of row spacing on stem percentage, stem dry mass per plant and per hectare

Row spacing (m)	Stem (%)	Stem dm per plant (x10^{-3} kg)	Stem dm per hectare (t ha^{-1})
0.34	67.5 a	81.5 a	22.9 a
0.50	68.5 a	75.6 a	23.3 a
Mean	68.0	78.4	23.1
Pr	NS	NS	NS
HSD	-	-	-

Means within the same column with the same letter are significantly different from each other

NS: not significant

Table 3.9. Effect of row spacing on leaf percentage, leaf dry mass per plant and per hectare

Row spacing (m)	Leaf (%)	Leaf dm per plant (x10^{-3} kg)	Leaf dm per hectare (t ha^{-1})
0.34	20.7 a	23.9 a	6.2 a
0.50	20.8 a	22.9 a	6.8 a
Mean	20.8	23.4	6.5
Pr	NS	NS	NS
HSD	-	-	-

Means within the same column with the same letter are significantly different from each other

NS: not significant

3.3.3. Chemical composition and dry matter content of bark fibre

As a dicot, kenaf has two distinct types of fibres; - long bark fibres, which account for 35% of its fibrous part, and - short core fibres, which account for the rest (Manzanares *et al.,* 1997). According to Van der Werf *et al*. (1994) fibre length and the contents of cellulose and lignin are important raw material quality parameters for paper making.

The plant cell wall provides mechanical support to individual cells and hence to the whole plant, this is due to its being made mainly of cellulose, hemicellulose, pectin, proteins, and/or lignin (Chiaiese *et al*., 2011). Lignocellulose, the major component of biomass, makes up about half of the matter produced by photosynthesis. It consists of three types of polymers; cellulose, hemicellulose, and lignin (Deobald & Crawford 1997; Pérez *et al*., 2002). Cellulose and hemicellulose are macromolecules from different sugars, whereas lignin is an aromatic polymer synthesized from phenylpropanoid precursors (Pérez *et al*., 2002). From an agro-economical point of view, lignin is considered as a negative factor in paper manufacturing (Chen *et al*., 2001), as residual lignin in the wood fibres cause discoloration and low brightness level of the pulp (Chiang *et al*., 1988). Wood and Sterwart (1981) pointed out that low lignin content is desirable in paper manufacturing as it requires few chemicals and shorter cooking times during pulping. The low lignin content of kenaf bark fibre results in it having higher mechanical strength and therefore makes it suitable for writing, printing, wrapping and packaging purposes (Neto *et al*., 1996; Saikia *et al*., 1997).

Similarly, the ash content which is defined as the total sum of carbonates, Ca, K and some trace elements is undesirable, as it has a negative impact on pulp mechanical strength properties. According to Berti *et al*. (2013) ash content and composition affect thermochemical conversion processes, such as gasification and pyrolysis, mainly at high temperatures. Crude fibre is not a common characteristic mentioned in terms of paper making, but it is one of the most important parameters influencing the quality of fodder crops. According to Ayub *et al*. (2007) the higher the crude fibre the lower the digestibility of the fodder.

One, however, need to take in consideration that the composition and the percentage of these polymers vary from one plant species to another (Jeffries, 1994; Malherbe & Cloete, 2002), but within a single plant they vary with growth stage and other conditions (Jeffries, 1994; Morrison *et al*. 1998), such as genetic and environmental factors (Malherbe & Cloete, 2002).

There is no available information in literature regarding the effect of agronomic practices on chemical composition of kenaf bark fibre grown in a South African environment. Hence, the opportunity was taken to assess its chemical and dry matter content. The initial aim of this study was to assess the kenaf material for a wide range of purposes including interior paneling for the automotive industry. However, due to budget constraint the study was restraint on the purpose of pulp and thus only the fibres from the bark were assessed. In this study the term cellulose will be used as reference to the sum of alpha cellulose + amorphous cellulose contents of kenaf bark. Also, it has to be noted that the bark material used in this study was stored in a cold room for about a year before being assessed and this could have an influence on its chemical quality.

Neither the main factors nor their interactions had significant effects on NDF (neutral detergent fibre), ADF (acid detergent fibre), dry matter and crude fibre (Tables 3.10, 3-12 & 3.14), or cellulose, hemicellulose, lignin and ash contents (Tables 3.11, 3.13 & 3.15). Furthermore, clear tendency was observed only on ADF, which tended to increase in response to increase in plant population. Adamson *et al*. (1979) reported positive response of kenaf bark cellulose to nitrogen.

The cellulose and hemicellulose contents found in this study are lower than those reported on by Adamson *et al*. (1979), Mambelli and Grandi (1995), Amaducci *et al*. (2000), Thi Batch *et al*. (2003), Bonatti *et al*. (2004), Jonoobi *et al*. (2009) and Abdul-khalil *et al*. (2010). In all mentioned literature, the cellulose content was above 55% while the hemicellulose content was above 15%. The reason for these discrepancies may be due to a combination of plant age, environmental, agronomical conditions and their interaction with cultivars as well as the procedures used to assess those components. It has to be noted that the material was processed approx. 12 months after harvesting.

With respect to lignin content, numerous reports have been provided in literature. For example; 7.7 % (Sabharual *et al*., 1994), respectively 3.2% and 3.7 % under rainfed and well watered conditions (Mambeli & Grandi, 1995), 10% (Neto *et al*., 1996), just above 10% (Pappas *et al*., 1998), 14 % (Zhou *et al*. 1998), 7.8 % and 8 % respectively under irrigated and rainfed conditions (Amaducci *et al*., 2000), 9.2% (Ohtani *et al*., 2001), 14.8 % (Nishimura *et al*., 2002), 9.2 % (Khristova *et al*., 2002), 14.7% (Thi Batch *et al*., 2003), 14% (Ververies *et al*., 2004) and 17.5% (Jonoobi *et al*., 2011). In their investigation on the comparison of pulp and paper making characteristics of five fast growing plants; *Hibiscus cannabinus*, *Hibiscus sabdariffa*, *Tephrosia candida*, *Crotalaria juncea* and *Neyraudia reynaudiana*, Saikia *et al*. (1997) have reported that kenaf (lignin content: 17.33 %) as well as four other species (lignin content > kenaf lignin content) may lead to satisfactory delignification levels in milder pulping conditions. This may indicate that the values found in our study (11%) are in acceptable range for paper making.

The ash content in the range between 1.84 and 2.24 % found in the present study is lower than the findings of Wood (1978), Neto *et al*. (1996), Khristova *et al*. (2002), Thi Batch *et al*. (2003) and Abdul-khalil *et al*. (2010). Overall, they reported ash contents of kenaf bark in the range between 2.9 to 6%. However, Ohtani *et al*. (2001) and Berti *et al*. (2013) reported respectively an average kenaf ash content of 1.1% and less than 0.2%. Nevertheless, according to Khristova *et al*. (2002) and Ververies *et al*. (2004) the ash contents found in this study are in the typical range for non-woody plants.

Table 3.10. Effect of plant population on ADF, NDF, dry matter, and crude fibre contents of kenaf bark

Plant population (plants ha^{-1})	ADF (%)	NDF (%)	Dry matter (%)	Crude fibre (%)
200,000	62.7 a	71.7 a	89.8 a	56.1 a
300,000	63.0 a	70.4 a	88.7 a	55.8 a
400,000	63.2 a	71.3 a	89.9 a	56.4 a
Mean	63.0	71.2	89.5	56.1
Pr	NS	NS	NS	NS
HSD	-	-	-	-

Means within the same column with the same letter are not significantly different from each other

NS: not significant

Table 3.11. Effect of plant population on cellulose, hemicelluloses, lignin and ash contents of kenaf bark

Plant population (plants ha^{-1})	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)
200,000	51.4 a	8.9 a	11.4 a	1.99 a
300,000	51.3 a	7.7 a	11.7 a	1.97 a
400,000	52.4 a	7.9 a	11.0 a	1.97 a
Mean	51.7	8.2	11.4	1.98
Pr	NS	NS	NS	NS
HSD	-	-	-	-

Means within the same column with the same letter are not significantly different from each other

NS: not significant

Table 3.12. Effect of nitrogen level on ADF, NDF, dry matter, and crude fibre contents of kenaf bark

Nitrogen level (kg ha^{-1})	ADF (%)	NDF (%)	Dry matter (%)	Crude fibre (%)
0	62.1 a	70.8 a	89.5 a	55.4 a
50	63.2 a	71.7 a	89.2 a	57.1 a
100	62.9 a	70.7 a	89.4 a	55.9 a
150	63.6 a	71.4 a	89.8 a	56.1 a
Mean	63.0	71.2	89.5	56.11
Pr	NS	NS	NS	NS
HSD	-	-	-	-

Means within the same column with the same letter are not significantly different from each other

NS: not significant

Table 3.13. Effect of nitrogen on cellulose, hemicelluloses, lignin and ash contents of kenaf bark

Nitrogen level (kg ha^{-1})	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)
0	51.42a	8.5 a	11.1 a	2.2 a
50	52.3 a	8.3 a	11.3 a	1.9 a
100	51.6 a	8.1 a	11.4 a	1.9 a
150	52.0 a	7.9 a	11.6 a	1.8 a
Mean	51.7	8.2	11.4	2.0
Pr	NS	NS	NS	NS
HSD	-	-	-	-

Means within the same column with the same letter are not significantly different from each other

NS: not significant

Table 3.14. Effect of row spacing on ADF, NDF, dry matter, and crude fibre contents of kenaf bark

Row spacing (m)	ADF (%)	NDF (%)	Dry matter (%)	Crude fibre (%)
0.34	62.9 a	71.4 a	89.5 a	55.6 a
0.50	63.0 a	71.0 a	89.5 a	56.6 a
Mean	63.0	71.2	89.5	56.1
Pr	NS	NS	NS	NS
HSD	-	-	-	-

Means within the same column with the same letter are not significantly different from each other

NS: not significant

Table 3.15. Effect of row spacing on cellulose, hemicelluloses, lignin and ash contents of kenaf bark

Row spacing (m)	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)
0.34	52.0 a	8.38 a	11.1 a	2.0 a
0.50	51.4 a	8.00 a	11.6 a	1.9 a
Mean	51.7	8.2	11.4	1.98
Pr	NS	NS	NS	NS
HSD	-	-	-	-

Means within the same column with the same letter are not significantly different from each other

NS: not significant

3.4. Conclusions and recommendations

Generally, plant population, nitrogen level, and row spacing did not affect different parameters investigated in the present study, resulting in rejection of all the hypotheses. An increase in plant population tended to decrease the plant height and stem diameter, and consequently the stem dry mass per plant, but the stem yield per hectare increased to reach a peak value at the highest plant population. No clear trend was seen as to the responses of different parameters studied to nitrogen and row spacing. In general, the chemical components and the dry matter content did not show clear responses to all the parameters. Furthermore, the ash and lignin contents found in this investigation are in acceptable range for papermaking. The reasons for this lack of responses are yet unknown at this stage, so additional works should be conducted to identify the real causes. In the coming season, the trial will be split as follows; nitrogen fertilization will be conduted as a separated trial, while plant population and row spacing will be combined in one trial. This will be done in attempt to determine the causes of the lack in responses.

CHAPTER 4.
RESPONSE OF KENAF YIELD AND QUALITY TO NITROGEN UNDER RAINFED CONDITIONS

4.1. Introduction

The importance of nitrogen in kenaf production has been highlighted in the literature review as well as Chapter 3. However, it is well known that the effect of nitrogen on any crop depends on many factors, including the form, the method and the way of application. In this study, the same nitrogen levels used in Chapter 3 were applied, but the application was done as two dressings, one part at planting and the rest at 35 days after planting (DAP).

Hypotheses

- increasing nitrogen will increase the growth parameters of the plants
- increasing nitrogen will increase the yield of kenaf
- increasing nitrogen will improve the chemical composition of fibre
- increasing nitrogen will increase the stem water use efficiency
- increasing nitrogen will increase nutrient use efficiency, nutrient extraction from the soil and nitrogen content of leaves and stems

4.2. Materials and Methods

As in the 2008/09 season, the trial was conducted in an open field (Fig. 4.1. A) at the Hatfield Experimental Farm of the University of Pretoria using kenaf 'Tainung 2'. The trial was planted on the 9th of December 2009 at a rate of 500,000 plants ha^{-1} with a row spacing of 0.50 m. During the winter season preceding the kenaf trial, the trial site was planted to wheat without any N, P and K added. This was done in an effort to deplete any residual N from previous trials. The experimental site was ploughed one month before planting. To ensure maximum soil-seed contact the soil was cultivated a day before planting using a rotovator (Fig. 4.1. B). The experiment was laid out in a completely randomized block design (CRBD) with four nitrogen levels (0, 50, 100 and 150 kg N ha^{-1}) replicated four times, giving a total of 16 plots (Fig. 4.2).

Nitrogen (LAN 28%) was applied in two dressings so that each plot received 0 or 50 kg N ha^{-1} at planting as basal dressing and 0, 50 or 100 kg N ha^{-1} after thinning out (35 DAP) as top dressing. Each plot comprised out of eight rows oriented in a north-south direction. The top 60 cm soil layer was sampled before planting and after final harvest, and analysed by the Soil Science Laboratory of the University of Pretoria to determine the chemical and physical characteristics.

From the soil analysis, the total N, P and K removal, and nitrogen, phosphorus and potassium use efficiency (NUE, PUE and KUE, respectively) of kenaf were determined.

The NUE, PUE and KUE were determined as follows;

$NUE = \text{Stem } DM_{final} / (N_{planting} + N_{fert}) - N_{harv}$

$PUE = \text{Stem } DM_{final} / (P_{planting} + P_{fert}) - P_{harv}$

$KUE = \text{Stem } DM_{final} / (K_{planting} + K_{fert}) - K_{harv}$

Where; Stem DM_{final} is the stem dry mass at final harvest,

N, P and $K_{planting}$ are the available soil N, P and K at planting

N, P and K_{fert} are the N, P and K from fertilizer application

N, P and K_{harv} are the available soil N, P and K after final harvest

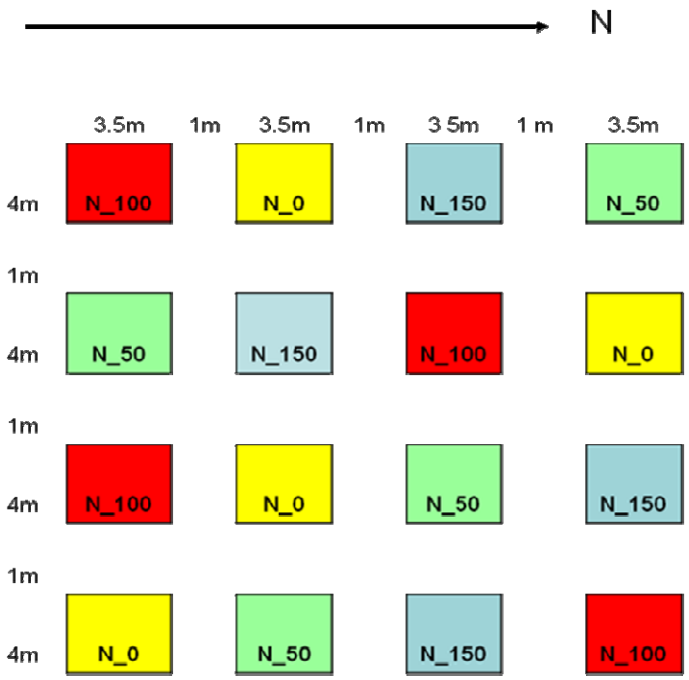
Available nitrogen was defined as the mineral nitrogen from NO_3-N and NH_4-N in the upper layers (top 60 cm) of the soil. The amount of N potentially released through mineralization, as well P and K released through different processes during the growing season were not considered.

All plots were kept weed free by hand weeding done once at 14 DAP. Similar to the 2008/09 season, there was no incidence of insects or diseases during the growing season.

A

B

Fig. 4.1. 54 day old kenaf plants (A) and the preparation of a seedbed using a Rotovator before planting (B) in the 2009/10 season



(N_0: 0 kg ha^{-1} N, N_50: 50 kg ha^{-1} N at plant + 0 ha^{-1} N at 35 DAP, N_100: 50 kg ha^{-1} N at plant + 50 kg ha^{-1} N at 35 DAP, N_150: 50 kg ha^{-1} N at plant + 100 kg ha^{-1} N at 35 DAP)

Fig. 4.2. Field layout of the nitrogen trial under rainfed conditions in the 2009/10 season

A neutron probe (Hyrophorbe®, Model 503 DR, Martinez, CA, USA) (Fig. 4.3) was used to monitor soil water content of the soil profile. The neutron probe was calibrated before the set up of the experiment in November and the field capacity of the upper 1.20 m depth was determined as 266 mm. The total plant available water (Total PAW) of the 1.20 m soil profile was determined as 116 mm with the initial PAW at planting of 96 mm. The first soil water content measurements during the growing season were taken six DAP and repeated once a week until the end of the trial. To ensure optimum soil water content for good crop emergence, 25 mm of water was applied at planting to the whole experimental area using an overhead sprinkler irrigation system. This also aimed at reducing nitrogen losses through volatilization. Thereafter, another 25 mm of irrigation water was applied at thinning out (35 DAP). Rainfall and sprinkler irrigation were monitored using six manual rain-gauges, of which two were placed in the southern part, two in the middle and two in

the northern part of the experimental site (Fig. 4.4). A neutron probe access tube was installed in the middle of each plot as showed in Fig. 4.4. The total water received by the crop (ET) was obtained by summing the rainfall during the growing season (R), the irrigation water (I) and the change in soil water content during the growing season (ΔQ), (ET = R + I ± ΔQ). The runoff/ runon were assumed to be zero because of dikes surrounding each experimental plot. Stem water use efficiency (WUE) was calculated using the stem dry mass (stem DM) and the total water received by the crop during each growing season.

Fig. 4.3. Measuring soil water content in a kenaf plot during the 2009/10 season, using a neutron probe

Fig. 4.4. Kenaf field trial area with neutron probe access tubes in the center of each plot and rain-gauges spread out over the field in the 2009/10 season

During the growing season, random plants were destructively sampled from the inner six rows of each plot (inner 7.50 m^2). Five plants were uprooted for growth parameters and biomass production analysis at 58, 96, 118 and 136 DAP. The samplings for growth analysis were made following the procedures described in Chapter 3, with the exception that the basal stem diameter was taken not from 10 cm soil level but at the contact point between the soil and the plant (0 cm soil level) in 50 cm increment. Meaning that the stem diameter was taken at 0, 50 and 100 cm soil levels. This was done in order do not to undermine the effect of agronomical practices on that stem section. Additionally, the leaf area index (LAI) and the water use efficiency over the growing season, the leaf area per plant (LA) at final harvest, as well as, the nutrient removal from the soil, nutrient use efficiency and the nitrogen content of leaves and stems were determined at or after final harvest (136 DAP). Furthermore, at the final harvest three one square meter from each plot were cut at ground level and used to separate plants in different categories according to the thickness of the basal stem diameter as follows; thick (> 20 mm), medium (< 20 mm > 15 mm), and thin plants (< 15 mm). At each sampling the biomass yield of five plants representing 0.1 m^2 was converted to the biomass yield per hectare by using the actual plant population for each plot. The LAI was taken at each sampling date by using a plant canopy analyzer (model LAI-2000 Li-Cor, Inc., Lincoln, NE, USA) following the procedures described by the manufacturer. The below canopy measurements were made over a four row area in the middle of each plot. At final harvest the leaf area (LA) of the same five plants used for biomass accumulation was measured, using a leaf area meter (model LI-3100, Li-Cor, Inc., Lincoln, NE, USA). Material from a one square meter used for chemical analysis and dry matter content of bark fibre was used to determine the bark and core weights in order to determine dry mass, bark-core ratio and bark percentage. The dry mass of bark per square mater was used to determine the bark dry mass per hectare.

All the data were analysed using analyses of variances (ANOVA) with the GLM procedures of SAS (SAS® Institute, inc., 2002-2010, 9.3 Software) to estimate treatment variations. At the difference of the chapter 3, it was used the Type III sum of square. The measured trait was considered significantly affected if Pr < 0.05, or highly significant affected if Pr < 0.01 and not significant if Pr > 0.05. Mean separation was done using Tukey's Honnestly Significant Difference (HSD) test at Pr

= 0.05. The results regarding different parameters studied in this chapter are presented in the Tables and Figures under each section regarding the concerning parameter, but the complete ANOVAs can be found in Appendix B, Tables 4.1 to 4.7.

4.3. Results and discussion

The results from the standard soil chemical and physical analysis of the top 60 cm soil layer are shown in Table 4.1 and Table 4.2. Using the recommendations by Crane (1947), Geus (1967) and Bhangoo and Cook (1993), it can be seen that the soil was suitable for kenaf production. From the comparison between the values of soil nutrients before the commencement of the experiment to those after the final harvest, the following observations may be made; the N, P and K decreased while Mg, Na and Ca increased. The decrease in N, P and K may indicate that the kenaf plants not only used the nutrients applied as fertilizer, but also the reserves from the soil.

Table 4.1. Nutrient content (kg ha^{-1}), soil texture (%) and bulk density (kg m^{-3}) of the top 60 cm soil layer of the experimental site before planting under rainfed conditions

			Ammonium acetate extractable nutrients			
pH (water)	**N**	**P Bray 1**	**K**	**Ca**	**Mg**	**Na**
5.93	410.8	248.5	514.6	4822.5	1213.7	504.4

Coarse sand (%)	**Silt (%)**	**Clay (%)**	**Bulk density**
71.3	7.1	17.9	1.5

Table 4.2. Average nutrient content (kg ha^{-1}) per treatment of the top 60 cm soil layer of the experimental site after final harvest under rainfed conditions

N level (kg ha^{-1})	N	P Bray1	K	Ca	Mg	Na
0	97.8	186.1	253.1	4519.2	1252.5	319.5
50	101.9	178.9	291.4	4542.2	1211.6	393.6
100	91.6	154.9	245.4	5234.8	1301.0	843.5
150	107.2	155.7	242.8	5114.7	1285.7	841.0

Pre-plant seed germination was ±53%, therefore, to ensure that target plant population was met, 125% more seeds were sown. To achieve the desired plant population per plot, plant population was determined by counting the number of plants per plot, followed then by thinning out at 35 DAP. Nitrogen level had no effect on kenaf seed germination. The date of 50% emergence and appearance of the first flowers were recorded at 4 and 113 DAP respectively.

Daily climatic parameters (Figs. 4.5 - 4.7) were recorded at the Automatic Weather Station as indicated in chapter 3. The average temperature was above 20ºC from the planting up to the end of March, thereafter it fell sharply to below 15ºC (Fig. 4.5.A). The relative humidity averaged at 60% for the entire growing season (Fig. 4.5.B). The rainfall (Fig. 4.6) showed variations across the growing season. Maximum rainfall of 35 mm was recorded at about two weeks after planting, while another ± 30 mm of rainfall was recorded twice on 28 March and 11 April 2010 respectively. The total rainfall over the growing season was 420 mm. This value is slightly lower than the total recorded in the previous season (2008/09) and also slightly lower than that recommended by Crane (1947) and Dempsey (1975) for kenaf production. Both these authors indicate that about 125 mm of rainfall per month or a total of about 600

mm of rainfall during the growing season should be adequate for kenaf growth. The solar radiation (Fig. 4.7.A) and the wind speed (Fig. 4.7.B) fluctuating over the growing season and declined towards the end of the growing season. The maximum solar radiation of about 25 Mj m^{-2} were recorded during the period between 20th December and 3rd of January, while the maximum wind speeds were recorded between 10th of December and 22nd of January. According to Meints and Smith (2003), for maximizing yield the temperature must remain above 10ºC throughout the growing season. The average solar radiation and temperatures were suitable for optimal growth and physiological responses of kenaf (Cosentino *et al*., 2004; Archontoulis *et al*., 2005).

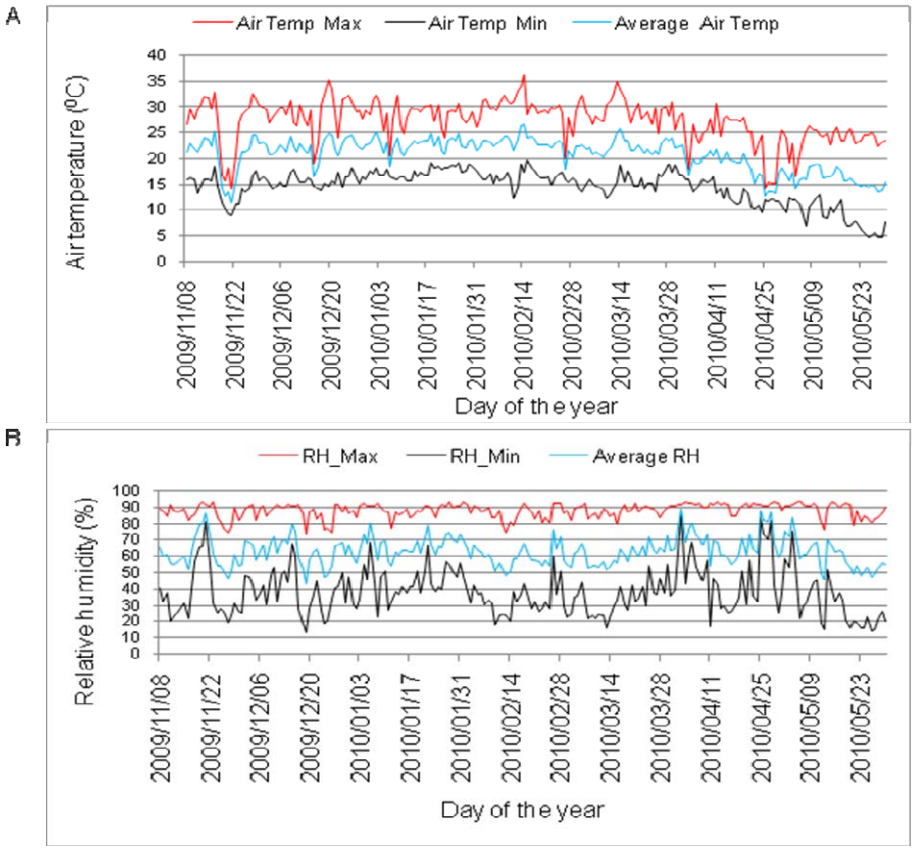


Fig. 4.5. Air temperature (A) and relative humidity (B) over the growth cycle in the 2009/10 season

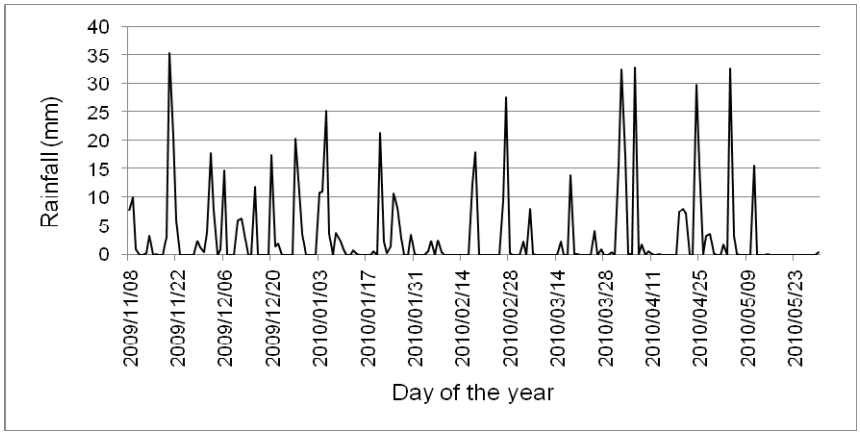


Fig. 4.6. Rainfall over the growth cycle in the 2009/10 season

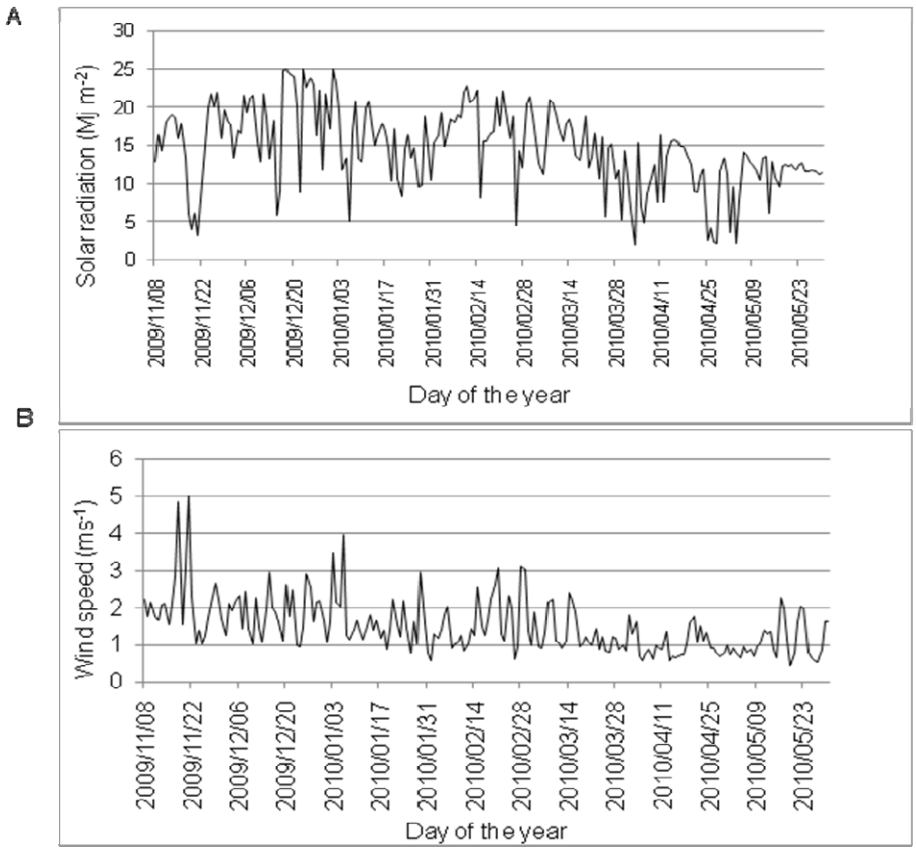


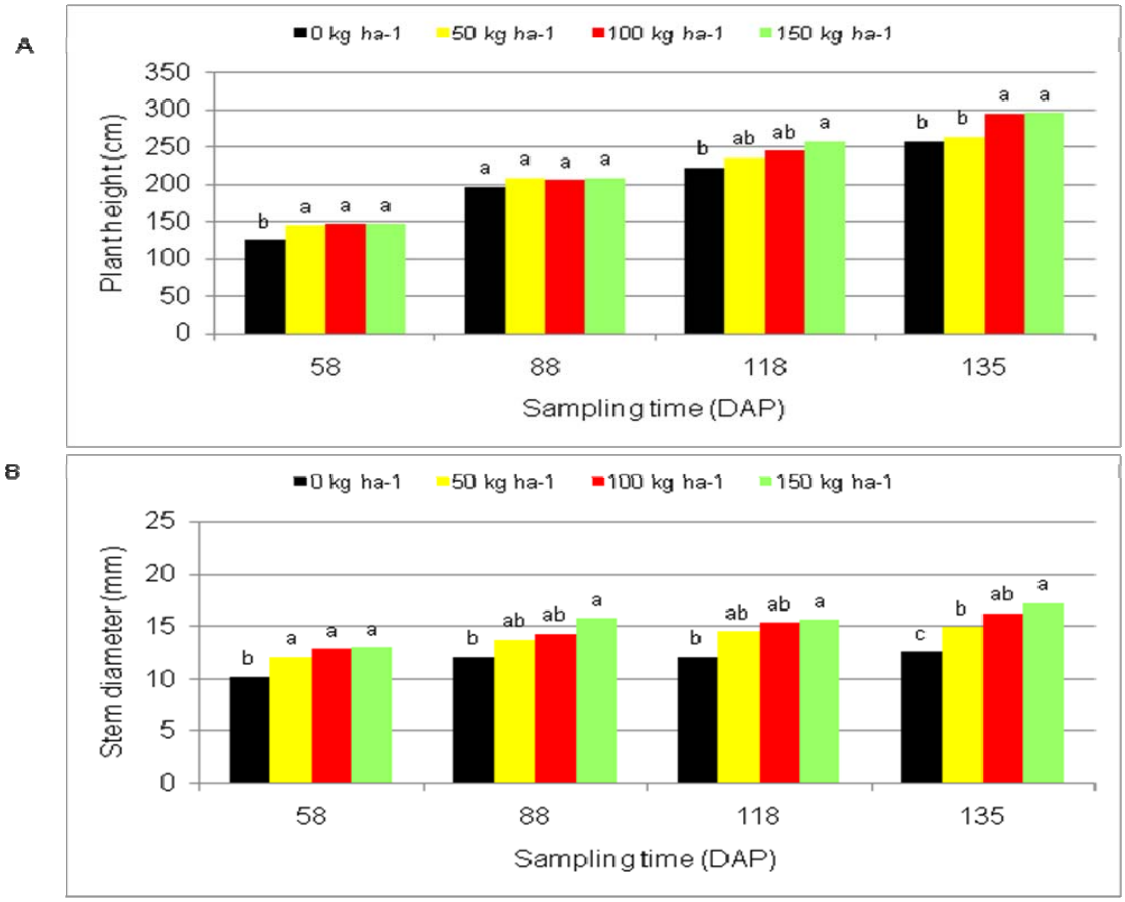
Fig. 4.7. Solar radiation (A) and wind speed (B) over the growth cycle in the 2009/10 season

4.3.1. Growth parameters

Plant height and stem diameter

Plant height reacted positively to nitrogen at all sampling dates, although it was not significantly so at 96 DAP (Fig. 4.8). This positive response is in agreement with the findings of other researchers (Muchow & Wood, 1980; Kuchinda *et al*. 2001). However, some did not observe any response (Webber, 1996 & 1999; Danalatos & Archontoulis, 2004 a & 2010). The final plant height (300 cm) for this season was higher than the peak value (283 cm) of the 2008/09 season. This could be attributed to the length of the growing season; 136 days for this crop versus 126 days for 2008/09. The average plant population 500,000 in this trial versus 300,000 plants per hectare for the 2008/09 season did not have significant effect on decreasing the height of the plants. The increase in plant height with nitrogen level may be related to the role of nitrogen on cell activity at the apical meristem. Finally, it was observed that kenaf growth continued up to the final sampling, which is in contrast with the observations of Crane (1947), who stipulated that kenaf growth ceases at flowering.

The stem diameter at different heights responded positively with significant effects to nitrogen from the start to the end of the growing season (Figs 4.8.B & 4.9). The maximum basal stem diameter (0 cm soil level) for this study (17.2 mm) was the same as that measured at 10 cm soil level in the 2008/09 season (Chapter 3). Furthermore, both these values were recorded with N_150 at the final harvest. The positive effect of N on stem diameter might be due to the role this nutrient plays in cell activities at the intercalary meristem, and also to the activities of vascular cambium, which generally increases by the application of nitrogen (Sosulski *et al*., 1963; Arkoll, 1971; Jessup & Fowler, 1976 a & b; Fagerstrom & Lohm, 1977; Rauzi, 1978). Ayre *et al*. (2009) reported an increase in stem girth of kenaf as a result of the activity of cells of the vascular cambium during secondary growth. The increase in stem diameter with nitrogen, corroborates with the findings of Hovermal (1993) and Kuchinda *et al*. (2001). However, some researchers reported a decrease in stem diameter with an increase in nitrogen level (Gonzalez-Moreno *et al*., 2004; Abdul-Hamid *et al*., 2009).



Bars of the same sampling date with the same letter are not significantly different from each other

Fig. 4.8. Plant height (A) and stem diameter at soil level (B) as affected by nitrogen level at different sampling times under rainfed conditions

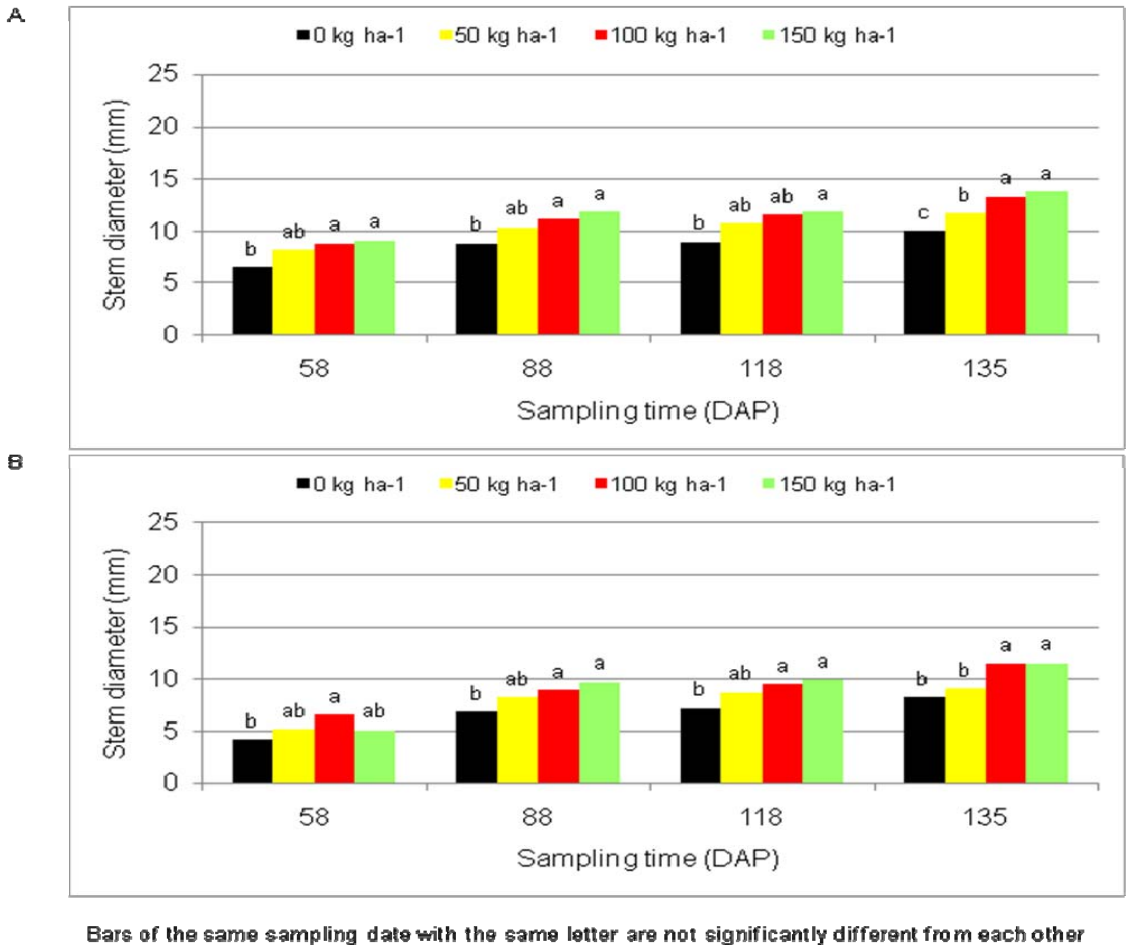


Fig. 4.9. Stem diameter at 50 cm (A) and 100 cm (B) soil level as affected by nitrogen level at different sampling times under rainfed conditions

Percentage of basal stem diameter spread at final harvest

The stems from a 1 m^2 area were divided into three classes based on the basal diameter, namely thin (0 cm soil level diameter < 15 mm), medium (0 cm soil level diameter > 15mm but < 20 mm) and thick (0 cm soil level diameter > 20 mm) stems (Table 4.3). The results showed a highly significant effect (Pr < 0.01) of nitrogen on the percentage of thin and medium sized plants, and a significant effect (Pr < 0.05) on the percentage of thick plants. A higher percentage of thin plants (89%) was obtained with no nitrogen applied (control), while adding higher levels of nitrogen decreased it to 57.8%. The medium plants ranged from 10.0% (0 kg ha^{-1}) to 37.2 % (150 kg ha^{-1}). Less than 5% of the plants could be classified as thick at the highest

nitrogen level (150 kg ha^{-1}), while for the remaining treatments only about 2% of the plants could be classified as thick.

Table 4.3. Percentage of basal stem diameter spread as affected by nitrogen level under rainfed conditions at the final harvest

Nitrogen level (kg ha^{-1})	Spread of plants (%)		
	Thin	Medium	Thick
0 kg ha^{-1}	88.95 a	9.95 b	1.10 b
50 kg ha^{-1}	74.67 ab	24.09 ab	1.26 b
100 kg ha^{-1}	62.34 bc	35.49 a	2.15 ab
150 kg ha^{-1}	57.82 c	37.15 a	4.85 a
Mean	70.95	26.67	2.34
Pr	***	***	*
HSD	15.188	14.16	2.9534

Means within the same column with the same letter are not significantly different from each other

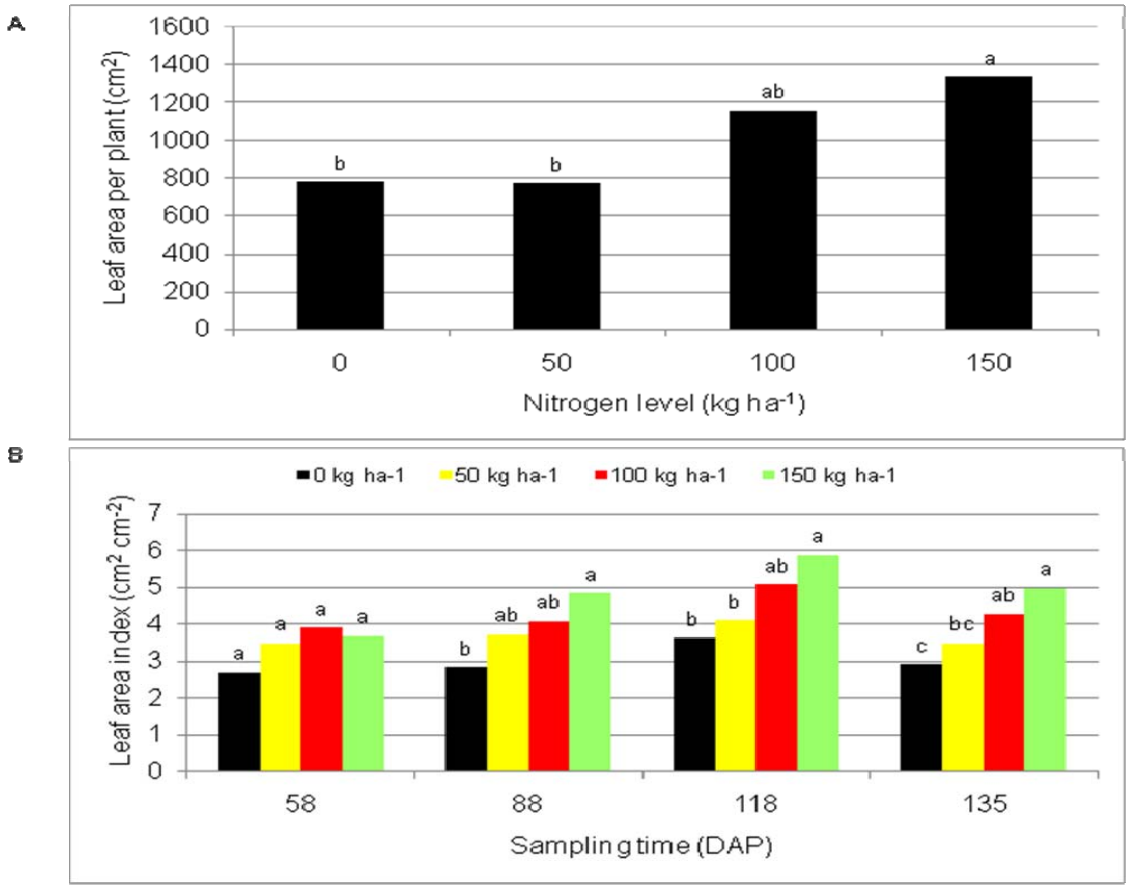
*: significant at 5% level of probability, ***: highly significant at 1% level of probability

Leaf area per plant (LA) and Leaf area index (LAI)

According to Ayub *et al*. (2007) leaf area is an indication of the size of the assimilatory system of the plant and is the product of leaf length and breadth. Furthermore, Carbery and Muchow (1992 a & b) indicate that leaf area determines the proportion of radiation intercepted, and consequently the stem yield. Similarly leaf area index (LAI), is of great importance for light interception and photosynthesis (Danalatos & Archontoulis, 2004 a). It also affects the evaporation and transpiration (Cooper *et al*., 1983). Kuo *et al*. (2011) mention that with an unfavourable fertilizer supply and scarcity of water, the plant lacks the raw materials for synthesis of an extensive leaf system, and the LAI remains insufficient for photosynthesis purpose.

Leaf area was measured only at final harvest and was significantly (Pr < 001) affected by nitrogen level, with the two higher nitrogen levels (100 and 150 kg ha^{-1}) giving significantly higher values than the two lower N treatments (Fig. 4.10.A).

Although LAI responded positively to nitrogen treatment at each sampling, a highly significant effect (Pr < 0.01) was only detected at the second, third and fourth samplings (Fig. 4.10.B). The increase in LAI with increase in nitrogen might be due to an increased plant height (Fig. 4.8.A). It is known that increasing plant height increase the insertion points for leaves on the plant and this may be one of the explanations as to the increase in LAI with nitrogen level. Across the growth cycle, the maximum LAI for each treatment was observed at 118 DAP which was then followed by a decline up to the final harvest. This might be due to sensescence of the older leaves. It could also have been accelerated by the onset of the flowering which was recorded at 114 DAP. In fact, at the onset of flowering a high percentage of photosynthates are diverted to those plant parts (sinks). However, the maximum LAI values reached in this study seemed to be in the same range of the results found under sufficient soil water content from Danalatos and Archontoulis (2004 a; b & 2005, 2010). Nevertheless, they failed to record any response of LAI to nitrogen level.



Bars with the same letter (A) and bars of the same sampling date with the same letter (B) are not significantly different from each other

Fig. 4.10. Leaf area per plant at final harvest (A) and leaf area index over the growth cycle (B) as affected by nitrogen level under rainfed conditions

4.3.2. Biomass production

The stem and leaf components

Nitrogen had a significant effect on stem dry mass per plant at each sampling date; highly significantly at 58 and 118 DAP ($Pr < 0.01$) and significantly at 96 and 136 DAP ($Pr < 0.05$) (Fig. 4.11.A). The final values of stem dry mass per plant obtained in this study were lower as compared to that of the previous year (2008/09), despite taller stems in this study. The low values found in this study compared to the values in the previous season may be related to the stem diameter. Similar to the findings of

the present study, Hossain *et al*. (2011 a & b) also found an increase in stem dm per plant with increasing nitrogen level in kenaf. Unlikely the stem dry mass per plant, the stem dry mass per hectare (Fig. 4.11.B) was significantly affected by nitrogen level only at 58 ($Pr < 0.01$) and 96 DAP ($Pr < 0.05$). Except some few cases, the trend of increase in stem dry mass per plant was observed at each sampling time. In agreement with our findings Abdul-Hamid *et al.* (2009) found a positive effect of nitrogen fertilization on stem dm per hectare. However, Danalatos & Archontoulis (2005) and Gonzalez-Moreno *et al*. (2004) found no response.

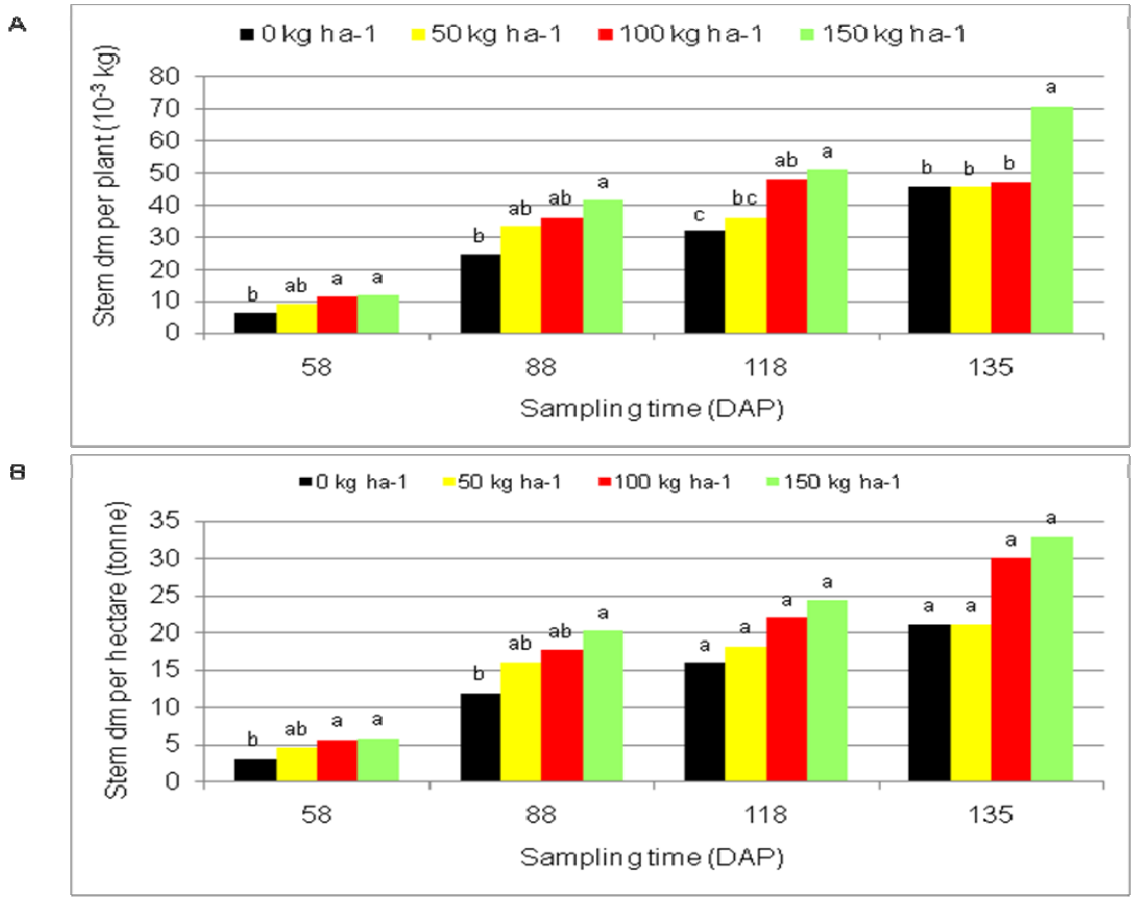
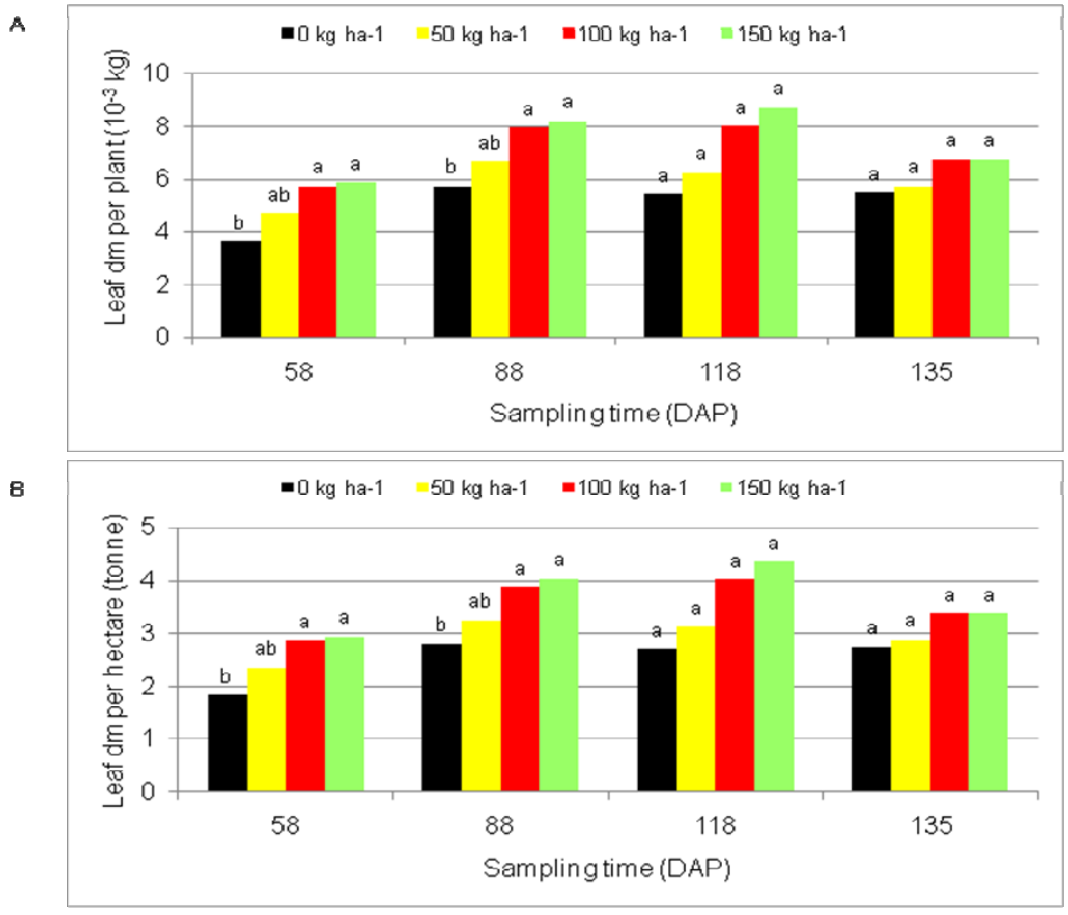


Fig. 4.11. Stem dry mass per plant (A) and per hectare (B) as affected by nitrogen level at different sampling times under rainfed conditions

Nitrogen application level increased the leaf dry mass per plant (Fig. 4.12.A) and leaf dry mass per hectare (Fig. 4.12.B). The effect was significant for the two parameters only at 58 and 96 DAP. However, a substantial decrease in leaf dry mass, which may be attributed to the ageing of leaves, was noted from the third to the last sampling. Abdul-Hamid *et al*. (2009) reported both the lack of response and a positive response of kenaf leaf dm to nitrogen in a dry and wet season respectively. Hossain *et al.* (2010) reported an increase in leaf dm with nitrogen level up to 200 kg ha^{-1}, whereafter it declined at 400 kg ha^{-1} N.



Bars of the same sampling date with the same letter are not significantly different from each other

Fig. 4.12. Leaf dry mass per plant (A) and per hectare (B) as affected by nitrogen level at different sampling times under rainfed conditions

The total dry mass per plant (Fig. 4.13.A) and the total dry mass per hectare (Fig. 4.13.B) responded positively to increased levels of nitrogen, however it was not significantly so at all sampling times. The trends are furthermore similar to that reported for the stem component.

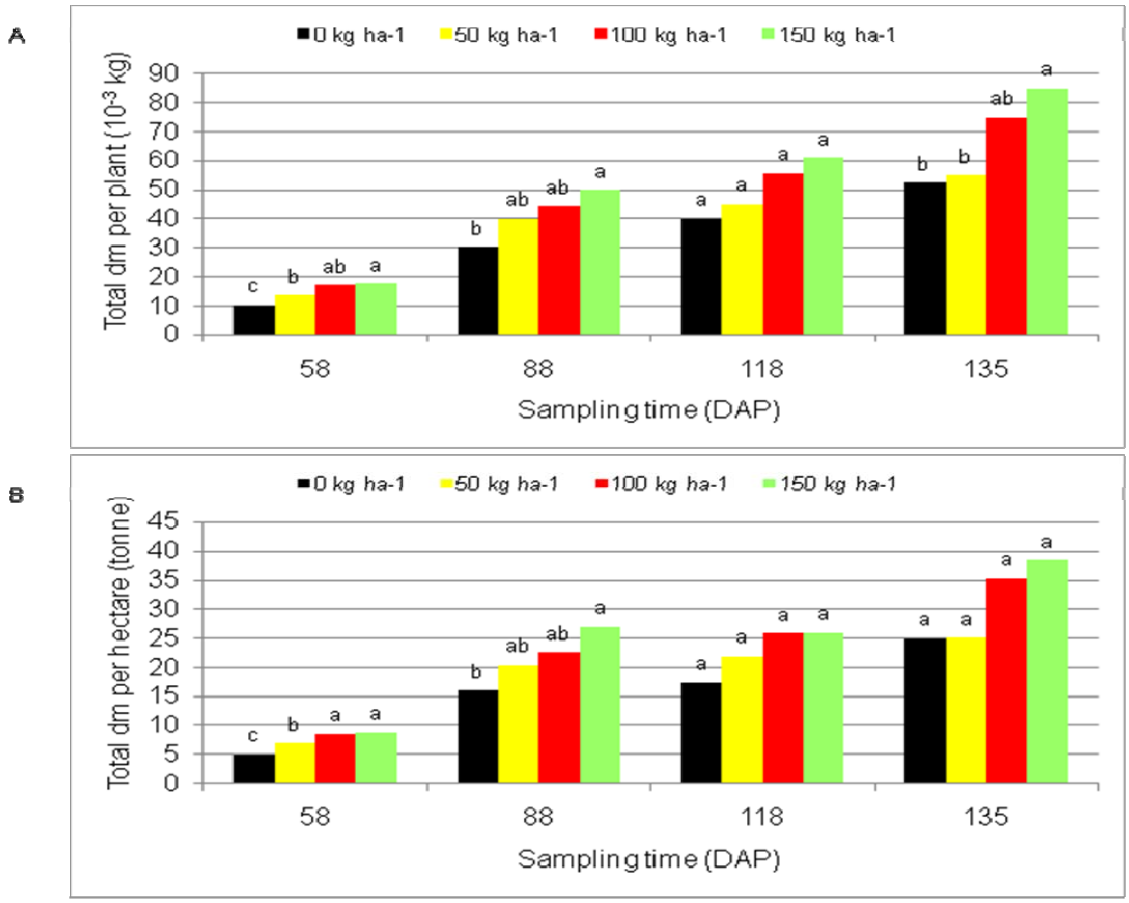


Fig. 4.13. Total dry mass per plant plant (A) and total dry mass per hectare (B) at different sampling times as affected by nitrogen level under rainfed conditions

Nitrogen had no significant effect on the contribution of stem and leaf dry mass to the total dry mass (Figs. 4.14). However, the decrease in leaf percentage observed from the first to final harvest might be due to the ageing of the plants and the increased contribution of the reproductive part (Data not showed).

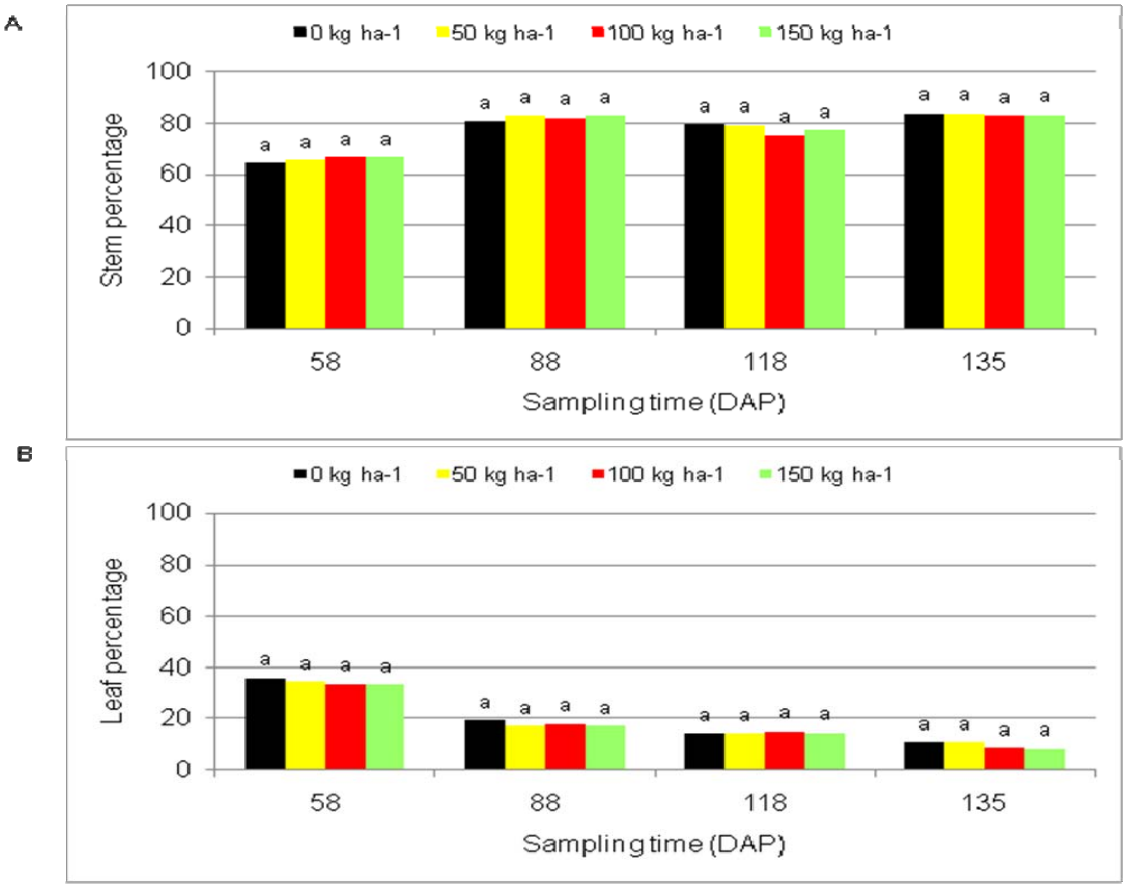


Fig. 4.14. Stem (A) and leaf percentage (B) at different sampling times as affected by nitrogen level under rainfed conditions

The bark component

The bark dry mass per hectare was significantly influenced by nitrogen fertilization with an increase in yield as nitrogen level increased (Table 4.4).

Although nitrogen level did not have a significant effect on bark-core ratio and bark percentage, plants receiving no nitrogen had the highest bark-core ratio and bark percentage of all the treatments (Table 4.4). This may be due to an increase in core content as promoted by nitrogen application. In general, the values of bark percentage and bark-core ratio from this experiment are in the same range with

those found by other researchers (Wood, 1978; Sellers *et al*., 1993; Mambeli & Grandi, 1995; Zhou *et al*., 1998; McMillin *et al*., 1998; Alexopoulou *et al*., 2000; Webber *et al*., 2002; Sullivan, 2003 a & b and Baldwin & Graham, 2006).

Table 4.4. Bark-core ratio, bark percentage and bark dry mass as affected by nitrogen level at the final harvest under rainfed conditions

Nitrogen level (kg ha^{-1})	Bark dry mass (tonne)	Bark-core ratio	Bark percentage
0	7.84 ab	0.59 a	36.98 a
50	7.05 b	0.51 a	33.53 a
100	10.27 ab	0.52 a	34.22 a
150	11.51 a	0.53 a	35.54 a
Mean	9.17	0.54	35.07
Pr	*	NS	NS
HSD	3.9486	-	-

Means within the same column with the same letter are not significantly different from each other

NS: not significant, *: significant at 5 % level of probability

4.3.3. Chemical composition and dry matter content of kenaf bark fibre

Of all the parameters under this section, nitrogen significantly affected only the acid detergent fibre (ADF) (Pr < 0.01) and crude fibre (Pr < 0.05) (Tables 4.5 and 4.6). However, ADF and neutral detergent fibre (NDF) tended to increase up to 100 kg ha^{-1}, followed by a decline at 150 kg ha^{-1}, conversery hemicellulose declined. Dry matter content and cellulose increased with increase in nitrogen, while ligninin decreased. Ash and crude fibre contents did not show clear trend in response to nitrogen level. In agreement with our results, Ayub *et al*. (2007) also reported an increase in dry matter content with increase in nitrogen level in maize forage. The ADF, NDF, dry matter content, crude fibre and cellulose contents found in this study were higher compared to the results from the 2008/09 season, while the lignin was slightly lower. The reason of higher values found in this study may be perhaps due to the fact that

the samples were not stored for a long period before their assessment as was the case for the 2008/09 samples. In fact, the 2008/09 samples were stored for about a year before their assessment, while the current samples were only stored for a month.

Table 4.5. ADF, NDF, dry matter content and crude fibre content as affected by nitrogen level under rainfed at the final harvest

Nitrogen level (kg ha-1)	ADF (%)	NDF (%)	Dry matter (%)	Crude fibre (%)
0	66.5 b	76.5 a	93.0 a	58.8 b
50	68.9 a	77.2 a	93.3 a	58.2 b
100	69.8 a	79.6 a	93.9 a	59.8 ab
150	67.6 ab	77.3 a	94.2 a	62.5 a
Mean	68.20	81.00	93.58	59.84
Pr	***	NS	NS	*
HSD	2.2451	-	-	3.4517

Means within the same column with the same letter are not significantly different from each other

NS: not significant, *: significant at 5 % level of probability; ***: highly significant at 1% level of probability

Table. 4.6. Cellulose, hemicellulose, lignin and ash contents as affected by nitrogen level under rainfed conditions at the final harvest

Nitrogen level (kg ha^{-1})	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)
0	56.0 a	10.08 a	10.45 a	1.87 a
50	58.9 a	8.32 a	10.04 a	1.81 a
100	59.1 a	9.73 a	9.61 a	1.93 a
150	60.2 a	8.97 a	9.26 a	1.97 a
Mean	58.58	9.28	9.84	1.90
Pr	NS	NS	NS	NS
HSD	-	-	-	-

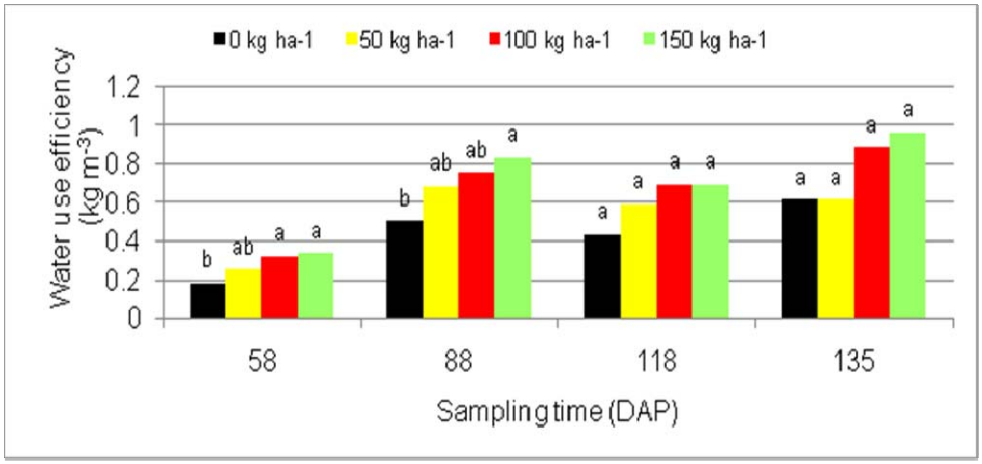
Means in the same column with the same letter are not significantly different from each other

NS: not significant

4.3.4. Water use efficiency (WUE)

Kenaf is a fast growing crop, which when produced under optimal conditions has the ability to quickly develop a canopy, which can cover the soil surface and reduce evaporation from the soil so that the water use efficiency increases. A significant effect of nitrogen on WUE was detected only at 58 DAP ($Pr < 0.01$) and at 96 DAP ($Pr < 0.05$). Generaly the WUE of the highest nitrogen level was similar to those recorded for 100 kg ha^{-1}, but was always significantly higher than the values recorded for the control (Fig. 4.15). A general increase in WUE from the first to the final harvest was observed for each nitrogen level, except the 50 kg N ha^{-1}, for which the WUE remained constant from 96 to 136 DAP. The increase in WUE with increasing nitrogen level may be a reflection of the increase in stem dm mass per hectare due to nitrogen. The final and maximum WUE obtained in this study ranging between about 0.6 and 1 kg of stem dry mass per m^3 were lower than the value reported by Fernando *et al*. (2004) (1.23 kg m^{-3}) . Reporting the WUE in terms of total dry mass, Quaranta *et al*. (2000), Danalatos and Archontoulis (2010) and Banuẽlos *et al*. (2002) reported about 4 kg of yield per m^3 of water. Brueck (2008) indicated that an increase in WUE in response to nitrogen level may be attributed to

the effect of this nutrient on the biomass water use efficiency and the decrease in soil evaporation from a bare soil surface due to faster plant canopy development.



Bars of the same sampling date with the same letter are not significantly different from each other

Fig. 4.15. Stem water use efficiency at different sampling times as affected by nitrogen level under rainfed conditions

4.3.5. Nitrogen, potassium and phosphorus removal by the crop, nitrogen content of leaves and stems and nitrogen, phosphorus and potassium use efficiency

Nutrient removal from the soil is of considerable importance in estimating fertilization requirements for optimum growth and development of the crop. By considering the nutrient content of the soil before planting and the amounts removed from the soil, including the amount of nutrients contained in the harvestable parts of the plants, as well as the losses due to different processes, one can have an idea on how to restore the nutrient status of the soil for sustainable agriculture production. The results showed a highly significant and positive effect ($Pr < 0.01$) of nitrogen level on N removal, but not on K and P removal (Table 4.7). Adamson *et al*. (1979) also reported an increase in nitrogen removal with increase in nitrogen level, but they considered only the amount removed with plant material. Interesting in this is the fact that where no nitrogen fertilizer was applied, the crop removed about 76% of the soil nitrogen, while more than 70% of the initial soil nitrogen was removed where

nitrogen fertilizer was applied regardless of the level. The fact that the kenaf plants have removed more than 76% of the soil nitrogen content under the control conditions is an indication of the good ability of kenaf roots to extract nitrogen from the soil. The percentages of K removed were in the range of 63.9 and 74.9 %, while P removed varied between 47 and 60 % of the initial soil content. As can be seen P removal showed very low values in comparison to the other two nutrients suggesting that the kenaf plants do not have a high P requirement. This viewpoint is supported by the observation of Adamson *et al*. (1979). On the other hand it can be seen that kenaf has a high nitrogen requirement, while it has a moderate potassium requirement.

The nitrogen content of both the stem and leaves tended to increase with an increase in nitrogen level (Table 4.7) although it was not significantly so. However, in terms of the stem N content, the maximum value (1.70 g kg^{-1}) was reached under control conditions (0 kg ha^{-1}). For all treatments, the nitrogen content of the leaves was 7 to 10 fold that of the stems. High leaf nitrogen content as compared to the stem may be explained by the fact that the leaf is the center of all physiological process for any plant. It is also widely accepted that leaf nitrogen content and photosynthetic capacity are highly correlated (Field & Mooney, 1983). According to Gulmon and Chu (1981) most plants respond to an increase in nitrogen availability with significant increases in leaf nitrogen content. Phillips *et al*. (2002), De Andrés *et al*. (2010) and Hossain *et al*. (2011 a & b) also found a higher nitrogen content in leaves compared to the stems. Rosolem and Mikhelsem (1989) also reported lower nitrogen content in stems compared to leaves in cotton.

Table 4.7. N, P and K removal, and leaf and stem N contents as affected by nitrogen level at the final harvest

Nitrogen level (kg ha^{-1})	N removal (kg ha^{-1})	P removal (kg ha^{-1})	K removal (kg ha^{-1})	Leaf N content (g kg^{-1})	Stem N content (g kg^{-1})
0	364.73 d	112.82 a	361.46 a	12.50 a	1.70 a
50	428.46 c	99.53 a	310.75 a	13.83 a	1.38 a
100	462.4 b	136.33 a	371.80 a	13.83 a	1.45 a
150	510.8 a	107.45 a	374.35 a	14.95 a	1.60 a
Mean	441.60	114.03	354.59	13.78	1.53
Pr	***	NS	NS	NS	NS
HSD	28.39	-	-	-	-

Means within the same column with the same letter are not significantly different from each other

NS: not significant, ***: highly significant at 1% level of probability

All the calculations were done with the assumption that the average soil bulk density of the 1.00 m soil profile is 1.5 kg m^{-3} and only the nutrients in the top 60 cm layer of the soil was used by the plants. In general the N-, P- and K use efficiency tended to increase with increase in nitrogen level (Table 4.8). A significant nitrogen effect was only recorded for K use efficiency. The N use efficiency recorded in the present study was far higher compared to the value of 0.8 kg kg^{-1} N reported by Fernando *et al*. (2004). The reason might be linked to the soil nitrogen reserve before planting, 410.8 kg ha^{-1} (Table 4.1) for our soil, which was substantially lower as compared to what has been indicated for their study (6500kg ha^{-1}). They have probably experienced substantial nitrogen losses through different mechanisms. However, some researchers found that N use efficiency decreased with increasing nitrogen level in cotton (Rochester *et al*., 2009). Nevertheless, Rochester *et al*. (2009) have used a different approach to that used in this trial. The authors divided the yield of lint by the nitrogen uptake and nitrogen content of the crop and reported higher N use efficiency where no fertilizer was applied.

Table 4.8. Nitrogen, phosphorus and potassium use efficiencyas affected by nitrogen level at 136 DAP

Nitrogen level (kg ha^{-1})	N use efficiency (kg stem kg^{-1} N	P use efficiency (kg stem kg^{-1} N	K use efficiency (kg stem kg^{-1} N
0	57.37 a	176.9 a	52.35 b
50	50.54 a	188.7 a	68.06 ab
100	64.73 a	198.7 a	81.64 ab
150	63.85 a	280.8 a	88.83 a
Mean	59.12	211.26	72.72
Pr	NS	NS	*
HSD	-	-	35.683

Means within the same column with the same letter are not significantly different from each other

NS: not significant, *: significant at 5 % level of probability

4.4. Conclusions and recommendations

Overall, the results of this study show that an increase in nitrogen level up to the maximum value used (150 kg ha^{-1}) promoted an increase in all growth parameters and biomass yield. The increase in stem yield was generally achieved via increased plant height and stem diameter. Nutrient removal, particularly nitrogen and potassium were substantialy increased by nitrogen, which suggests that consideration should be given to replenish these nutrients through fertilization management. There was also a general tendency of increase in nutrient use efficiency with increasing N fertilization. An increase in the amount of nitrogen also played an important role in reducing the lignin content of the bark, which is undesirable in pulp and paper production, but it also decreased the hemicellulose content. However, the cellulose content increased up to 100 kg ha^{-1} only. Water use efficiency also responded positively to nitrogen, which may indicate the importance of sufficient nitrogen for soil water uptake by the plants.

The increase in the stem yield up to the maximum nitrogen level applied, suggests that further studies should be conducted with higher nitrogen levels to determine the optimum nitrogen rate for efficient productivity. Much more information is needed about the interaction effects between nitrogen and other nutrients such as potassium and phosphorus and their combined effects on growth, yield and quality of kenaf.

CHAPTER 5.

RESPONSE OF KENAF YIELD AND QUALITY TO NITROGEN UNDER IRRIGATED CONDITIONS

5.1. Introduction

Increasing concern over the effect of climate change on water resources necessitates that water should be used more effectively in irrigated agriculture to increase and sustain productivity (Istanbulluoglu, 2009). Andersen (1979) pointed out that low rainfall is the factor behind most of the adversities of the agricultural sector. Bloch *et al*. (2006) singled out that low water availability is one of the major causes for crop yield reduction, affecting the majority of the arable land around the world. Furthermore, it has also been indicated that when the occurrence of water stress coincides with crop sensitive growth periods (Istanbulluoglu, 2009), the crop yield and farmer's income decrease (Fatemi *et al*., 2011). Thus maintaining a high soil water status plays an important role in tolerance to water stress and in yield stability of crops (Teulat *et al*., 1997). One should also take in consideration that nutrient uptake by plants and microbial transformation of nutrients responds differently to water availability. Furthermore, it is well known that South Africa is a relatively dry country, with very erratic rainfall leading to substantial variation in productivity across locations and across years within the same location. Hence, irrigation needs to be applied adequately to enable optimum growth and production of a crop.

However, information on the effect of nitrogen level on kenaf under irrigated conditions in a South African environment is scarce. Hence, the purposes of the present study is to investigate the effect of nitrogen level on growth parameters, biomass production, stem yield composition, nutrient removal from the soil by the crop and nutrient use by kenaf "Tainung 2" under optimal water supply conditions.

Hypotheses

- increasing nitrogen fertilization under optimal water supply will increase the growth parameters of kenaf plants

- increasing nitrogen fertilization under optimal water supply will increase the yields of kenaf
- increasing nitrogen fertilization under optimal water supply will improve qualitatively the chemical characteristics of fibre
- increasing nitrogen fertilization under optimal water supply will increase the stem water use efficiency
- increasing nitrogen fertilization under water supply will increase the nitrogen use efficiency, the nutrient removal from the soil and the nitrogen content of leaves and stems

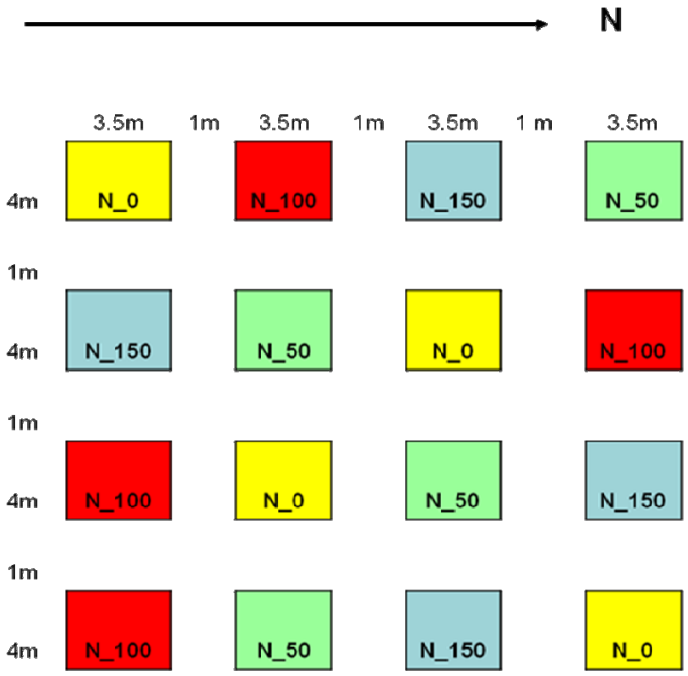
5.2. Materials and Methods

The details of this experiment are in general similar to what have been described in Chapter 4. However, some exceptions must be noted as the planting took place on the 8th of December or a day before the rainfed trial and the final harvest was on 135 versus 136 DAP (Days after planting) for the rainfed trial. During the growth cycle the harvesting dates for the two crops were similar for the first and third samplings only (58 and 118 DAP), while the second sampling was done on 88 DAP and the last on 135 DAP for this trial. Soil water content was recorded similarly to the rainfed trial with installation of rain gauges and neutron access tubes. This crop received sprinkler irrigation only directly after planting (25 mm), while for the rest of the growing season the water was supplied via drip irrigation. In addition, it should be noted that the weather data were identical to that of the rainfed crop (Fig.4.6). The layout of the experimental site is given in Fig.5.1. The crop received water via a drip irrigation system starting from the 31st of December (23 DAP) to the end of the growing season. One dripper line was placed between two adjacent plant rows, giving a total of seven dripper lines per plot (Fig. 5.2). Each of the dripper lines had 12 drip emitters spaced 30 cm apart with an average drip rate of 2.175 L h^{-1}. The dripper lines from each plot were then connected to a sub-subline (Fig 5.2). The water flow to each experimental unit was controlled by an individual valve. A border was made around each plot with a band of soil to avoid lateral flow of water onto the plot, as shown in Fig. 5.3. The design of the irrigation system is shown in Fig. 5.4.

The irrigation water was applied to refill the soil profile of each plot to field capacity on a weekly basis.

Irrigation was managed using an excel-based calculator to combine meteorological, soil and plant data to determine the soil water balance in the top 1.20 m of soil. The total water received by the crop was obtained by summing the 25 mm sprinkler irrigation, the water from the rainfall during the growing season and the total amount of drip irrigation, as well as the initial soil water content.

The weather data were identical to that of the rainfed crop (Fig. 4.3 to Fig. 4.5). All the data were statistically analysed as indicated in chapter 4. The results regarding different parameters studied in this chapter are presented in the Tables or Figures under each section regarding the parameter studied, but the complete ANOVAs can be found in Appendix C, Tables 5.1 to 5.7.



(N_0: 0 kg ha^{-1} N, N_50: 50 kg ha^{-1} N at plant + 0 ha^{-1} N at 35 DAP, N_100: 50 kg ha^{-1} N at plant + 50 kg ha^{-1} N at 35 DAP, N_150: 50 kg ha^{-1} N at plant + 100 kg ha^{-1} N at 35 DAP)

Fig. 5.1. Field layout of the nitrogen trial under irrigated in the 2009/10 season at the Hatfield Experimental Farm, UP

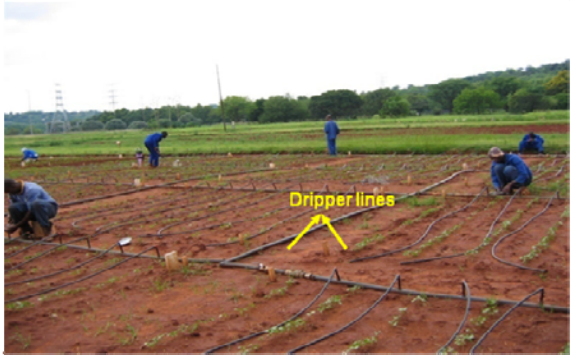


Fig. 5.2. Dripper lines being installed at the kenaf experimental site in the 2009/10 season

Fig. 5.3. A kenaf plot with ridges of soil all around to avoid the in and out flow of water from the plots, in the 2009/10 season

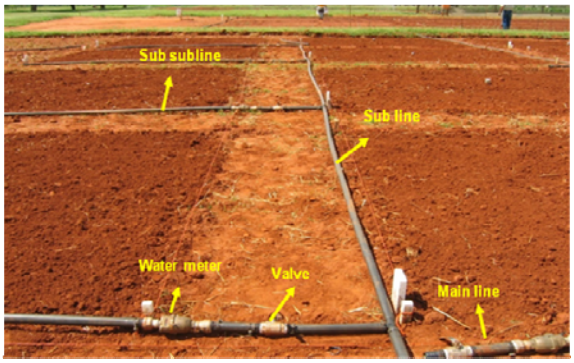


Fig. 5.4. Design of the irrigation system at the kenaf experimental site in the 2009/10 season

5.3. Results and discussion

The chemical characteristics of the soil after the final harvest are given in Table 5.1. The average values of N, P, K and Mg were substantially lower in comparison to their initial values (Table 4.1. A). The Na and Ca showed higher values at the final harvest than they were at the beginning of the season. Furthermore, it has to be noted that the average values found at the end of the season for N, P, K, and Ca with exception to Mg and Na were lower under irrigated than under rainfed conditions. This may be due to the fact that nutrient uptake by the plants and microbial transformations of nutrients respond differently to water availability.

Table 5.1. Nutrient content (kg ha^{-1}) of the top 60 cm soil layer of the experimental site at the final harvest under irrigated conditions

N level (kg ha^{-1})	N	P Bray1	K	Ca	Mg	Na
0	47.14	165.89	240.27	5840.63	1433.96	907.41
50	48.02	175.09	245.38	5066.14	1293.37	593.01
100	44.22	184.8	194.26	4733.85	1232.03	498.43
150	47.18	187.1	217.27	4887.22	1278.04	570.00

The germination percentage recorded in the field was similar to that of the rainfed trial regardless of nitrogen level, as result the target plant population was achieved. The 50% emergence date was recorded at 4 DAP and the first flowers appeared at 116 DAP. Unlikely under rainfed conditions, lodging was observed at final harvest irrespectively of nitrogen level.

5.3.1. Growth parameters

Plant height and stem diameter

Conflicting results were found across the sampling dates in terms of plant height (Fig. 5.5.A). Nitrogen significantly increased plant height only at 58 DAP. However, the maximum plant height at that sampling date was reached with 100 kg ha^{-1}. At 118 and 135 DAP, though not significantly so the plant height increased with nitrogen from 0 kg ha^{-1} to 150 kg ha^{-1}. In general the average values found in this study towards the end of the season were higher than the values showed for the previous year as well as the ones found under rainfed conditions. For example, even with 0 kg ha^{-1} at 135 DAP, the control plants measured an average height of 307 cm which was taller than the maximum height (296 cm) recorded for the rainfed crop at final harvest. The good plant growth with no additional nitrogen (control) for this study may show that sufficient water supplied could have mobilized nitrogen and other nutrients from the soil and made them available for plant uptake. Furthermore, both positive and zero responses of kenaf plant height to nitrogen have been shown in literature (Muchow & Wood, 1980; Webber, 1996 & 1999; Kuchinda *et al*. 2001; Danalatos & Archontoulis, 2004 a & 2010).

The stem diameter at different heights responded positively to nitrogen (Figs. 5.5.B & 5.6). A significant nitrogen effect ($Pr < 0.01$) was recorded for basal stem diameter (0 cm) and at a height of 100 cm from soil level at each sampling date. Regarding the stem diameter at 50 cm soil level, a significant nitrogen effect was recorded only at 58 and 135 DAP. The stem diameter at 50 cm and 100 cm from the soil surface of the irrigated plants were higher in comparison to those from the rainfed trial. The basal stem diameter was, however, within the same range regardles of water regime. The general increase in stem diameter with increased levels of nitrogen of this study corroborates with the findings of Hovermal (1993) and Kuchinda *et al*. (2001) and our own results from Chapter 4. Nevertheless, as indicated in Chapter 4, some researchers reported a decrease in stem diameter with an increase in nitrogen (Gonzalez-Moreno *et al*., 2004; Danalatos & Archontoulis, 2005; Abdul-Hamid *et al*., 2009).

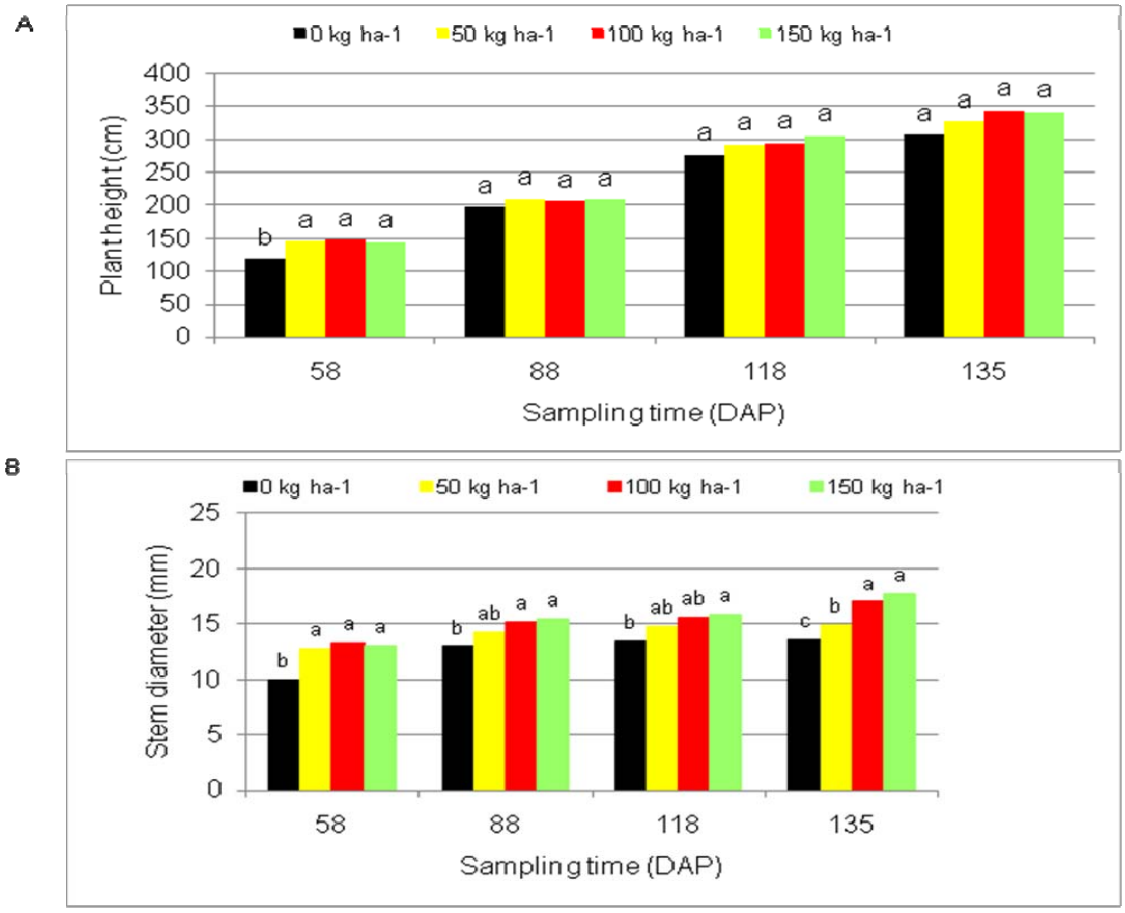


Fig. 5.5. Plant height (A) and stem diameter at 0 cm soil level (B) as affected by nitrogen level at different sampling times under irrigation

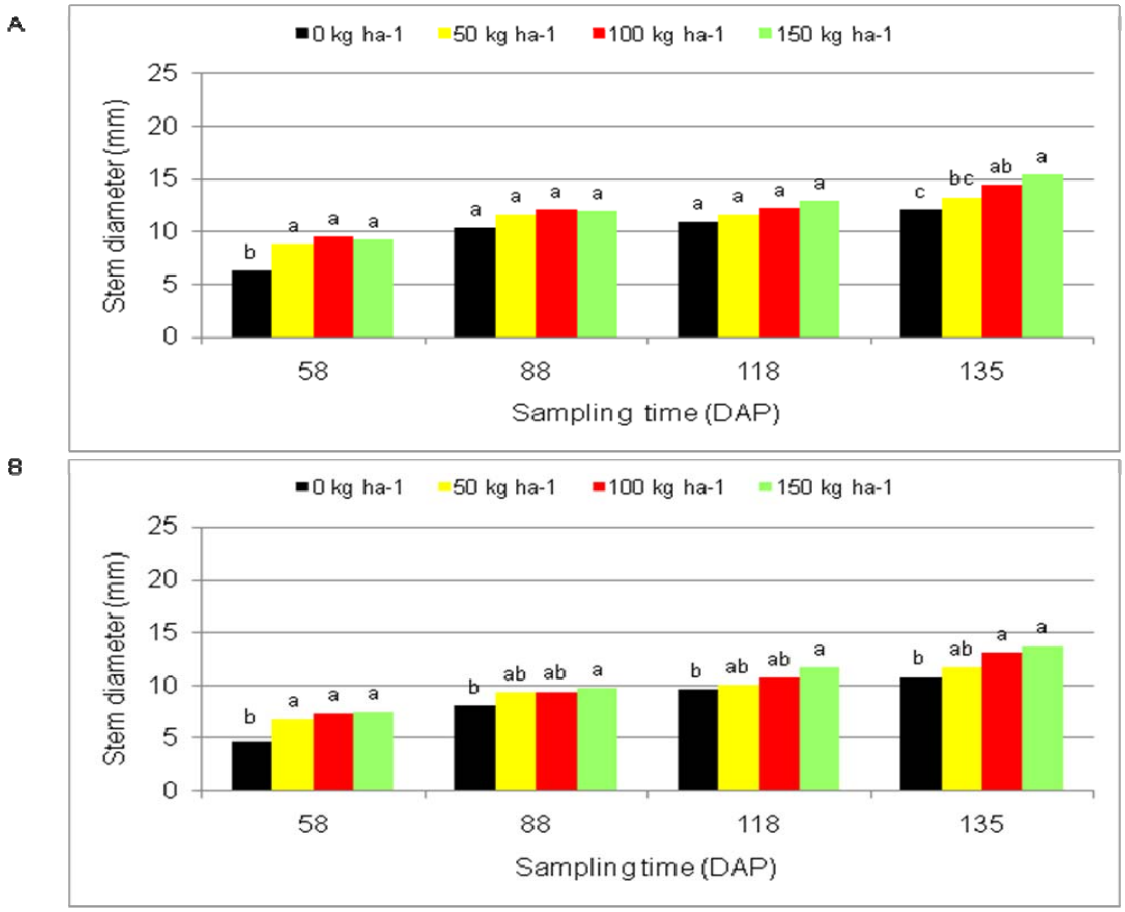


Fig. 5.6. Stem diameter at 50 cm (A) and 100 cm (B) soil level as affected by nitrogen level at different sampling times under irrigation

Percentage of basal stem diameter spread at final harvest

The percentage of thin plants (basal diameter < 15 mm) decreased significantly (Pr < 0.01) with an increase in nitrogen, while those of the medium (basal diameter > 15mm but < 20 mm) and thick plants (basal diameter > 20 mm) increased significantly (Pr < 0.01) (Table 5.2). The control treatment (0 kg ha^{-1}) had a significantly larger percentage (81.59%) of thin plants and a lower percentage (17.52%) of medium plants as compared to the plants receiving nitrogen. Regarding thick stemmed plants, less than 10% of the stems could be classified as being thick in all the treatments. The proportions of thick and medium plants found in this study

were higher than those from the rainfed but lower than those from the 2008/09 season (Data not showed). Generally the lower percentage of thick plants found in the two studies (rainfed and irrigated trials) in comparison to the 2008/09 trial could be due to the higher plant population (500,000 plants ha $^{-1}$) used in the nitrogen trial of the 2009/10 season as compared to the average 300,000 plants ha^{-1} of the 2008/09 season.

Table 5.2. Percentage of basal stem diameter spread as affected by nitrogen level under irrigated conditions at the final harvest

Nitrogen level (kg ha^{-1})	Spread of plants (%)		
	Thin	Medium	Thick
0	81.59 a	17.52 b	0.89 b
50	54.56 b	40.67 a	4.78 ab
100	50.24 b	41.69 a	8.26 a
150	44.05 b	51.01 a	7.47 a
Mean	57.61	37.72	5.35
Pr	***	***	***
HSD	23.119	21.425	5.1659

Means in the same column with the same letter are not significantly different from each other

***: highly significant at 1% level of probability

Leaf area per plant (LA) and leaf area index (LAI)

The LA increased significantly as the nitrogen level increased resulting in values between 1,000 cm^2 and 2,000 cm^2 (Fig. 5.7.A). The response of LA to nitrogen may indicate that when nitrogen supply is sufficient the plant increases the number of leaves (Data not shown). The size of each individual leaf also plays an important role in increasing the leaf area per plant. As for other parameters, the values recorded under irrigated conditions were substantially higher than those from the rainfed trial. Taheri-Agrami *et al*. (2009) indicated that in order to resist water stress plants may

reduce the length and the width of the leaf, resulting in a reduced LA, explaining what could have happened in the rainfed trial.

Generally, the LAI tended to increase significantly with an increase in nitrogen level for each sampling date, with exception of 58 DAP (Fig. 5.7.B). At 58 and 135 DAP the maximum LAI of 4.7 cm cm^{-2} and 8.6 cm cm^{-2} were respectively reached with 150 kg ha^{-1} of N, while for the rest of the sampling dates the maximum values of 7.5 cm cm^{-2} at 88 DAP and 9.5 cm cm^{-2} at 118 DAP were found when applying 100 kg ha^{-1} of N. Taken over time and for each treatment separately, the LAI increased from emergence to 118 DAP then declined towards the final harvest (135 DAP). This may be due to ageing and senescence of leaves. With a plant population slightly higher (50.2 plants m^{-2}) than that used in the present trial, Muchow (1990) did not observe LAI values higher than 4.9 over the growth cycle. In another study, Danalatos and Archontoulis (2004 a) found a maximum LAI of 7.5 with 20 plants m^{-2} and nitrogen rate of 150 kg ha^{-1} under sufficient soil water conditions. However, the maximum values obtained in both the above-mentionned studies were still lower than those recorded at 88, 118 and 135 DAP in the present investigation. This could be attributed to the combined effect of optimum nitrogen and water supply, and also the cultivar itself as well as the environment in which the plants were grown. Additionally, as in the case of LA, in general the LAI of the irrigated crop was higher as compared to that of the rainfed crop, except at the first sampling when the plants from the two trials exhibited similar values. This could be attributed to low water consumption due to a small leaf canopy with both crops receiving adequate water (rainfal (Fig 4.6) and or irrigation) over this time period.

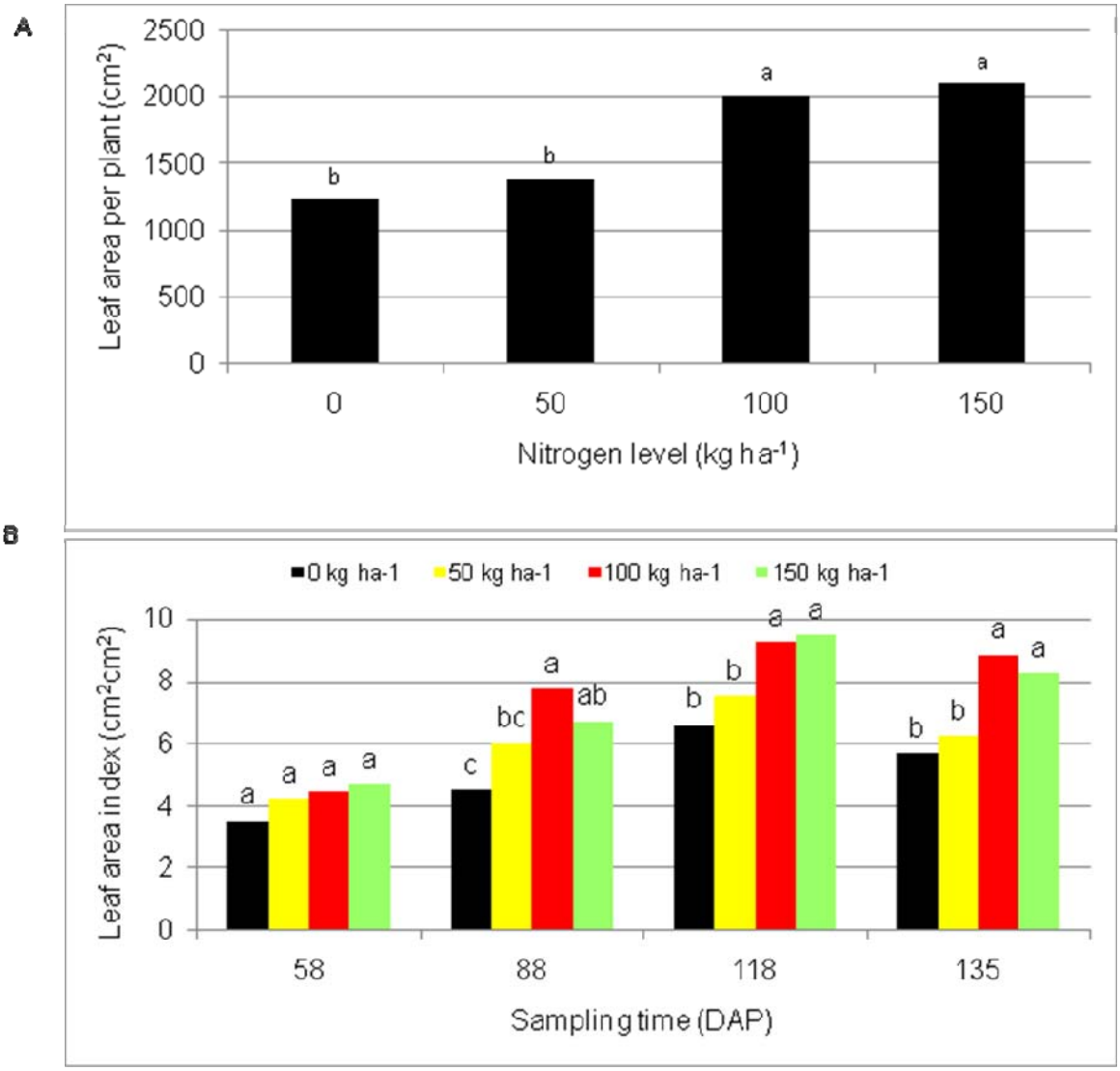


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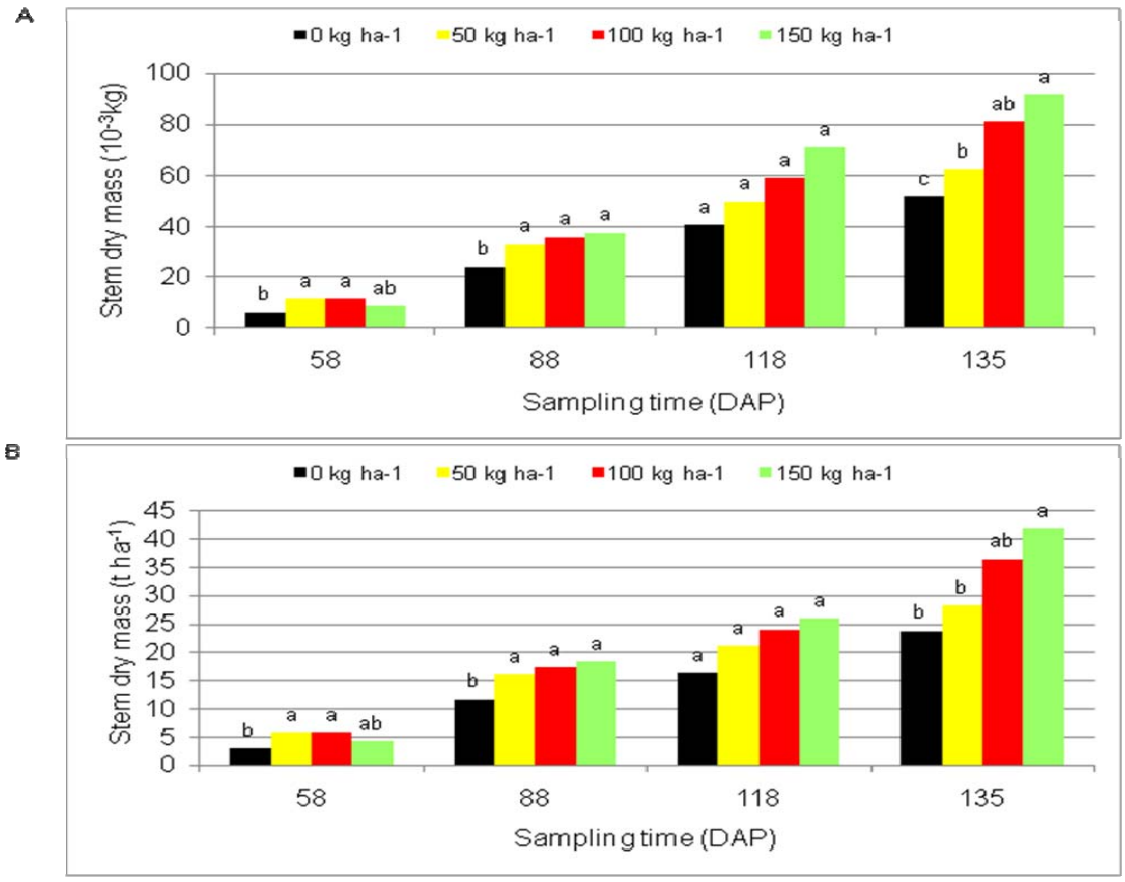
Fig. 5.7. Leaf area per plant at final harvest (A) and leaf area index over the growth cycle (B) as affected by nitrogen level under irrigated conditions

5.3.2. Biomass production

Stem and leaf components

The stem dry mass per plant increased for each nitrogen level from the second to the final harvest (Fig. 5.8.A). The effect of nitrogen was highly significant ($Pr < 0.01$) at 58, 88, and 135 DAP, but no significant effect was found at 118 DAP. The stem dm per hectare (Fig. 5.8.B) responded to nitrogen in a similar way as the stem dm per plant. On average the 150 kg ha^{-1} treated plants had about 5 t ha^{-1} more stem dm per hectare than the 100 kg ha^{-1} N plants at final harvest. An increase in stem dm per plant was also found in chapter 4 and by Hossain *et al*. (2011 a & b). However, Danalatos & Archontoulis (2005) and Gonzalez-Moreno *et al*. (2004) found no response.

The irrigated and rainfed plants reacted similarly in terms of stem dm per plant and stem dm per hectare at 58 DAP. However, as the plants were growing, the irrigated plants performed better in terms of plant height and stem diameter resulting in higher dry mass per plant, and consequently stem dm per hectare. This advantage can be attributed to the combined effect of nitrogen and sufficient soil water on plant height and stem diameter as well as the leaf area per plant which increase the photosynthetic ability of the plants. The lack in response at the first sampling may be attributed to the absence of competition between plants at that stage.



Bars of the same sampling date with the same letter are not significantly different from each other

Fig. 5.8. Stem dry mass per plant (A) and stem dry mass per hectare (B), as affected by nitrogen level at different sampling times under irrigated conditions

The leaf dry mass per plant (Fig. 5.9.A) and leaf dry mass per hectare (Fig. 5.9.B) increased with increased level of nitrogen. Nitrogen had a highly significant effect (Pr < 0.01) on both leaf dm per plant (58 and 118 DAP) and leaf dm per hectare (58 and 135 DAP. No significant effects were found at the other sampling dates.

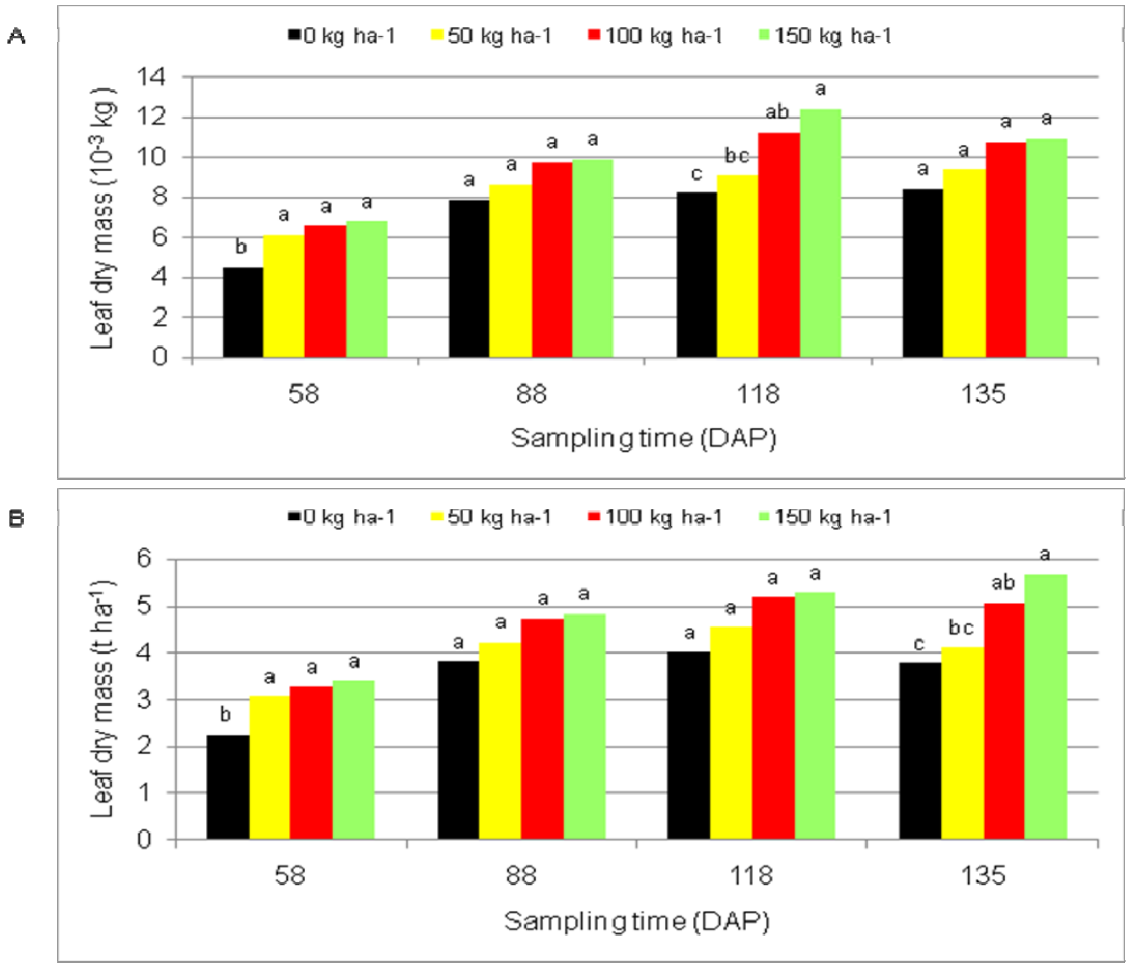


Fig. 5.9. Leaf dry mass per plant (A) and leaf dry mass per hectare (B) as affected by nitrogen level at different sampling times under irrigated conditions

Generaly, the total dm per plant and the total dm per hectare (Fig. 5.10) showed a similar trend to that of stem dm per hectare (Fig. 5.8.B). The final total dm per hectare ranged between 28 and 50 t ha^{-1} from 0 to 150 kg ha^{-1}. No significant effects of nitrogen on the contribution of stem and leaves were found (Figs. 5.11.A & B).

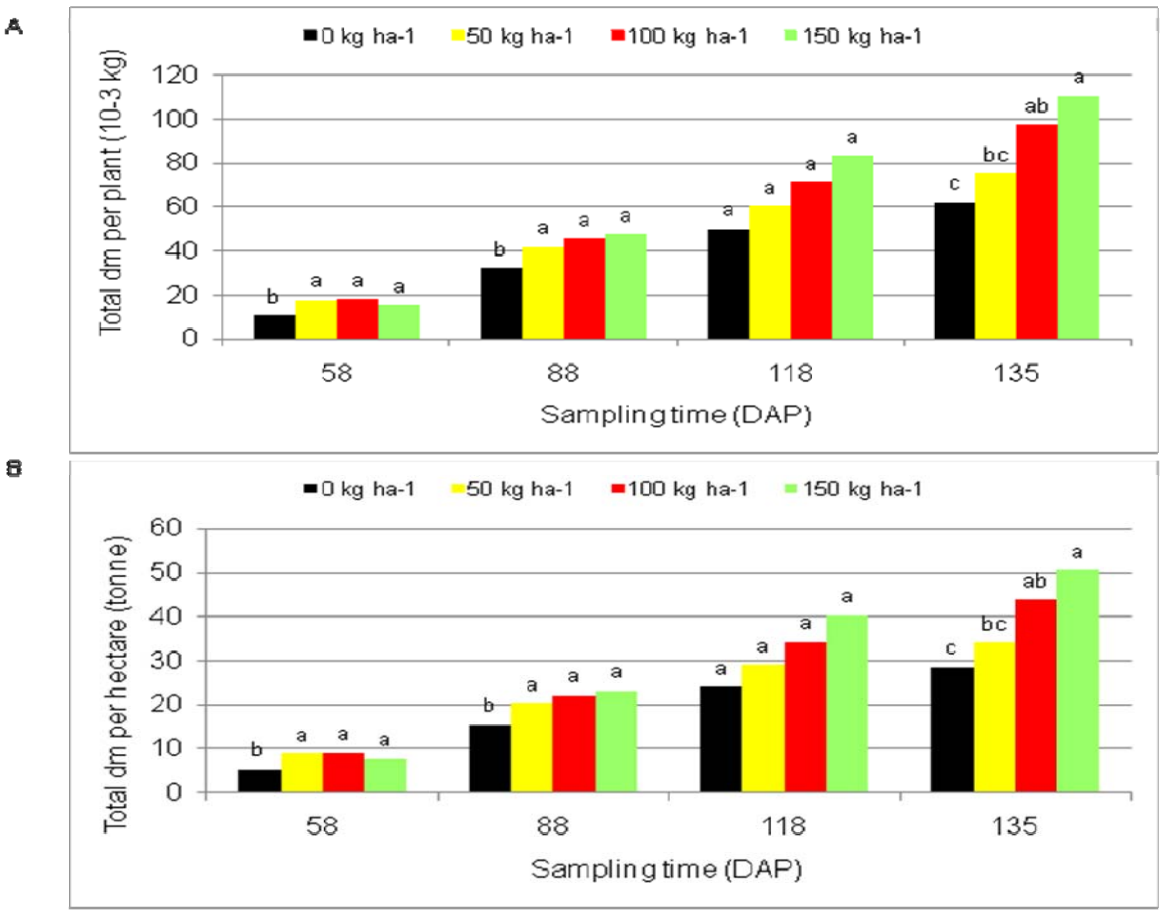
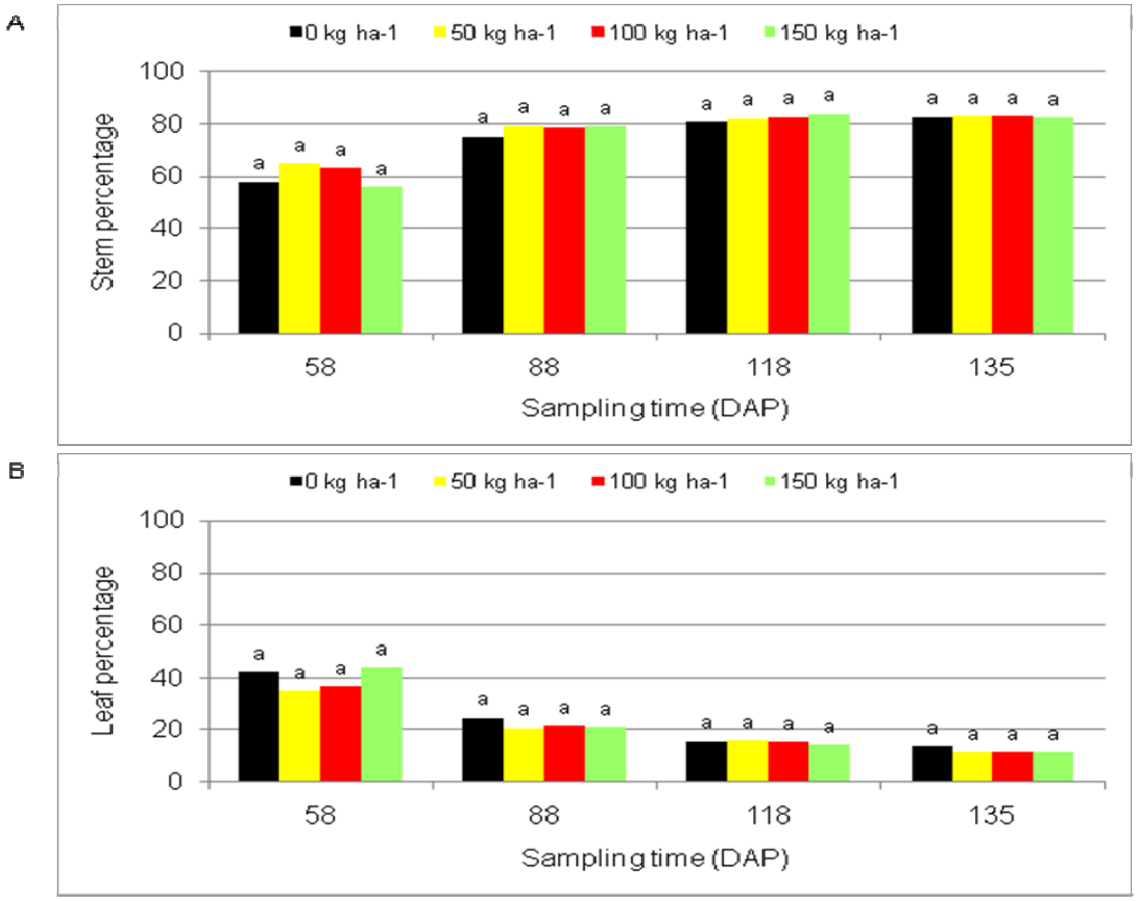


Fig. 5.10. Total dry mass per plant (A) and total dry mass per hectare (B) as affected by nitrogen level at different sampling times under irrigation



Bars of the same sampling date with the same letter are not significantly different from each other

Fig. 5.11. Stem percentage (A) and leaf percentage (B) at different sampling times as affected by nitrogen level under irrigated conditions

Bark components

The bark dry mass responded positively and significantly so ($Pr < 0.01$) to increased levels of nitrogen (Table 5.3), with the two higher nitrogen levels giving significantly higher values than the control (0 kg ha^{-1}). The bark percentage and the bark-core ratio tended to respond positively to increase in nitrogen level, but the differences between means were not significant (Table 5.2). The values from this experiment were in the same range with the findings of other researchers (Wood, 1978; Sellers *et al*., 1993; Mambeli & Grandi, 1995; Zhou *et al*., 1998; McMillin *et al*., 1998; Alexopoulou *et al*., 2000; Webber *et al*., 2002; Sullivan, 2003 a & b and Baldwin &

Graham, 2006). However, the values from this trial were higher than those from the rainfed trial.

Table 5.3. Bark-core ratio, bark percentage and bark dry mass as affected by nitrogen level at the final harvest under irrigated conditions

Nitrogen level (kg ha^{-1})	Bark dry mass (t ha^{-1})	Bark – core ratio	Bark percentage
0	8.04 c	0.51 a	33.60 a
50	9.60 bc	0.52 a	34.05 a
100	11.02 ab	0.55 a	35.52 a
150	14.96 a	0.56 a	36.72 a
Mean	11.38	0.53	34.72
Pr	***	NS	NS
HSD	4.8628	-	-

Means in the same column with the same letter are not significantly different from each other

NS: not significantly different, ***: highly significantly different at 1% level of probability

5.3.3. Chemical composition and dry matter content of kenaf bark fibre

Nitrogen application significantly affected the acid detergent fibre (ADF) ($Pr < 0.01$) and the neutral detergent fibre (NDF) ($Pr < 0.05$) (Table 5.4). Both parameters increased with increasing level of nitrogen to reach peak values of 72.17 % and 82.66% respectively for the ADF and NDF at 100 kg N ha^{-1}, thereafter it declined with further increases in nitrogen. This decrease was drastic for the ADF which reached the lowest value with 150 kg N ha^{-1}. The crude fibre content increased significantly ($Pr < 0.05$) with increasing nitrogen level from 0 up to 100 kg ha^{-1} only (Table 5.4). The dry matter content was not significantly affected by nitrogen level (Table 5.4). Nitrogen level had no significant effect on cellulose, hemicellulose, and lignin contents, while it significantly decreased the ash content ($Pr < 0.01$) (Table 5.5). The ash content of the two higher nitrogen levels had significantly lower values than that recorded for 0 and 50 kg ha^{-1} (Table 5.5). The decrease in ash content due to increase in nitrogen is an interesting fact because the ash content negatively

affects the quality of the pulp. Unfortunately, while decreasing the ash content the nitrogen level tended to increase the lignin content which is also undesirable in pulping. Generally, except the lignin content the values found under irrigated conditions were higher than those found under rainfed conditions.

Table 5.4. ADF, NDF, dry matter content and crude fibre content as affected by nitrogen level at the final harvest

Nitrogen level (kg ha^{-1})	ADF (%)	NDF (%)	Dry matter (%)	Crude fibre (%)
0	69.55 b	80.01 b	91.47 a	63.17 b
50	70.89 a	80.66 ab	92.18 a	63.73 ab
100	72.17 a	82.66 a	94.63 a	68.10 a
150	68.73 b	80.66 ab	95.2 a	65.79 ab
Mean	70.33	81.00	93.38	65.20
Pr	***	*	NS	*
HSD	1.3131	2.5406	-	4.4914

Means in the same column with the same letter are not significantly different from each other

NS: not significant, *: significant at 5% level of probability, ***: highly significant at 1% level of probability

Table 5.5. Cellulose, hemicellulose, lignin and ash contents as affected by nitrogen levelat the final harvest

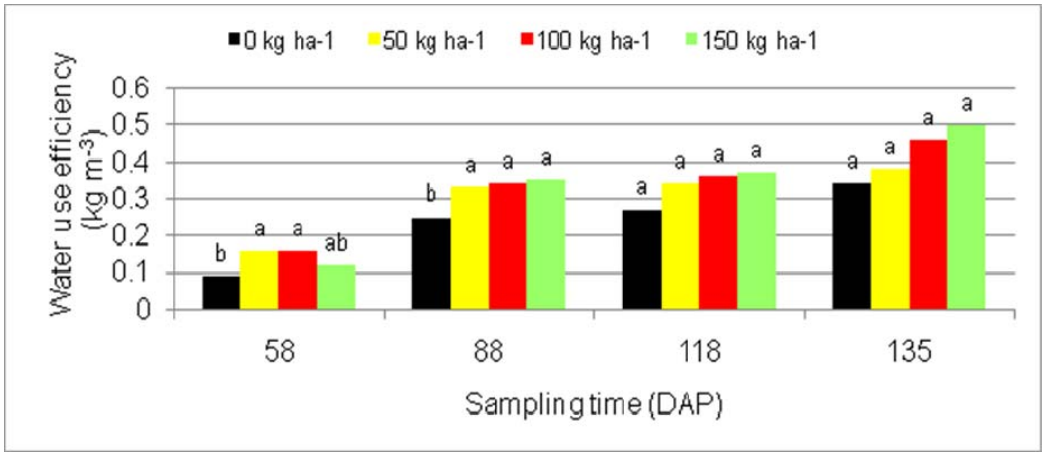
Nitrogen level (kg ha^{-1})	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)
0	59.79 a	10.47 a	9.76 a	2.07 a
50	60.17 a	9.77 a	10.72 a	2.05 a
100	60.26 a	10.49 a	11.14 a	1.67 b
150	57.59 a	11.94 a	11.91 a	1.63 b
Mean	59.45	10.67	10.88	1.85
Pr	NS	NS	NS	***
HSD	-	-	-	0.3005

Means in the same column with the same letter are not significantly different from each other

NS: not significant, ***: highly significant at 1% level of probability

5.3.4. Water use efficiency

The water use efficiency based on stem dry matter was generally improved by nitrogen level (Fig. 5.12), although it decreased (Pr< 0.01) when the nitrogen level increased higher than 100 kg ha^{-1} at the first sampling. At the second sampling, the plants receiving nitrogen used water more efficiently (Pr< 0.05) than the plants which did not receive nitrogen. At the third and fourth samplings all the treatments resulted in similar stem water use efficiencies. Stem water use efficiency increased from the first to the final harvest as in the case of the rainfed trial (Chapter 4). The values of stem water use efficiency recorded in this study were lower than those recorded under rainfed conditions. This may indicate that with sufficient water supply plants exhibited luxury water consumption.



Bars of the same sampling date with the same letter are not significantly different from each other

Fig. 5.12. Water use efficiency based on stem dry matter, as affected by nitrogen level under irrigation at different sampling times

5.3.5. Nitrogen, potassium and phosphorus removal by the crop, nitrogen contents of leaves and stems, and nitrogen, phosphorus and potassium use efficiency

Water content is an important property of soils, influencing soil solution chemistry and nutrient uptake by plants (Misra & Tyler, 1999). Nitrogen removal was positively and significantly affected by nitrogen level and ranged from 367 to 517 kg ha^{-1} (Table 5.6). As in the case of the rainfed crop, the lowest nitrogen removal value from the soil (90% of the soil initial content) was found under control conditions (0 kg ha^{-1}), while for the other N treatments it was more than 100% of the initial soil nitrogen content. Potassium and phosphorus removal were not significantly affected by nitrogen level (Table 5.6). The low removal of phosphorus from the soil confirms the lower phosphorus requirements for kenaf production as indicated by Adamson *et al*. (1979). This study also confirmed the results from chapter 4 as to the high and moderate requirements for nitrogen and potassium respectively.

The nitrogen content of both leaves and stem were not significantly affected by nitrogen level (Table 5.6). However, the higher nitrogen content of the leaves as compared to the stem was reported and discussed in Chapter 4. Overall the stem and leaf nitrogen content were much higher under irrigation than under rainfed

conditions. This illustrates the importance of water in the solubilisation of nutrients to make them available for absorption by plants. This observation can be strengthened by the view of Warder *et al*. (1963) who indicated that deficiency in soil moisture content may slow the depletion of plant nutrients due to the fact that their mobilization is negatively affected. An increase in the total nutrient content of plants with an increase in soil water content has been reported by many researchers (Metwally & Pollard, 1959; Henderson *et al*., 1968; Misra & Tyler, 1999).

Table 5.6. N, P and K removal, and leaf and stem N contents as affected by nitrogen level at the final harvest under irrigated conditions

Nitrogen level (kg ha^{-1})	N removal (kg ha^{-1})	P removal (kg ha^{-1})	K removal (kg ha^{-1})	Leaf N content (g kg^{-1})	Stem N content (g kg^{-1})
0	367.70 d	128.5 a	397.5 a	16.40 a	1.93 a
50	417.17 c	135.2 a	392.9 a	14.38 a	1.68 a
100	470.38 b	118.9 a	439.1 a	16.63 a	1.80 a
150	517.74 a	132.5 a	418.3 a	15.30 a	1.80 a
Mean	443.25	94.749	411.92	15.68	1.80
Pr	***	NS	NS	NS	NS
HSD	17.724	-	-	-	-

Means in the same column with the same letter are not significantly different from each other

NS: not significant, ***: highly significant at 1% level of probability

In general, nitrogen fertilization positively affected N-, K- and P use efficiency (Table 5.7). However, differences were only significant for K use efficiency, with the highest nitrogen level resulting in significantly higher K use efficiency than the 0 and 50 kg ha^{-1} of N. The nutrient use efficiency ranged between 62 and 80 kg kg^{-1} for N use efficiency, 60 and 99 kg kg^{-1} for K use efficiency, and 197 and 323 kg kg^{-1} for P use efficiency. The values of N, K and P use efficiency found in this study were far higher compared to the values from chapter 4. This might be attributed to a high stem yield.

Table 5.7. Nitrogen, phosphorus and potassium use efficiency as affected by nitrogen level at the final harvest under irrigated conditions

Nitrogen level (kg ha^{-1})	N use efficiency (kg stem kg^{-1} N	P use efficiency (kg stem kg^{-1} N	K use efficiency (kg stem kg^{-1} N
0	62.1 a	197.3 a	60.6 b
50	67.8 a	248.2 a	72.4 ab
100	77.4 a	323.8 a	83.0 ab
150	80.8 a	321.2 a	99.8 a
Mean	72.09	272.6	78.96
Pr	NS	NS	*
HSD	-	-	31.338

Means in the same column with the same letter are not significantly different from each other

NS: not significant, *: significant at 5% level of probability

5.4. Conclusions and recommendations

The performances of the growth parameters, leaf area per plant and leaf area index and consequently the yield, vary markedly depending on the management of nitrogen. This is an indication that increasing nitrogen up to the highest level (150 kg ha^{-1}) might be practiced to achieve the highest yield. The ash content decreased with an increase in nitrogen as in the case of the rainfed crop, but the lignin, cellulose and crude fibre content had a tendency to increase with N application up to 100 kg ha^{-1} and then slightly decreased with a higher application level. Water use efficiency was also positively affected by increasing nitrogen level due to an increase in stem dry mass. Nitrogen also increased the nitrogen and potassium removal rates, probably due to an increase in stem dry mass, but this was not the case for phosphorus. Consequently maximum N use efficiency and K use efficiency were observed with the maximum nitrogen level, while the P use efficiency increased with application of nitrogen up to a level of 100 kg ha^{-1} and then declined if more N was applied. The amount of phosphorus removal was much lower when compared to that of nitrogen and potassium, revealing lower requirement of kenaf for this nutrient. The nitrogen content of the leaves and stems seemed not to be affected by nitrogen as it was in

the case of the rainfed plants. In general the values for different parameters measured, were higher under irrigated than rainfed conditions.

The hypotheses formulated are generally accepted for the growth parameters and biomass production. They are also accepted for NDF, crude fibre, NUE, KUE, PUE and N removal. Conversely, the hypotheses are only partially accepted for the WUE, lignin, cellulose and hemicellulose contents. Finally, they are rejected for the nitrogen content of the leaves and stems, K and P removal and ash content.

Further studies should be conducted using different levels of nitrogen, different water regimes and different levels of other nutrients such as potassium and phosphorus to confirm these results.

CHAPTER 6.
RESPONSE OF KENAF YIELD AND QUALITY TO PLANT POPULATION AND ROW SPACING UNDER RAINFED CONDITIONS

6.1. Introduction

As indicated in the introduction of section 2, the plant population treatments were reviewed in the 2009/10 season resulting in leaving out the lowest plant population (200,000 plants ha^{-1}) and adding two higher plant populations namely 500,000 plants ha^{-1} and 600,000 plants ha^{-1}. This resulted in four plant populations as compared to the three for the previous season's study. The row spacings were kept as in the previous season at 0.17, 0.34 and 0.50 m.

Hypotheses

- increasing plant population will increase the growth parameters; plant height, stem diameter, leaf area and leaf area index
- increasing plant population will decrease the yield per plant while increasing the yield per hectare
- increasing plant population will increase the nutrient use efficiency by kenaf plants
- increasing plant population will decrease the nitrogen content of stems and leaves
- increasing row spacing will not have effect on the growth parameters, yield per plant and per hectare, nutrient use efficiency and nitrogen conetent of stems and leaves

6.2. Materials and Methods

Generally, the details of this experiment are similar to those from the two previous chapters of the 2009/10 season. However, some exceptions must be noticed as the planting took place on the 16th of December 2009 or respectively 7 and 8 days after the Nitrogen rainfed and irrigated trials. A split-plot experiment with the treatments arranged in a randomized complete block design with four replications for each

treatment combination was used. The main plots represented plant population (300,000 plants ha^{-1}, 400,000 plants ha^{-1}, 500,000 plants ha^{-1}, and 600,000 plants ha^{-1}), while the sub-plots of 3.5 m wide by 4 m long each represented row spacing (0.17, 0.34 and 0.50 m). In order to achieve desired plant populations, more seeds were sown and then thinned out to the correct plant population following the procedures indicated in chapter 4. Nitrogen fertilization in the form of LAN 28% was applied at a rate of 150 kg ha^{-1} in a split application, with 50 kg N ha^{-1} at planting and 100 kg N ha^{-1} after thinning out or at 35 days after planting (DAP).

The other nutrients; potassium and phosphorus were applied at planting at a rate of 30 kg P ha^{-1} as super phosphate (8.3%) and 100 kg K ha^{-1} as potassium chloride (50%). Sequential samplings were done over the growing season at 63, 90, 122 and 140 DAP to determine the growth parameters and the biomass production. The nutrient use efficiency for the three nutrients, N, K and P and the nitrogen contents of the stems and leaves were also investigated at the final sampling. Assessment of the leaf area index (LAI) was always done a day before the sampling of growth parameters and biomass production. The leaf area per plant was assessed only at the end of the growing season. Furthermore, due to budget constraints chemical analyses of bark fibres were not assessed. The crop was dependent only on the rainfall over the growth cycle, with the exception of 20 mm irrigation water at planting to ensure good establishment. Data were statistically analysed as indicated in previous chapters. The results regarding different parameters studied in this chapter are presented in the Tables or Figures under each section regarding the parameter studied, but the complete dataset can be found in Appendix D, Tables 6.1 to 6.15.

6.3. Results and discussion

The results of the chemical analyses of the top 60 cm soil layer after final harvest are given in Table 6.1. Furthermore, when comparing the results from the beginning of the experiment to those from the end, it is clear that all the nutrients except Mg decreased. Seedling emergence occured at 4 DAP and the first flowers were observed on the 10th of April (115 DAP). No lodging was observed for any plant population or row spacing in this study.

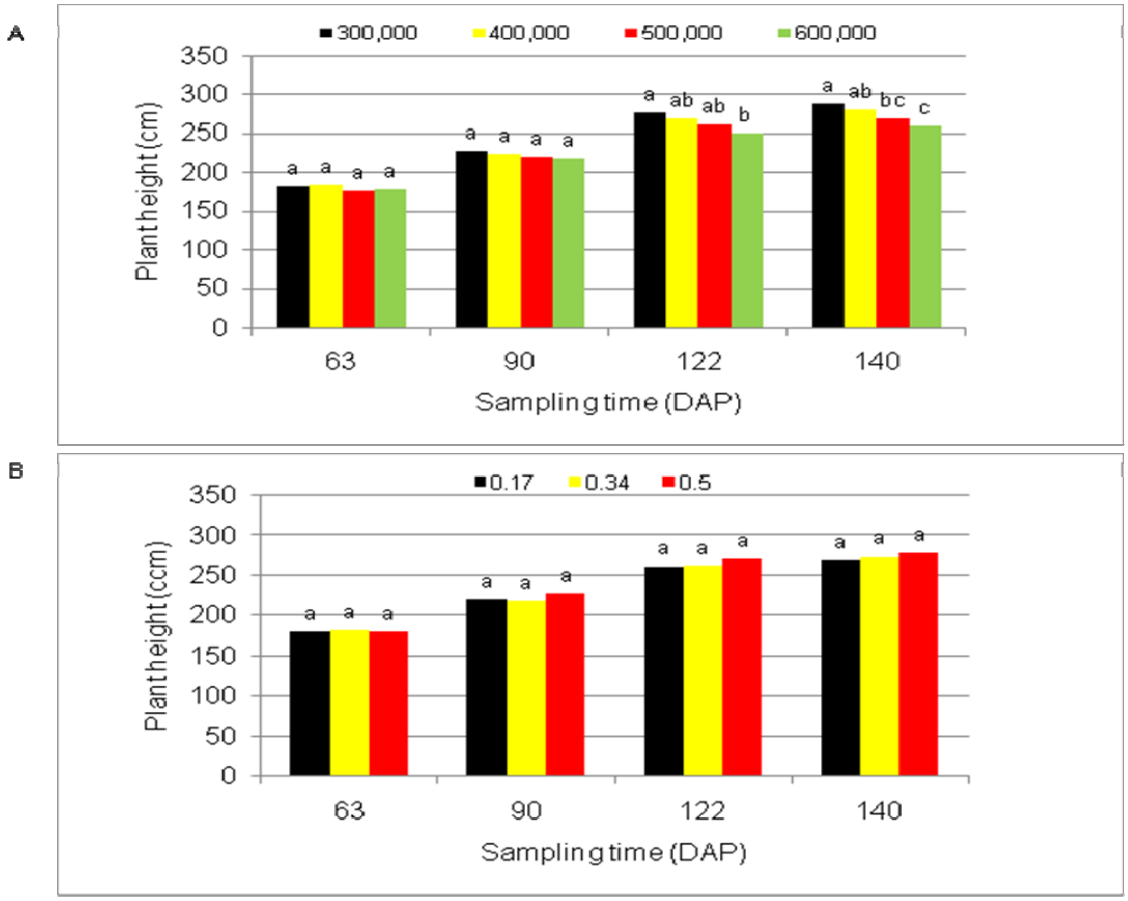
Table 6.1. Average nutrient content per treatment of the top 60 cm soil layer of the experimental site after final harvest

Plant population (plants ha^{-1})	N	P Bray 1	Ammonium acetate extractable			
			K	Ca	Mg	Na
300,000	114.91	175.43	293.38	4804.7	1384.54	451.57
400,000	126.67	156.76	345.07	5043.99	1403.55	414.08
500,000	100.30	159.21	340.81	4652.05	1459.50	425.16
600,000	106.40	151.55	341.95	4761.40	1258.44	441.35
Row spacing (m)						
0.17	130.41	167.23	318.87	4704.46	1417.98	442.84
0.34	109.68	158.42	340.60	4834.59	1391.14	396.83
0.50	96.14	156.56	331.44	4907.24	1340.66	459.45

6.3.1. Growth parameters

Plant height

An increase in plant population resulted in a decrease in plant height, but it was only significantly so at 122 and 140 DAP (Fig 6.1. A). The poor response of plant height to plant population at the beginning of the growing season may be attributed to the lack of competition for resources at the beginning of the growth cycle. However, as the plants grew, the intraspecific competition for light and other resources increased resulting in a decrease in plant height. Plant height (Fig. 6.1.B) were not significantly affected by row spacing, altough wider rows tended to have a positive effect on plant height towards the end of the growing season. No interaction effect between plant population and row spacing was observed for plant height.



Bars of the same sampling date with the same letter are not significantly different from each other

Fig. 6.1. Plant height as affected by plant population (A) and row spacing (B) at different sampling times

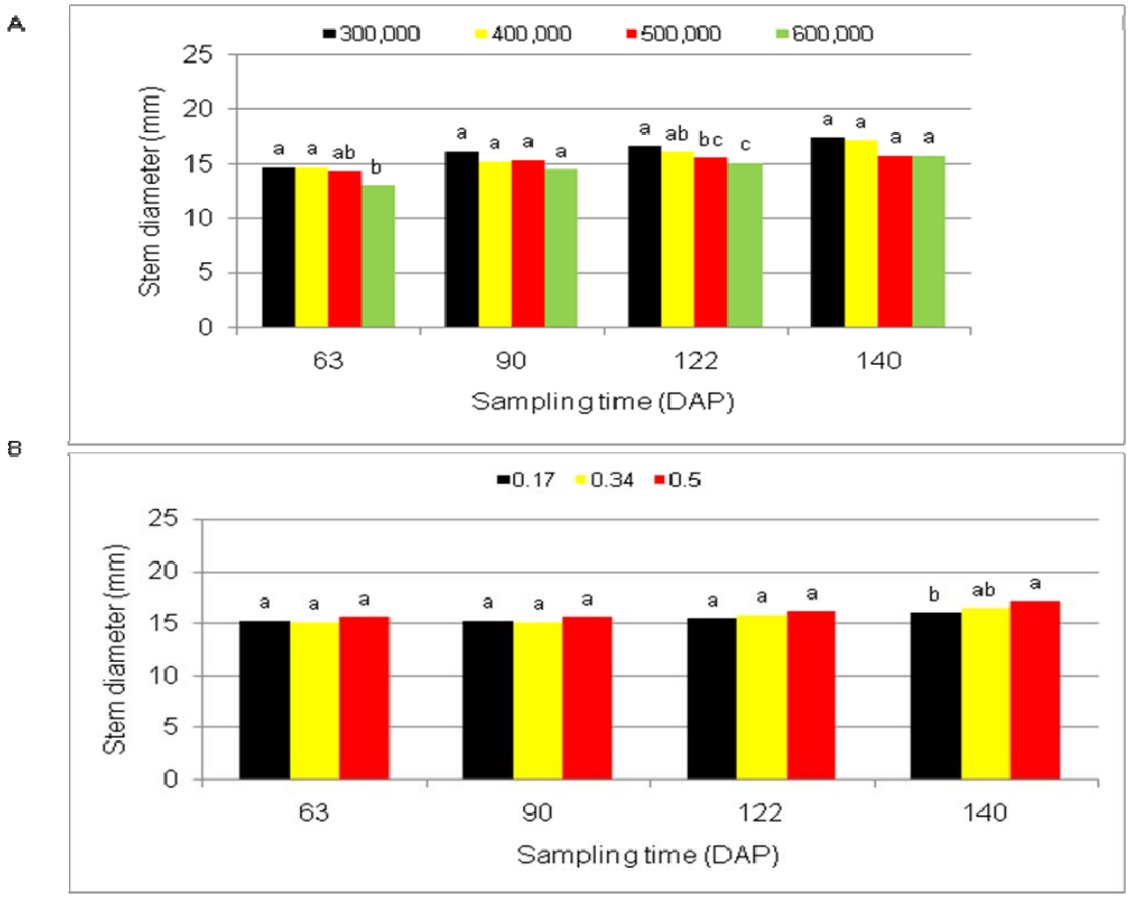
Stem diameter (mm)

Increased plant population significantly reduced the stem diameter at soil level (63 and 122 DAP – Fig 6.2.A) and at 50 cm above soil level (90 DAP – Fig 6.3.A). The decrease in stem diameter with increase in plant population may suggest an increase in pressure for resourses under high plant population. The decrease in stem diameter with an increase in plant population was also observed and discussed in chapter 3, as well as in other studies (Muchow, 1979 a & b, Manzanares *et al.*, 1997, Zhou *et al*., 1998, Danalatos & Archontoulis, 2004 a). At 100 cm above soil level the trends were the same as lower down on the plant, but there was very little

differences between treatment means leading to no significant differences at any sampling time.

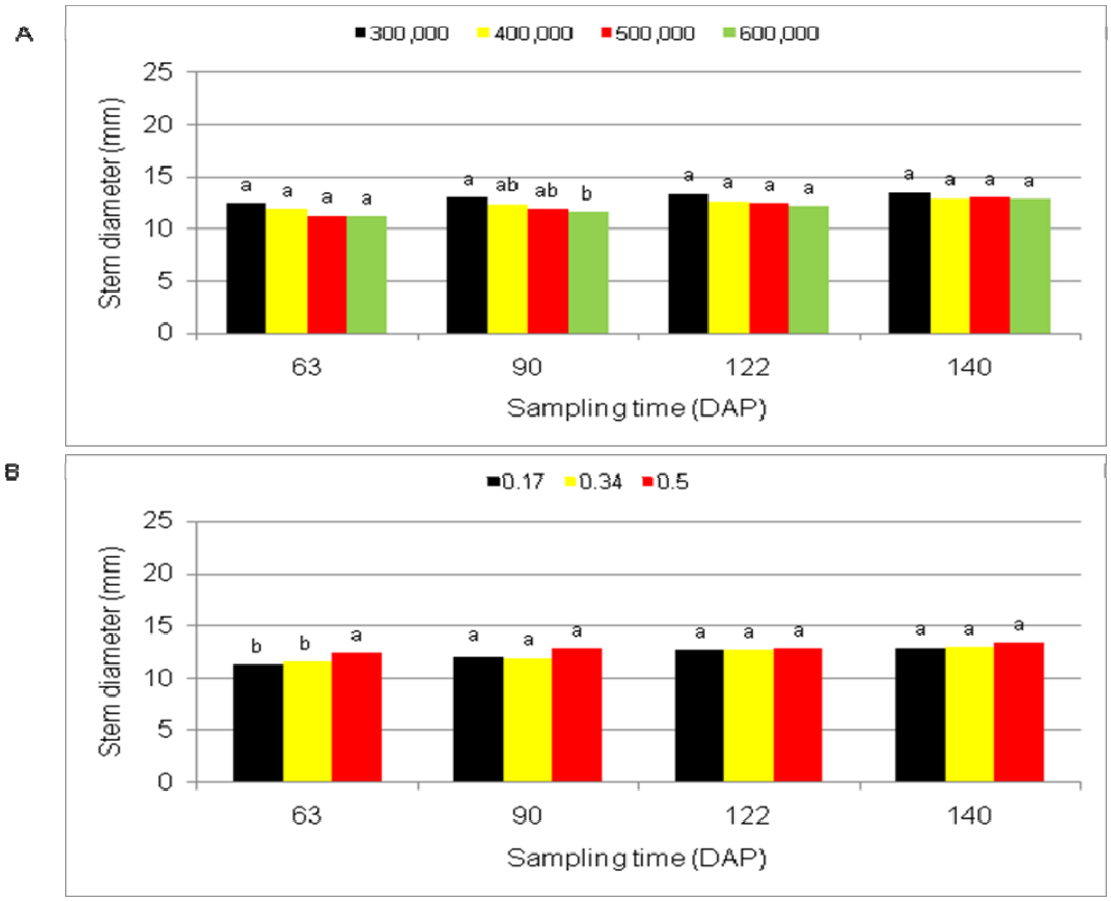
No significant effect and no clear effect of row spacing on stem diameter (Figs 6.2.B, 6.3.B and 6.4.B) were observed, except at 140 DAP where the stem diameter at soil level was significantly decreased at the narrower row spacing. An increase in stem diameter due to increase in row spacing may suggest a decrease in competition for growth factors due to plants being further appart from each other. This may indicate that the increase in space between plants from adjacent rows played a more important role of decreasing the competition than the reduction in space between plants in a row. The increase in stem diameter with increase in row spacing, are in agreement with the findings of Joyner and Wilson (1967), Massey (1974) and Acrèche (2005). However, contrary results were found in the 2008/09 season.

No interaction effect between plant population and row spacing was detected on stem diameter at any plant height.



Bars of the same sampling date with the same letter are not significantly different from each other

Fig. 6.2. Stem diameter at soil level as affected by plant population (A) and row spacing (B) at different sampling times



Bars of the same sampling date with the same letter are not significantly different from each other

Fig. 6.3. Stem diameter at 50 cm above soil level as affected by plant population (A) and row spacing (B) at different sampling times

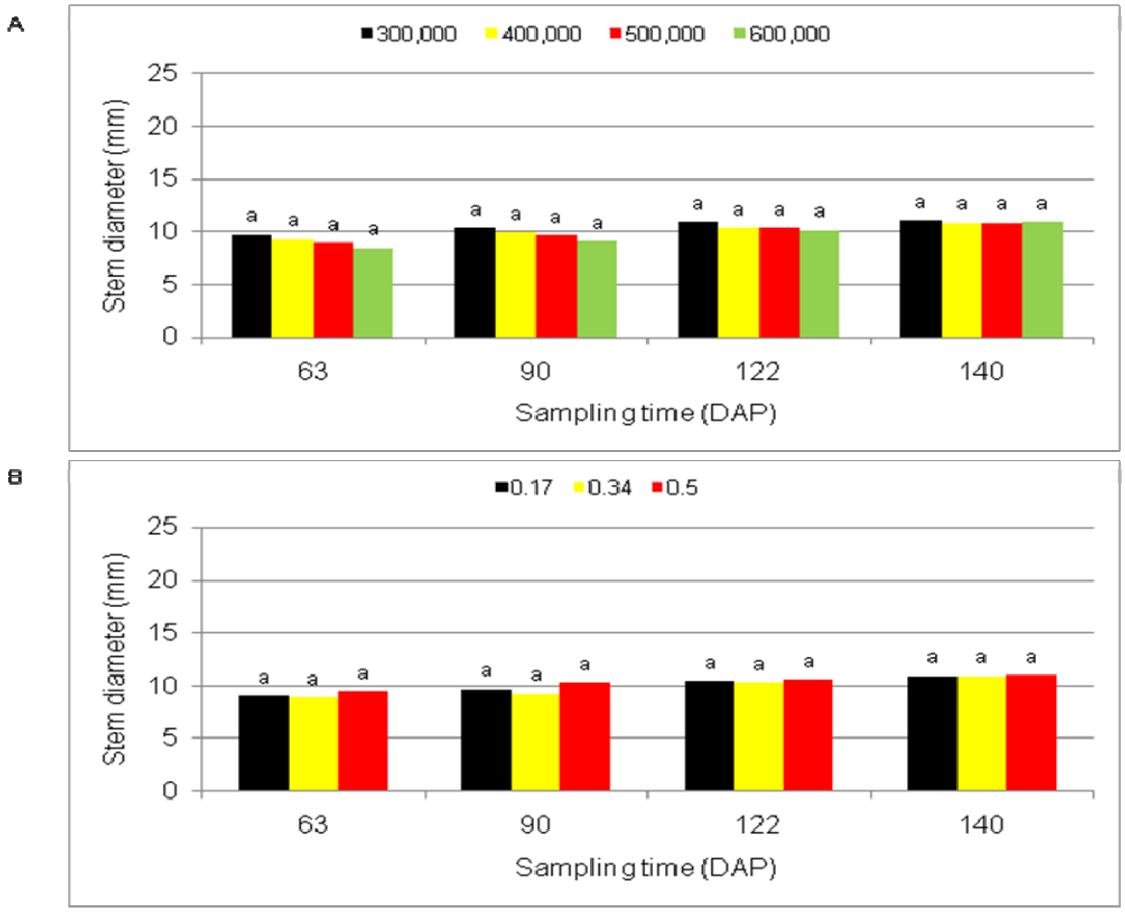


Fig. 6.4. Stem diameter at 100 cm above soil level as affected by plant population (A) and row spacing (B) at different sampling times

Percentage of basal stem diameter spread at final harvest

The percentage of thin plants significantly increased with increase in plant population in such way that the lowest plant population had a significantly lower percentage of thin plants than all the other plant populations (Fig. 6.5.A). This might be the result of an increase in competition for resources at the higher plant populations.

Conversely, the increase in row spacing significantly decreased the number of thin plants (Fig. 6.5.B). The narrower row spacing had significantly high percentage of thin plants than the wider row spacing. This may be due to the same factors as described for plant height and stem diameter.

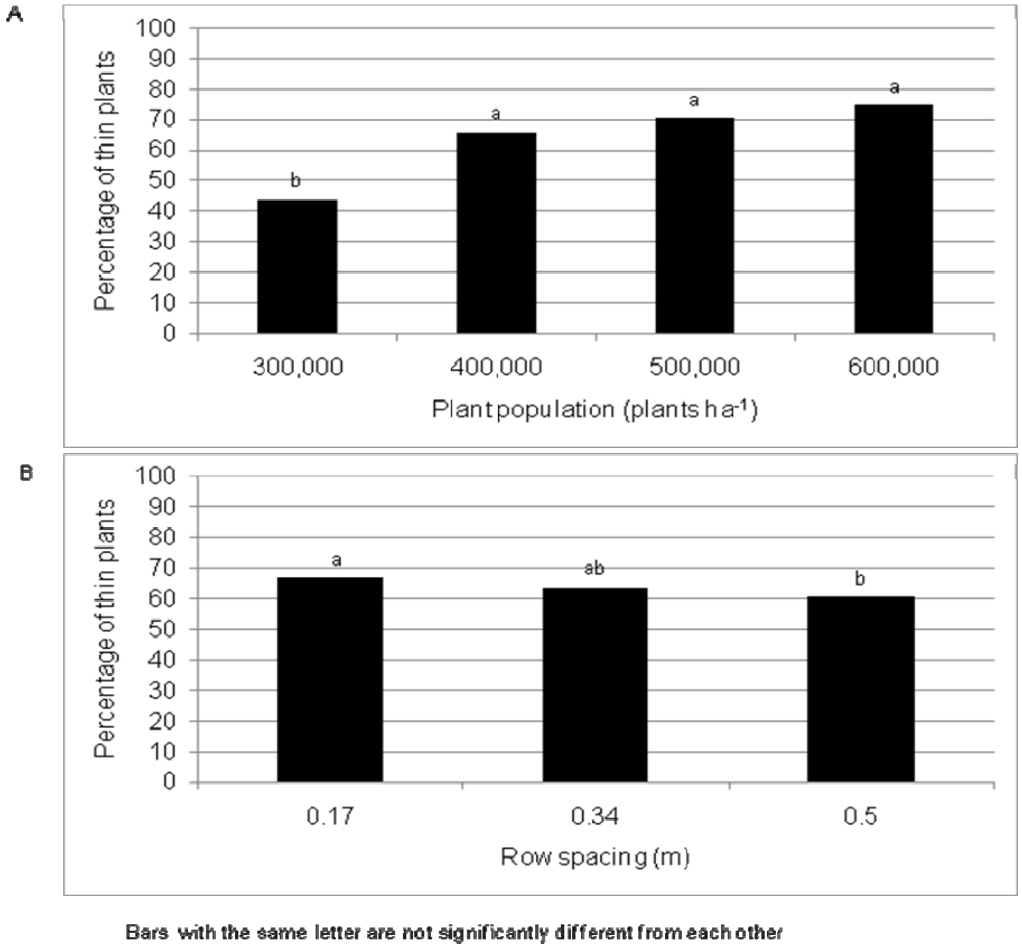


Fig. 6.5. Effect of plant population (A) and row spacing (B) on the percentage thin plants at 140 DAP

An interaction effect between plant population and row spacing was found in terms of the percentage of medium and thick plants (Table 6.2). An increase in the percentage of medium plants with increase in row spacing, were observed at 300,000 and 500,000 plants per hectare only. No clear effect was observed within the other plant populations. With regads to the thick plants, an increase in plant population decreased the percentage of thick plants within each row spacing. However, within plant population the trends of the percentage of thick plants in response to row spacing were not consistent. That is, the percentage of thick plants decreased with increase in row spacing at 300,000 plants per hectare, while it increased with 500,000 and 600,000 plants per hectare. So apprently the optimum combination between plant population and row spacing appeared to be 300,000 plants per hectare and 0.50 m between rows for the specific trial site.

Table 6.2. Interaction effect between plant population and row spacing on the percentage of medium and thick stems at 140 DAP

Plant population (plants ha^{-1})	Percentage of plant spreads			Mean
	0.17	0.34	0.50	
Medium plants				
300,000	41.84 abc	47.78 ab	48.85 a	46.16
400,000	24 24 de	36.58 abcd	30.08 cde	30.3
500,000	26 51 de	27.00 de	34.02 bcde	29.18
600,000	24 00 de	19.68 e	28.35 cde	24.01
Mean	29.15	32.76	33.33	32.41
Pr		*		
HSD		14.739		
Thick plants				
300,000	11.66 a	9.92 ab	7.79 ab	9.79
400,000	2.64 cd	2.20 d	6.71 bc	3.85
500,000	0 90 d	1.56 d	1.62 d	1.36
600,000	0 45 d	0.47 d	1.10 d	0.67
Mean	3.91	3.54	4.31	3.92
Pr		***		
HSD		4.2306		

Means of the medium or thick plants with the same letter are not significantly different from each other

*: significant at 5%, ***: highly significant at 1% level of probability

Leaf area per plant (LA) and leaf area index (LAI)

Though not significantly so, an increase in plant population caused a reduction in LA (Fig. 6.6.A). Taheri-Agrami *et al*. (2009) indicated that in order to resist water deficit plants use different ways to reduce leaf area, one of which is to reduce the length and width of the leaf. In addition, Muchow (1979 a) stipulated that where kenaf plants are subjected to plant competition, those growing at a lower plant population produced more nodes and leaves resulting in a higher LA. Similarly to our results, other researches also indicated a decrease in LA as plant population increased (Muchow, 1979 a; b; 1992). This is even evident in other crops such as taro (Pardales & Belmonte, 1984) and sunflower (Sadras & Hall, 1988). Although not significantly, LA increased with increase in row spacing (Fig. 6.6.B) probably due to delayed leaf senescence at wider rows.

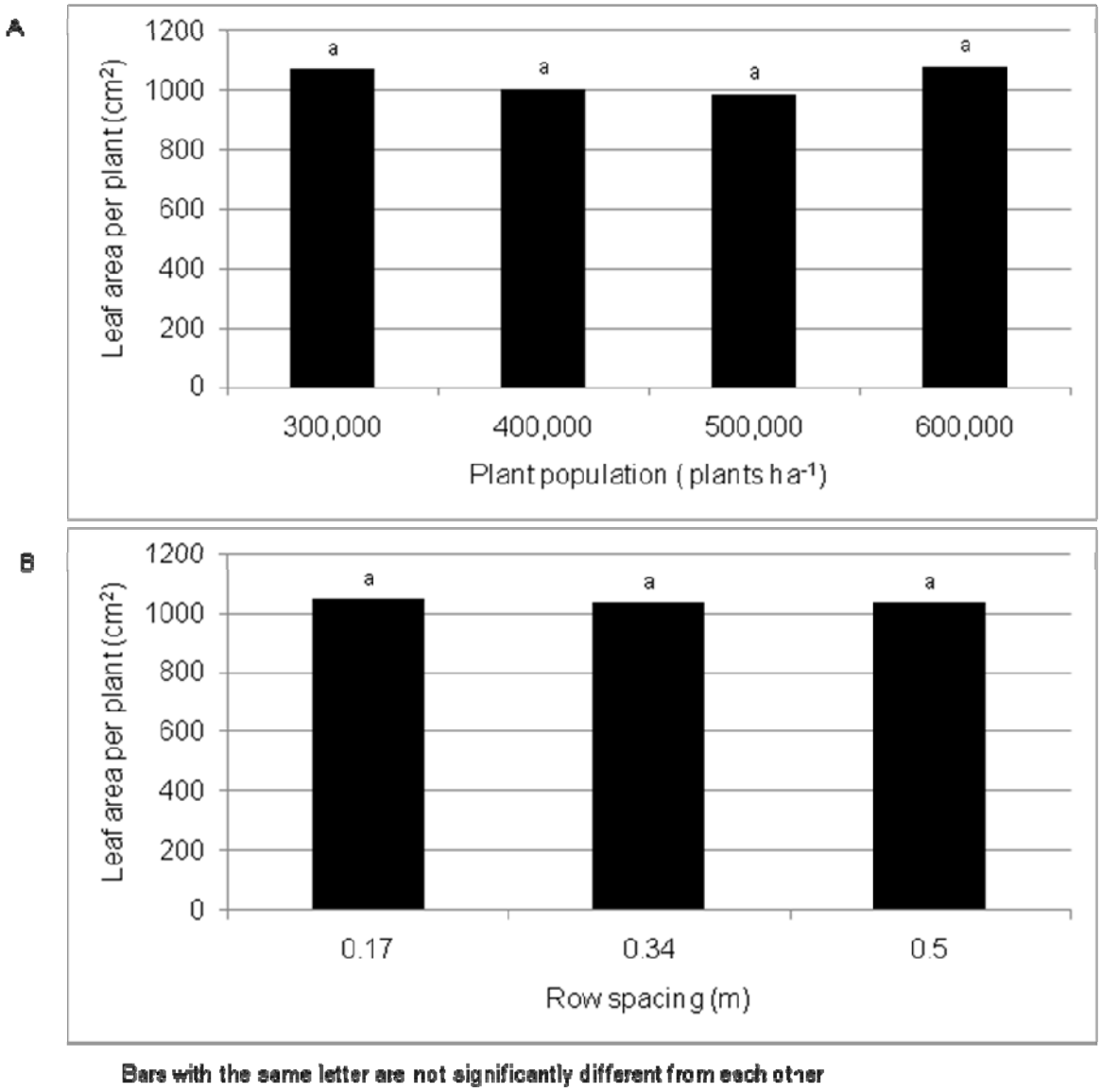
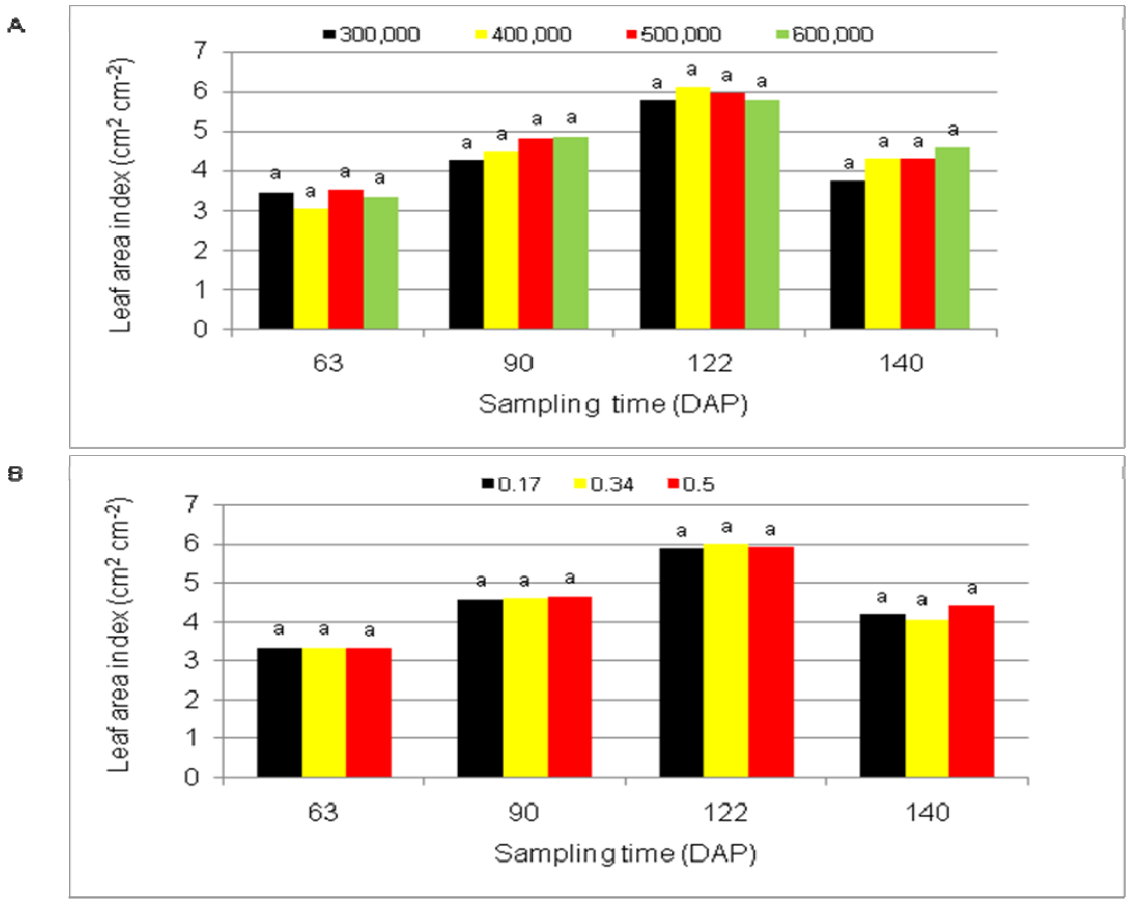


Fig. 6.6. Effect of plant population (A) and row spacing (B) on leaf area per plant at 140 DAP

No significant effect of plant population was detected on LAI throughout the growing season (Fig. 6.7.A). However, there was tendency of increase in LAI as plant population increased at 89 and 139 DAP only. Over the growth cycle, the LAI increased from the first up to the third sampling where after it declined, apparently due to a decrease in leaf number caused by senescence, shading and competition between plants for light and other resources. On the other hand, the LAI was not sensitive to increase in row spacing (Fig. 6.7. B), and only increased over time from

the first to the third sampling time, followed by a decline due to the ageing of the leaves and defoliation. However, Ghadiri and Bayat (2004) and Zhou *et al*. (2011) showed a reduction in LAI due to an increase in row spacing in other crops.



Bars of the same sampling date with the same letter are not significantly different from each other

Fig. 6.7. Effect of plant population (A) and row spacing (B) on leaf area index at different sampling times

6.3.2. Biomass production

No significant effect of plant population was observed on stem dry mass per plant despite the general decrease in plant height and stem diameter due to increase in plant population (Fig. 6.8.A). Conversely, the stem dm per hectare significantly increased with increase in plant population (Fig. 6.8.B). This was observed despite the high percentage of thin plants and low percentage of medium and thick plants

observed at high plant populations. The stem dry mass per plant and the stem dm per hectare were not significantly affected by row spacing (Figs 6.9.A & B).

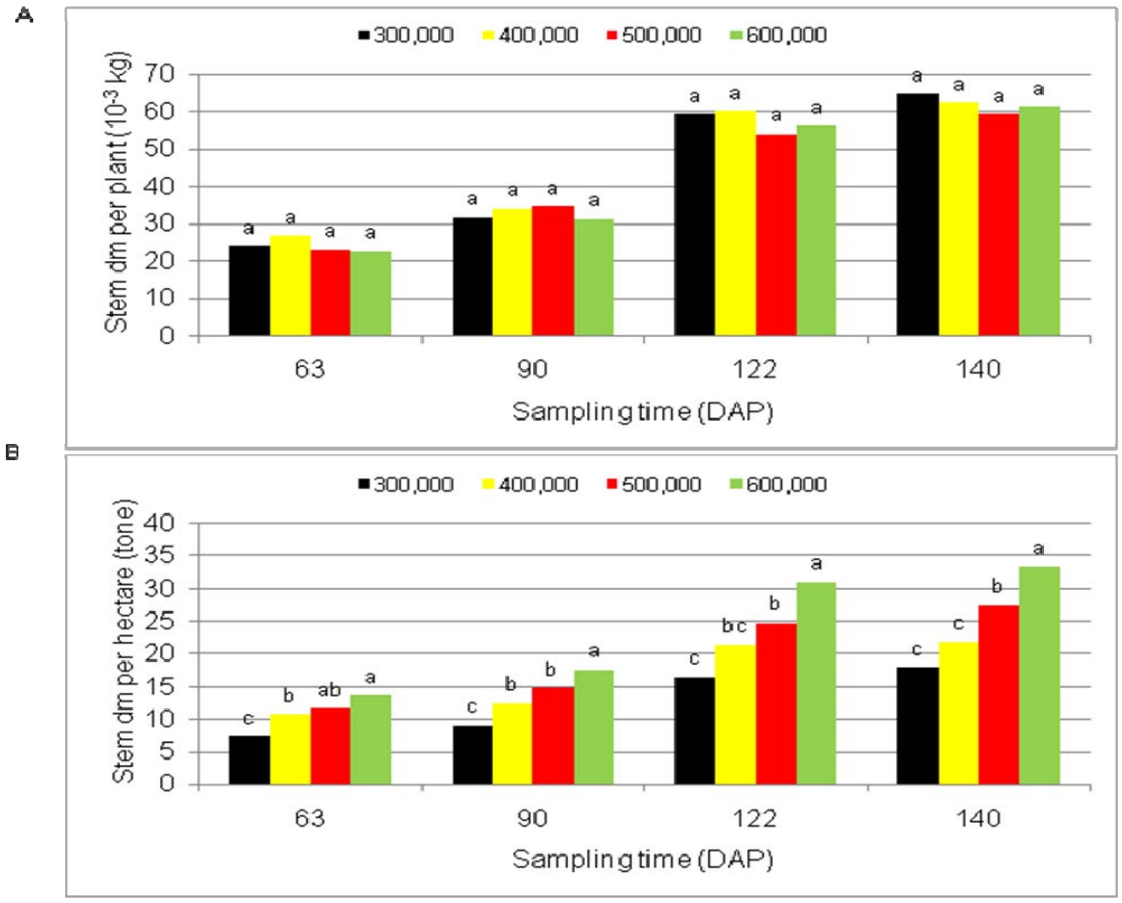
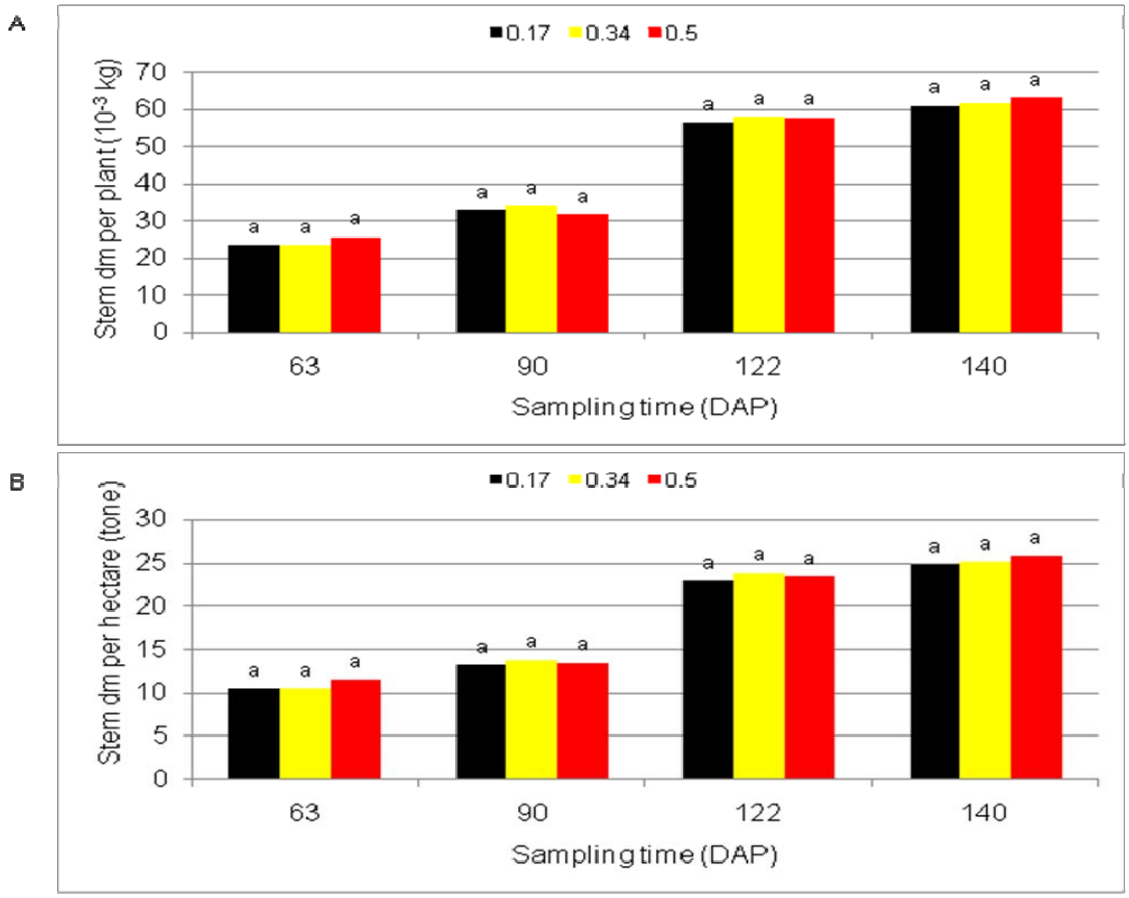


Fig. 6.8. Effect of plant population on stem dry mass per plant (A) and stem dry mass per hectare (B) at different sampling times



Bars of the same sampling date with the same letter are not significantly different from each other

Fig. 6.9. Effect of row spacing on stem dry mass per plant (A) and stem dry mass per hectare (B) at different sampling times

The leaf dm per plant (Fig. 6.10.A) and per hectare (Fig. 6.10.B) showed opposite trends as one decreased and one increased in response to increase in plant population. Although the trend was observed up to 122 DAP, the decrease in leaf dm per plant as plant population increased was only significantly so at 63 DAP. However, the positive impact of increase plant population on leaf dm per hectare was observed throughout the growth cycle. The leaf dry mass per plant (Fig. 6.11.A) and per hectare (Fig. 6.11.B) were not significantly affected by an increase in row spacing.

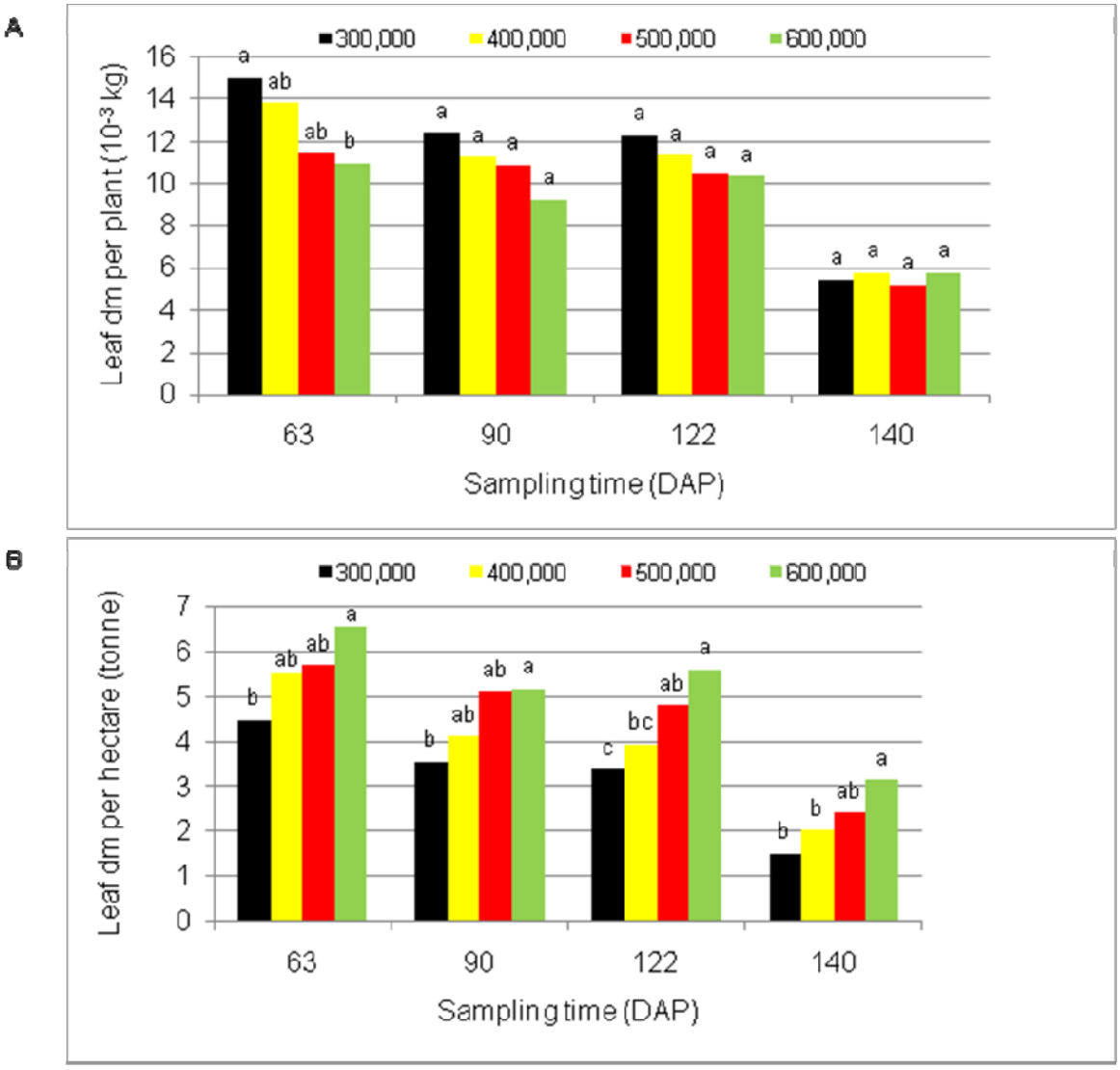


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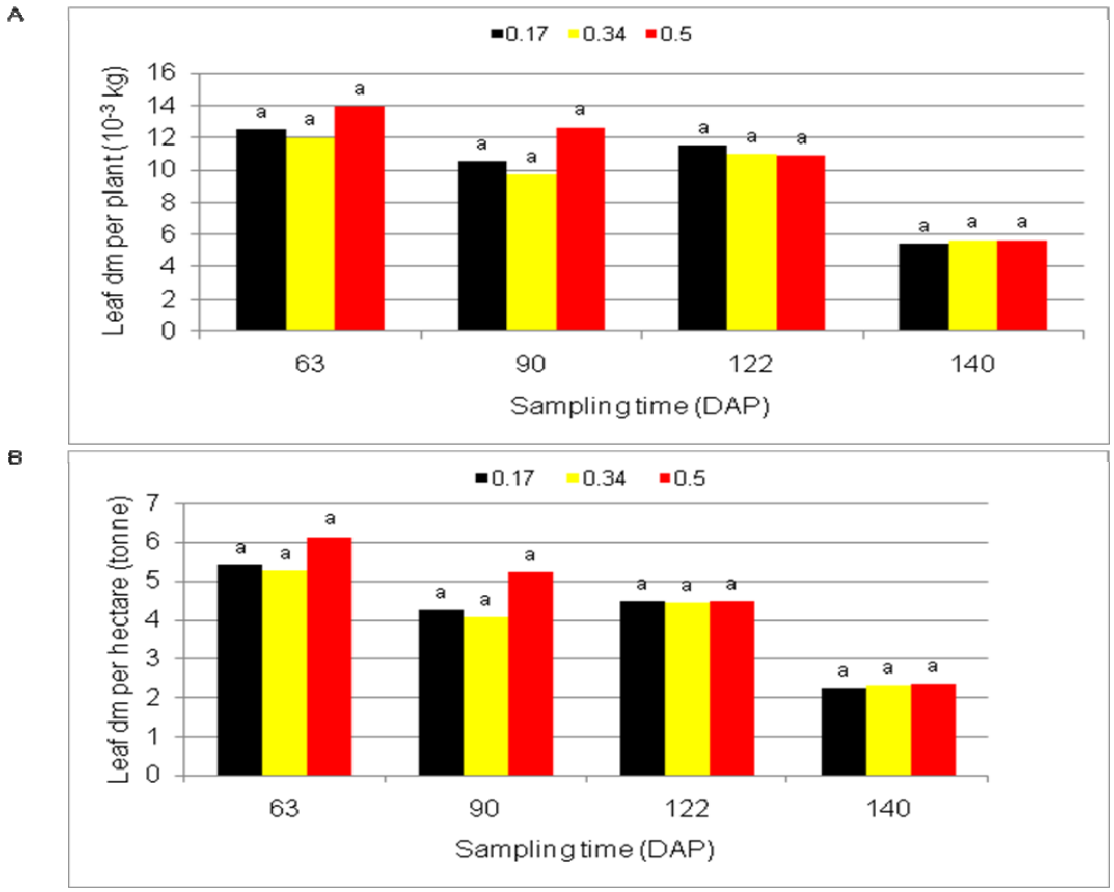
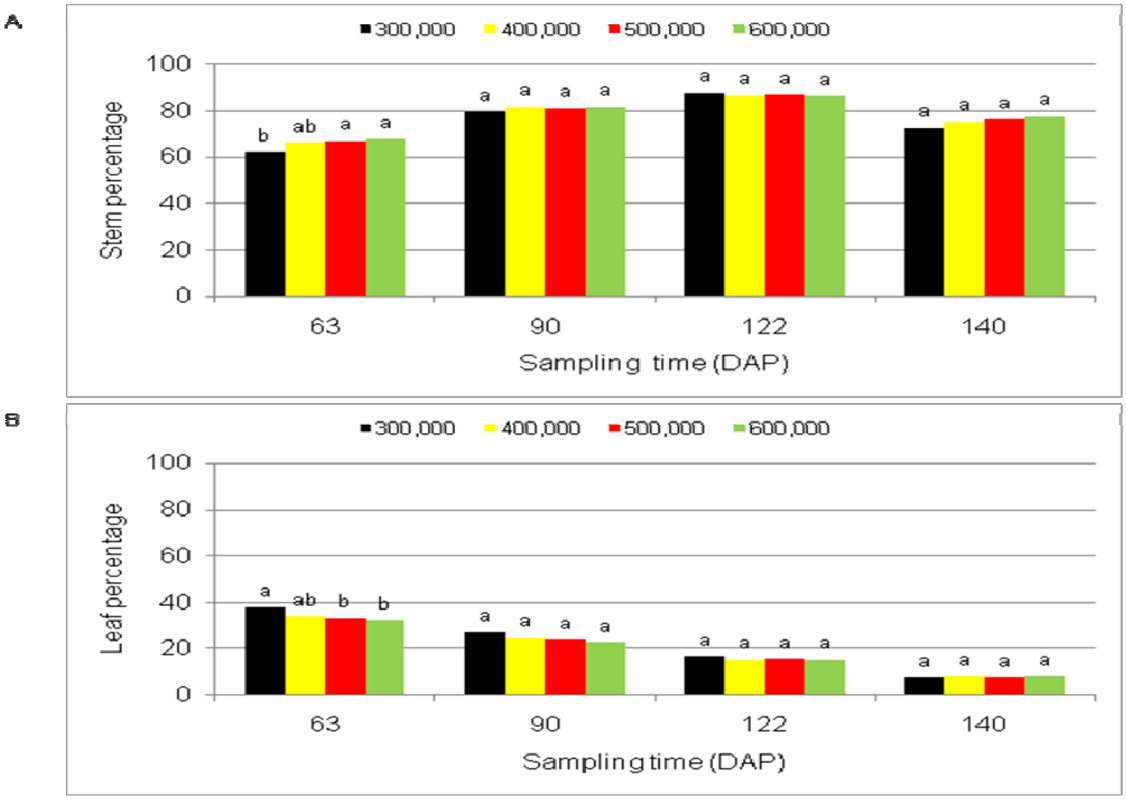
Fig. 6.10. Effect of plant population on leaf dry mass per plant (A) and leaf dry mass per hectare (B) at different sampling times



Bars of the same sampling date with the same letter are not significantly different from each other

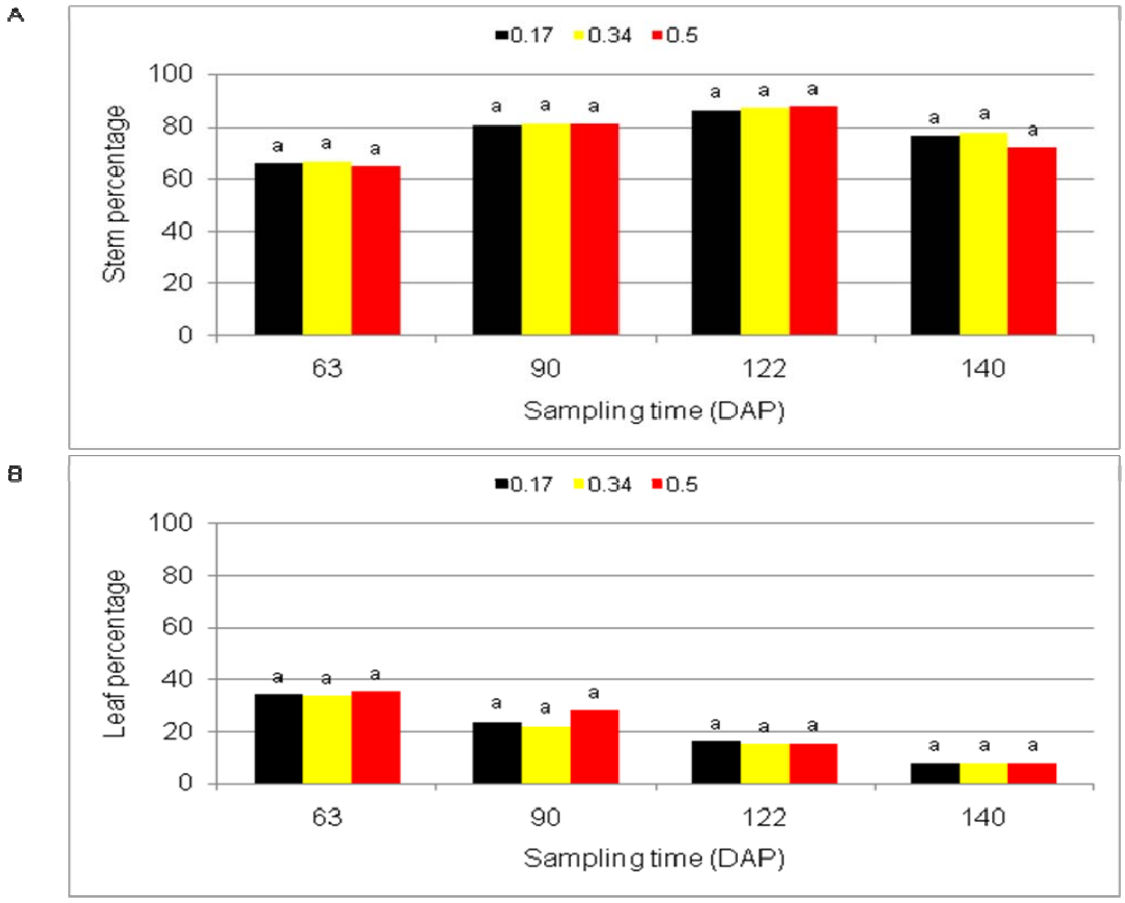
Fig. 6.11. Effect of row spacing on leaf dry mass per plant (A) and leaf dry mass per hectare (B) at different sampling times

Both stem (Fig. 6.12.A) and leaf percentages (Fig.6.12.B) were significantly affected by plant population only at 63 DAP. At this sampling date, the two parameters showed opposite trends with the stem percentage increasing and the leaf percentage decreasing. At the rest of sampling dates the stem percentage did not show clear response to plant population, while the leaf percentage kept decreasing due to senescence. The stem percentage increased from the first to the third sampling date with the values ranging from 60 to more than 80% then declined to less than 80% at the fourth sampling. At this stage the plants started to flower which could account for the reduction in the contribution on the stem. The fact that the lowest leaf percentage was found at the high plant population may suggest quick senescence of leaves due to increase in intraspecific competition for growth resources. Neither the stem percentage (Fig 6.13.A) nor the leaf percentage (Fig. 6.13.B) was significantly affected by an increase in row spacing.



Bars of the same sampling date with the same letter are not significantly different from each other

Fig. 6.12. Effect of plant population on stem (A) and leaf percentages (B) at different samplng times

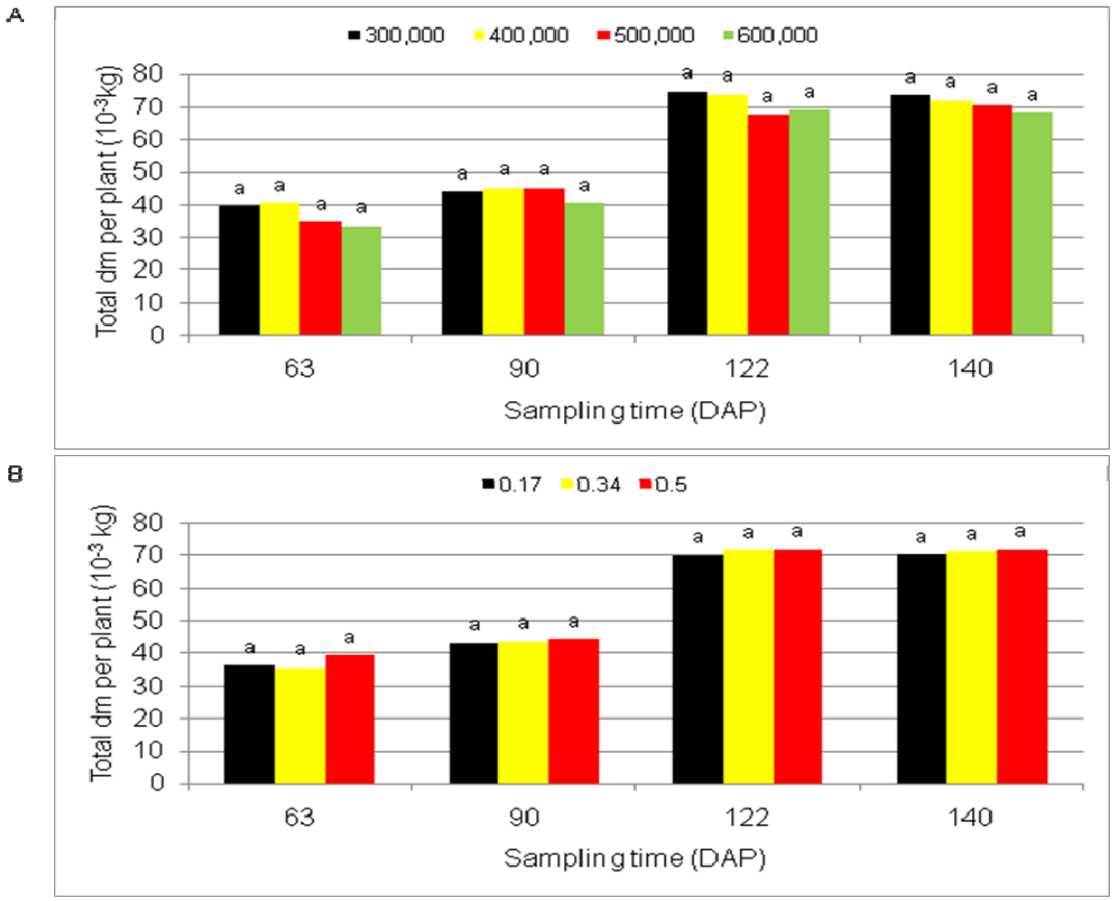


Bars of the same sampling date with the same letter are not significantly different from each other

Fig. 6.13. Effect of row spacing on stem (A) and leaf percentages (B) at different samplng times

Total dry mass

The total dry mass per plant seemed to decrease with an increase in plant population (Fig. 6.14.A), although there was no significant differences. The reaction of total dm per plant (Fig. 6.14.B) as affected by row spacing was also not significant. It does, however, seem if wider rows (0.50 m) initially favoured total dry mass per plant, but as crop competition increased over time, the differences between row spacings were neglegible.



Bars of the same sampling date with the same letter are not significantly different from each other

Fig. 6.14. Effect of plant population (A) and row spacing (B) on total dry mass per plant at different sampling times

The total dm per hectare was significantly affected by the increase in plant population at 63, 90 and 140 DAP (Fig. 6.15.A). At those sampling dates, the lowest plant population had significantly lower dm per hectare than the two higher plant populations. Also, conversely to total dm per plant the total dm per hectare increased with increase in plant population. Similarly to total dm per plant the total dm per hectare was not affected by row spacing (Fig. 6.15.B).

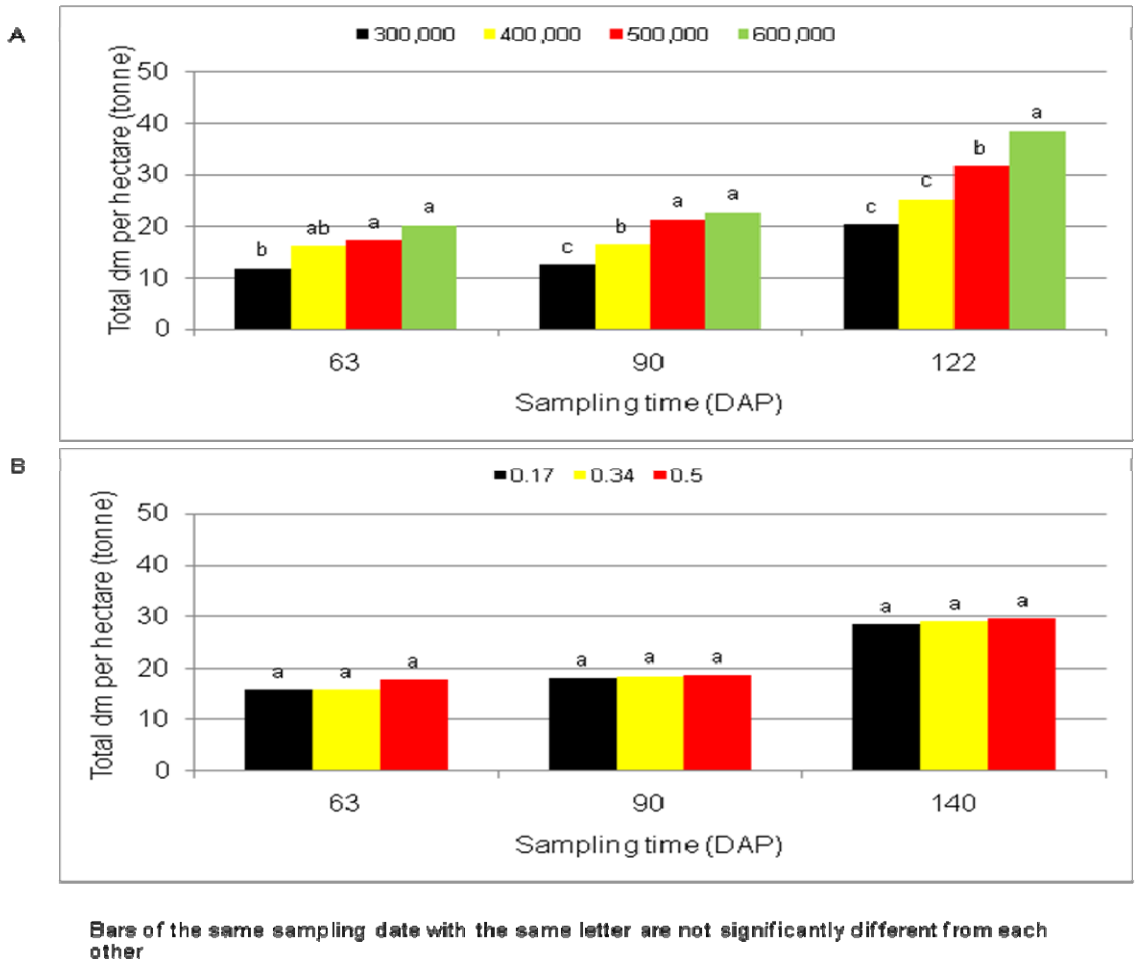
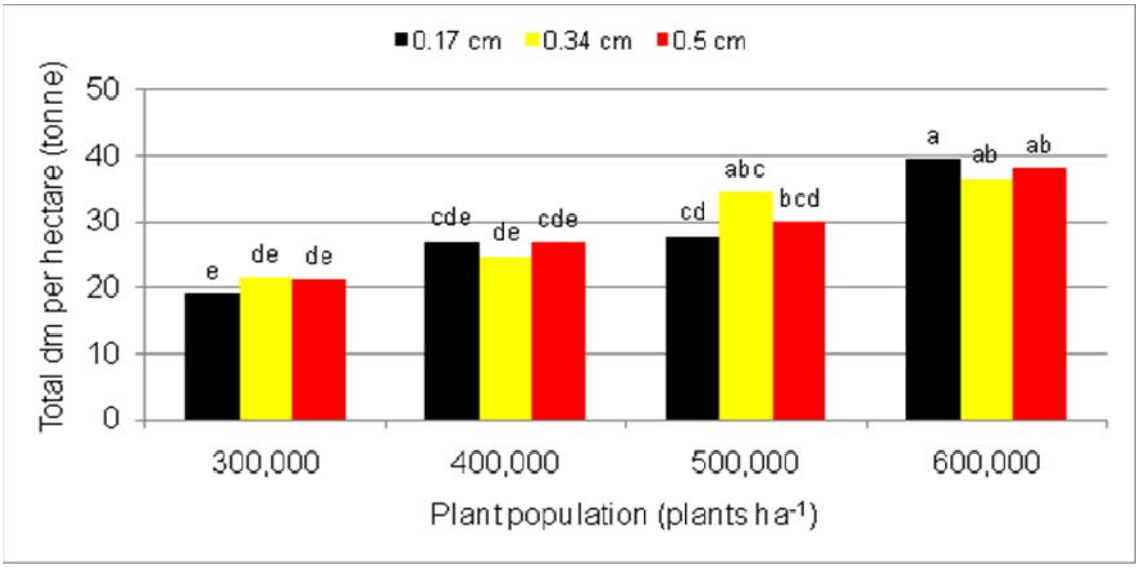


Fig. 6.15. Effect of plant population (A) and row spacing (B) on total dry mass per hectare at 63, 90 and 140 DAP

Interaction between plant population and row spacing on the total dm per hectare was observed at 122 DAP (Fig. 6.16). However, no clear trend of the total dm per plant in response to increase in row spacing was observed within any plant population.



Bars with the same letter are not significantly different from each other

Fig. 6.16. Interaction effect between plant population and row spacing on total dry mass per hectare at 122 DAP

Bark components

Plant population significantly increased bark dry mass per hectare, with the two higher plant populations having significantly higher yields than the two lower plant populations (Table 6.3). This might be attributed to final plant stand rather than to any other factor. On the other hand, neither bark percentage nor bark-core ratio was significantly affected by plant population (Table 6.3). Although no clear effect on any of the three parameters, row spacing significantly affected the bark dry mass (Table 6.4) with the 50 cm spacing giving significantly better yields than the 34 cm spacing.

Table 6.3. Bark percentage and bark-core ratio as affected by plant population at the final harvest

Plant population (plants ha^{-1})	Bark dry matter (t ha^{-1})	Bark-core ratio	Bark percentage (%)
300,000	7.24 b	0.69 a	40.69 a
400,000	8.30 b	0.62 a	37.9 a
500,000	11.20 a	0.65 a	39.07 a
600,000	13.15 a	0.65 a	39.40 a
Mean	9.97	0.65	39.27
Pr	***	NS	NS
HSD	2.7713	-	-

Means within the same column with the same letter are not significantly different from each other

NS: not significant, ***: highly significant at 1% level of probability

Table 6.4. Bark percentage and bark-core ratio as affected by row spacing at the final harvest

Row spacing (m)	Bark dry matter (t ha^{-1})	Bark-core ratio	Bark percentage
0.17	9.65 ab	0.68 a	40.2 a
0.34	9.41 b	0.61 a	37.6 a
0.50	10.86 a	0.67 a	40.0 a
Mean	9.97	0.65	39.3
Pr	*	NS	NS
HSD	1.2247	-	-

Means within the same column with the same letter are not significantly different from each other

NS: not significant, ***: highly significant at 1% level of probability

6.3.3. Nitrogen, potassium and phosphorus use efficiency and nitrogen content of kenaf leaves and stems

Increasing plant population significantly increased the N-, K-, and P use efficiency (Fig. 6.17.A). This may be the results of the increase in stem dm per hectare. In all three cases, the highest plant population resulted in significantly higher nutrient use efficiencies than the lowest plant population. The effect of row spacing was significant only on K use efficiency (Fig. 6.17.A). The 0.50 m row spacing resulted in a significantly higher K use efficiency than the 0.17 m row spacing. The increase in K use efficiency with increase in row spacing may be the results of a slight increase in stem dry mass in responst to an increase in row spacings. However, this was not evident for N or P use efficiency. Although there was not significant effect of row spacing on P use efficiency, there was a tendency of decrease of this parameter in response to increase in row spacing.

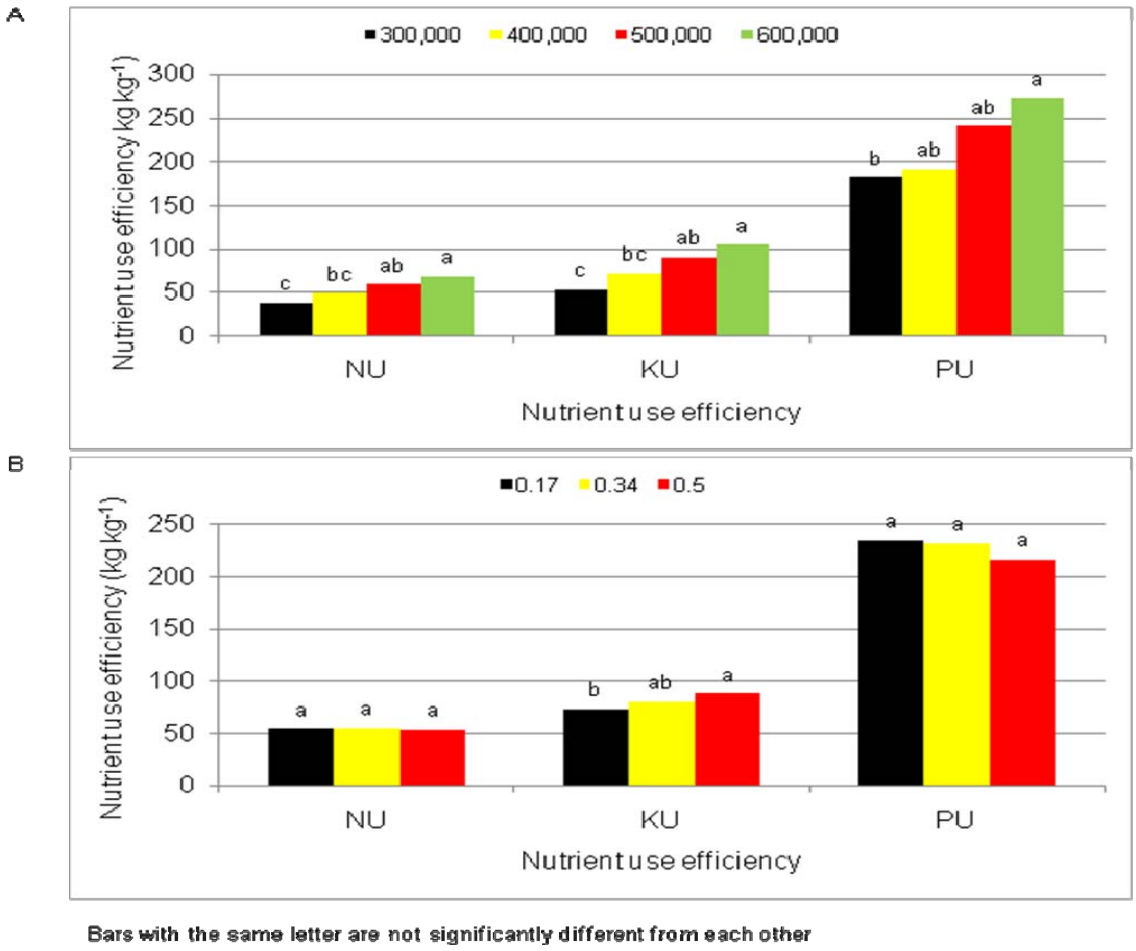


Fig. 6.17. Effect of plant population (A) and row spacing (B) on N use efficiency, K use efficiency and P use efficiency at 140 DAP

Neither plant population nor row spacing had significant effect on nitrogen contents of stem or leaf. Again, the leaf nitrogen content (± 19%) was much higher than the stem nitrogen content (± 2%). The reason of this was given in previous chapters.

6.4. Conclusions and recommendations

Generaly increasing plant population beyond 600,000 plants per hectare induced the production of shorter, thin plants due to higher plant competition. However, an increase in plant population had a positive effect on dry mass production and

particularly the stem dry mass. With the row spacings used in this study, there was generally an increase in dry mass production but not necessarily in terms of growth parameters. The plant height increased as row spacing increased, but only at the final harvest, while the response of stem diameter was inconsistent. Contrarily to plant population, wider rows reduced the number of thin plants so increasing the stem dry mass as well as the total dry mass. The bark dry mass increased with increase in plant population as the results of increase in stem dry mass, however the effect of row spacing was not clear on this parameter. The N, K and P use efficiency increased with increase in plant population in response to increase in stem dry mass. The effect of row spacing was clear only on K use efficiency.

Overall, the results of this investigation agree with other studies indicating that higher kenaf stem yield may be obtained with an increase in plant population and row spacing. However, further research is needed to define the optimum combination of row spacing and planting rate. Future research should also include other agronomic practices such as nutrient and irrigation management to maximize the yield qualitatively and quantitatively.

CHAPTER 7.
KENAF BARK FIBRE PRODUCTION AS AFFECTED BY AGRONOMIC PRACTICES

7.1. Introduction

Plant anatomy plays an important role in the interpretation of morphology, physiology and phylogeny which are based on knowledge of the structure of cells and tissues (Yeung, 1998). Therefore the appreciation of a plant's anatomy is fundamental to the understanding of many aspects of its biology (Cutler *et al*., 2008). Ayre *et al*. (2009) pointed out that the bark or phloem fibres are the primary economic incentive to grow kenaf.

The development and differentiation of fibres are dependent upon signals induced by stimuli or phytohormones such as auxins, cytokinins and gibberellins and originated in the leaves and shoot apaces. From here it flows downward along the internodes to the root (Aloni, 1976; 1979 & 1987; Saks *et al*., 1984; Hwang *et al*., 2010). It is important to note that the signals as well as the concentrations of phytohormons such as auxins, gibberellins, and cytokinins are positively influenced by environmental stimuli such as light, water and nutrients (Goldsmith, 1967; Halliday *et al*., 2009; Liu *et al*., 2010). This may imply that any factor affecting the environmental resources will impact on phytohormons and consequently on fibre production. For example, Hwang *et al*. (2010) observed an increase in gibberellin (GAi) and its immediate precurssor (GA_{20}) content due to nitrogen application, while, Mishra *et al*. (2009) found that lower nitrogen availability lead to a lowered auxin content.

According to commercial terminology, kenaf stem consists out of two distinct fibrous regions; namely core xylem fibres and bark- or phloem fibres with a makeup respectively of about 40 and 60% of stem dry weight (Chiaise *et al*., 2011). However, the bark to core ratio varies with the environment, agronomic practices and cultivar used. The bark and core can be distinguished by their anatomical characteristics, chemical composition, and chemo-physical properties, and are considered as two distinct types of raw material (Kuroda *et al*., 2005; Edeerozey *et al*., 2007). The fact is, however, that the 'core' consists of the pith, without fibres and the xylem

containing short, xylem fibres with lignified cell walls, while the phloem/bark fibres are much longer and the walls contain more cellulose. According to Webber *et al*. (2002), each of the two types of fibres possesses particular uses. Bark fibres are specialized cells, also called sclerenchyma fibres, which have extensive secondary cell wall thickenings and are usually dead at maturity (Esau, 1977). Ayre *et al.* (2009) indicated that fibre bundles may differentiate either from cells derived from the procambium during primary growth, or from cells of the vascular cambium during secondary growth. It was pointed out that fibre bundle shape, size, density and the number of ultimate cells in a bundle may vary greatly within an individual plant (Gorshkova *et al*., 2012).

Several studies conducted around the world, including a one year research project at the Agriculture Research Council (ARC) in South Africa, have highlighted the importance of agronomic management on better kenaf plant height, stem diameter and consequently stem yield (Phillips *et al*., 1999; Pretorius *et al*., 2002 a & b; Banũelos *et al*., 2002; Abdul-Khalil *et al*., 2010; Hossain *et al*., 2011 b). However, none of these studies has focused on the responses of fibre development to agronomic practices. Hence, this study was conducted to examine the relationship between agronomic practices and fibre development (i.e. the number of fibre wedges, fibre rings and fibre bundles per individual stem), especially those from the phloem region. The study was restricted to the bark/phloem fibres only because of their importance and suitability for local demand, in particular and the pulping industry in general.

Hence, it was hypothesized that the number of fibre wedges, rings and bundles;

- will increase with increase in nitrogen level
- will increase with regular water supply (irrigated plants as compared to rainfed plants)
- will decrease with increase in plant population
- will not respond to increase in row spacing

7.2. Materials and Methods

Plants were harvested at 96, 104, and 108 days after planting (DAP) respectively for the irrigated (Chapter 5), rainfed (Chapter 4), and plant population/row spacing trials (Chapter 6). Four plants were randomly harvested from the middle of each plot or each sub-plot by cutting the stem at ground level. The leaves were removed and the stem height of each plant was measured from the cutting point up to the tip of the stem. Three 2cm-segments were cut from each of three different positions; bottom, middle and top of each stem after removing the 10 cm apical part containing undifferentiated tissues. Thereafter the diameter of each segment was measured using a digital calliper. The segments were taken to the Physiological Laboratory of the Department of Plant Production and Soil Science, University of Pretoria, where they were fixed and stored in Formaldehyde Acetic Acid (FAA) solution until the day of microscopic analysis. A hand-cut cross-section of approximately 0.02 mm thickness was made from each segment using a sharp blade. Sections were stained with 1% toluidine blue and phloroglucinol, rinsed with tap water and mounted in glycerol. The sections were examined by means of a light transmission microscope (Leitz) fitted with a digital camera to determine fibre development. During the sectioning care was taken to cut a uniform disc from the proximal end of each segment, containing at least a fourth of the total stem circumference of the bottom portion, one half of the middle portion and a complete section of the top portion. The number of fibre wedges, fibre rings, and fibre bundles in each section were then counted and photographed. In order to determine the total number of fibre wedges, fibre rings and fibre bundles per section (circumference of the segment) for the bottom and the middle segments, the counted numbers were multiplied by 4 and 2 respectively.

All the data were analysed as indicated in chapter 3, 4, 5 and 6. The results regarding different parameters studied in this chapter are presented in the Tables or Figures under each section regarding the parameter studied, but the complete dataset can be found in Appendix E, Tables 7.1 to 7.3.

7.3. Results

7.3.1. Kenaf anatomy

In kenaf, the phloem fibres consist almost entirely of secondary fibres produced by the vascular cambium as part of the secondary phloem and are grouped together in separate bundles which are produced alternatively with thin-walled functional phloem elements. The result is that the fibre bundles occur in successive concentric rings, but also in radial rows separated by phloem ray parenchyma (Figs. 7.2. A & B; Fig. 7.3. B). As a result of the dilation of some phloem rays, groups of fibre bundles from successive rings are divided into uneven triangular or wedge-shaped bundles, referred to in this paper as *fibre wedges* (FW) (Fig. 7.2. A). Adjacent to the vasular cambium (Vc) the wedges are broad, containing a number of fibre bundles per tangential row, with only one or two fibre bundles towards the epidermis adjacent to the cortex (Fig. 7.3. B). As illustrated in Fig. 7.3. A and when comparing Figs. 7.1. A, B; Figs. 7.2. A, B and Fig. 7.3. B the number of concentric fibre bundle rings decreases from the base of the stem to the apex. Therefore, no or only one concentric ring of fibre bundles appears close to the stem apex (Figs. 7.1. A & 7.1. B). Fig. 7.2. A shows that the midldle segments had three concentric rings of differentiated fibre bundles, while in Fig. 7.2. B it is clear that the third concentric ring closer to the vascular cambium was still differentiating. The bottom segment had eight concentric rings (Fig. 7.3. B).

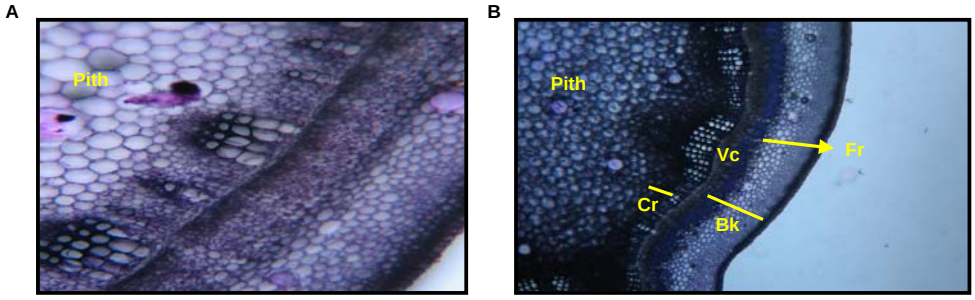


Fig. 7.1. Cross section through the top segment; A) Young portion with undifferentiated fibres without the presence of vascular cambium, B) One ring of differentiated fibre rings (Fr), bark section (Bk) containing phloem fibres and core section (Cr), the latter two sections are separated by the vascular cambium (Vc) indicating that the secondary growth had initiated. The pith occupies the rest of the stem.

The outer fibre bundles (oldest) are shorter and the inner ones (youngest) are longer (Fig. 7.3. A). Within the fibre wedges (FW) the fibre bundles are arranged in tangential rows, while individual bundles are separated from each other tangentially by thin-walled axial phloem parenchyma, and radially by phloem ray parenchyma (Figs 7.2. A, B & 7.3. B). The lignin in the fibre cell walls reacted positively after staining with toluidine blue and phloro glucinol (Figs. 7.4. A & B). The fibre bundles may contain different numbers of fibres cells, resulting in differences in their sizes and shapes (Fig. 7.4. A). During retting the fibre bundles start separating (Fig. 7.5. A), while over-retting will cause separation of individual fibre cells (Fig. 7.5. B). Bel-Berger *et al*. (1999) stated that retting is a wet process by which the bundles of cells in the outer layers of the stem are separated from nonfibrous matter by removal of pectins and other gummy substances.

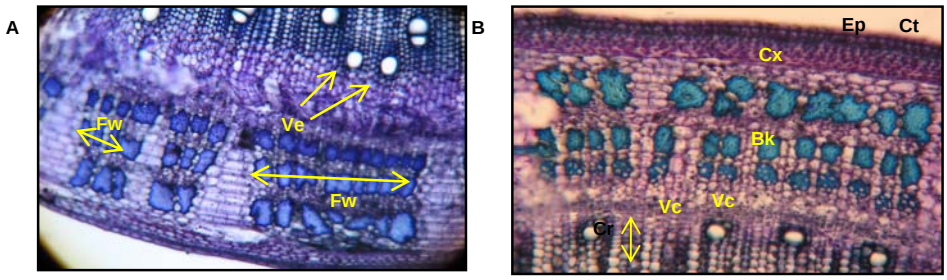


Fig. 7.2. Cross section through the middle segment of the stem; A) Fibre wedges (Fw), vessel elements (Ve), fibre rings in blue, B) The bark section (Bk) is found outside the vascular cambium (Vc) and core section (Cr) but inside, the cortex (Cx), epidermis (Ep) and cuticle (Ct) are also showed

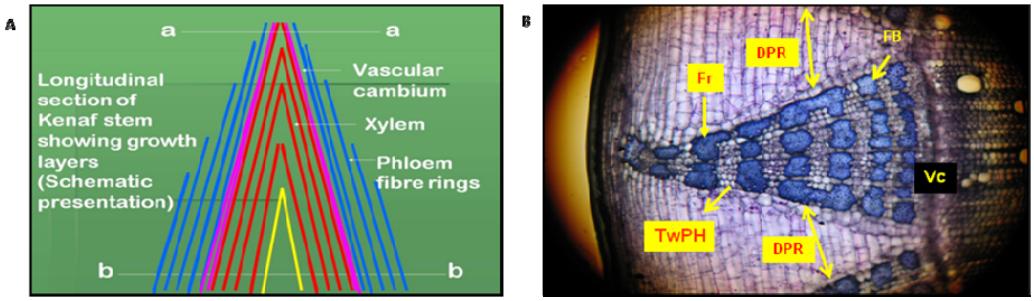


Fig. 7.3. (A) Diagram of longitudinal section of a kenaf stem showing growth layers, with “a-a” indicating the top and “b-b” the bottom of the stem, (B) cross section through the bottom segment of the stem, showing dilated phloem rays (DPR), fibre rings (Fr) containing fibre bundles (FB), the thin walled phloem (TwPh) and vascular cambium (Vc).

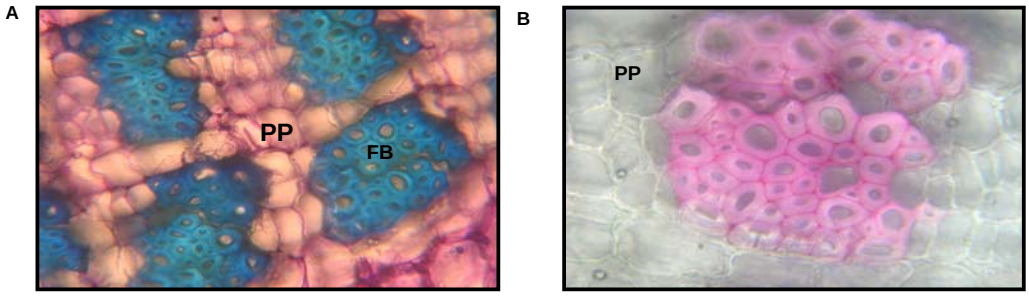


Fig. 7.4. Cross section of kenaf fibre bundles embedded in phloem parenchyma. (A) Stained with toluidin blue and (B) stained with phloro glucinol. FB = fiber bundle; PP = phloem parenchyma.

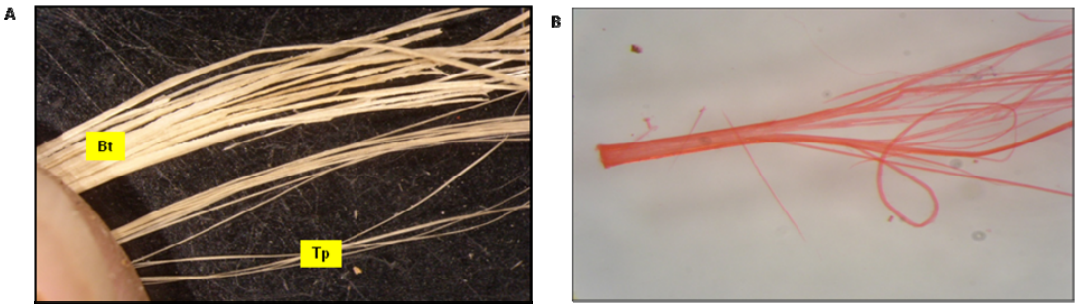


Fig. 7.5. Stages of kenaf fibre retting. (A), two partly retted fibre wedges, one from the bottom section (Bt) and one from the top segment (Tp) showing separating fibre bundles; (B), retted single fibre bundle showing separate single fibre cells.

7.3.2. Effect of different agronomic practices on stem height, diameter of segments and fibre development

The number of fibre wedges, fibre rings and fibre bundles were used as criteria to compare the effect of different agronomic practices on fibre development. The term *fibre wedge*s is a visual concept based on the image seen under the microscope. However, it appears that the number of fibre wedges does not follow any rule in their development. Therefore only the number of fibre rings and fibre bundles will be used as anatomical criteria for further discussion.

Stem height and thickness of different segments

The stem height and the thickness of different segments were increased with high significant effect (Pr < 0.01) in response to increase in nitrogen level under both rainfed and irrigated conditions (Tables 7.1 & 7.2), except the top segment of the plants from the irrigated conditions (Pr < 0.05). Furthermore, in most of the cases the two higher nitrogen levels performed significantly higher than the control.

Table 7.1. Effect of nitrogen level on stem height and segment thickness at 104 DAP under rainfed conditions

Nitrogen level ($kg\ ha^{-1}$)	Stem height (cm)	Segment thickness (mm)		
		Bottom	Middle	Top
0	194.2 b	12.3 b	7.0 b	5.2 b
50	200.3 b	13.1ab	6.6 b	6.1 ab
100	237.2 a	14.1 ab	8.9 a	6.4 a
150	241.1 a	14.9 a	9.7 a	7.0 a
Mean	218.2	13.6	8.04	6.18
Pr	***	***	***	***
HSD	19.09	1.83	1.07	1.11

Means within the same column followed by the same letter are not significantly different from each other

***: highly significant at 1% level of probability

Table 7.2. Effect of nitrogen level on stem height and segment thickness at 96 DAP under irrigated conditions

Nitrogen level (kg ha^{-1})	Stem height (cm)	Segment thickness (mm)		
		Bottom	Middle	Top
0	192.1 c	12.9 b	9.9 b	5.9 b
50	223.1 b	14.1 ab	14.4 a	6.3 ab
100	241.8 a	15.4 a	11.8 ab	7.2 ab
150	258.2 a	15.8 a	13.4 a	7.5 a
Mean	228.8	14.5	12.3	6.7
Pr	***	***	***	*
HSD	18.27	1.82	3.33	1.47

Means within the same column followed by the same letter are not significantly different from each other

*: significant at 5% level of probability, ***: highly significant at 1% level of probability

In general, the stem height and different stem thickness decreased with high significant effect (Pr < 0.01) due to increase in plant population, except the diameter of the bottom segment (Pr < 0.05) (Table 7.3). The row spacing had highly significant effect (Pr < 0.01) only on the thickness of the bottom and top segments (Table 7.4). The stem height and the thickness of the middle segment were not affected by the increase in row spacing (Table 7.4).

Table 7.3. Effect of plant population on stem height and segment thickness at 108 DAP under rainfed conditions

Plant population (plants ha^{-1})	Stem height (cm)	Segment thickness (mm)		
		Bottom	Middle	Top
300,000	244.7 a	15.0 a	10.9 a	6.8 a
400,000	234.2 ab	14.3 ab	10.0 b	5.9 ab
500,000	229.0 bc	14.0 b	9.8 b	4.7 b
600,000	219.9 c	13.9 b	9.8 b	4.7 b
Mean	231.9	14.3	10.1	5.6
Pr	***	*	***	***
HSD	11.33	0.97	0.69	1.49

Means within the same column followed by the same letter are not significantly different from each other

*: significant at 5% level of probability, ***: highly significant at 1% level of probability

Table 7.4. Effect of row spacing on stem height and segment thickness at 108 DAP under rainfed conditions

Row spacing (m)	Stem height (cm)	Segment thickness (mm)		
		Bottom	Middle	Top
0.17	232.9 a	13.7 b	9.9 a	5.17 b
0.34	231.1 a	14.4 a	10.4 a	5.7 ab
0.50	271.8 a	14.7 a	10.1 a	6.0 a
Mean	231.9	14.3	10.1	5.6
Pr	NS	***	NS	***
HSD	-	0.55	-	0.59

Means within the same column followed by the same letter are not significantly different from each other

NS: not significant, *: significant at 5% level of probability, ***: highly significant at 1% level of probability

Fibre development

The numbers of fibre rings under irrigation of the bottom and middle segments were highly significantly increased ($Pr < 0.01$) and significantly increased ($Pr < 0.05$) by nitrogen level (Table 7.5) respectively. The number of rings of the top segment under irrigated conditions (Table 7.5), and of all segments under rainfed conditions were

not significantly affected (Table 7.5). On the other hand, nitrogen level significantly increased the number of fibre bundles of the top segment under rainfed conditions (Pr < 0.05), and highly significantly increased (Pr < 0.01) the number of fibre bundles of the remaining segments under rainfed as well under irrigated conditions (Table 7.6).

Table 7.5. Effect of nitrogen level on the number of fibre rings under rainfed and irrigated conditions

Nitrogen level	Rainfed			Irrigated		
(kg ha^{-1})	Bottom	Middle	Top	Bottom	Middle	Top
0	7.78a	3.0 a	1.0 a	7.8 b	3.1 b	1.1 a
50	7.8 a	2.9 a	1.2 a	7.8 b	3.3 ab	1.1 a
100	7.8 a	3.1 a	1.2 a	8.0 b	3.4 ab	1.2 a
150	8.0 a	3.3 a	1.4 a	9.1 a	3.5 a	1.3 a
Mean	7.8	3.1	1.2	8.1	3.3	1.2
Pr	NS	NS	NS	***	*	NS
HSD	-	-	-	0.62	0.30	-

Means within the same column followed by the same letter are not significantly different from each other

NS: not significant, *: significant at 5% level of probability, ***: highly significant at 1% level of probability

Table 7.6. Effect of nitrogen level on the number of fibre bundles under rainfed and irrigated conditions

Nitrogen level	Rainfed			Irrigated		
(kg ha^{-1})	Bottom	Middle	Top	Bottom	Middle	Top
0	515.0 b	381.5 bc	165.3 c	483.0 c	308.5 c	127.5 b
50	624.3 ab	362.8 c	166.5 bc	607.3 b	379.0 bc	183.0 a
100	690.5 a	473.5 ab	193.0 ab	607.8 b	430.3 ab	202.8 a
150	757.5 a	550.5 a	193.5 a	878.5 a	516.6 a	206.0 a
Mean	646.8	442.1	179.6	644.1	409.6	179.8
Pr	***	***	*	***	***	***
HSD	161.39	92.43	26.82	72.85	99.57	36.59

Means within the same column followed by the same letter are not significantly different from each other

*: significant at 5% level of probability, ***: highly significant at 1% level of probability

Neither plant population nor row spacing had significant effect on the number of fibre rings of the top segment (Table 7.7). The number of fibre rings of the middle segment tended to significantly decrease (Pr < 0.05) with increase in plant population (Table 7.8). The number of fibre rings of the middle segment tended to be significantly higher at the widest row spacing as compared to the two narrower spacings (Table 7.8). Significant interaction effect (Pr < 0.05) between plant population and row spacing was detected on the number of fibre rings of the bottom segment (Table 7.9). It was only within the 400,000 and 600,000 plants per hectare where the number of fibre rings of the bottom segment showed a clear trend by increasing in response to row spacing. As to per each row spacing, the number of fibre rings did not show clear response to increase in plant population. At 0.17 m row spacing, the number of fibre rings remained the same from the 300,000 to 400,000 plants per hectare then decreased to reach the lowest value at the maximum plant population. This was also the case at 0.50 m row spacing, but here it also stabilised from 500,000 to 600,000 plants per hectare. At 0.34 m, it increased from 300,000 to 400,000 plants per hectare and then decreased to the lowest value at 600,000 plants per hectare.

Table 7.7. Effect of plant population and row spacing on the number of fibre rings of the top segment under rainfed conditions

Plant population (plants ha^{-1})	Number of fibre rings	Row spacing (m)	Number of fibre rings
300,000	1.7 a	0.17	1.4 a
400,000	1 4 a	0 34	1 4 a
500,000	1.4 a	0.50	1.6 a
600,000	1.4 a		
Mean	1.48		1.48
Pr	NS		NS
HSD	-		-

Means within the same column followed by the same letter are not significantly different from each other

NS: not significant

Table 7.8. Effect of plant population and row spacing on the number of fibre rings of the middle segment

Plant population (plants ha^{-1})	Number of fibre rings	Row spacing (m)	Number of fibre rings
300,000	4.0 a	0.17	3.4 b
400,000	3.6 ab	0.34	3.3 b
500,000	3.3 b	0.50	3.9 a
600,000	3.3 b		
Mean	3.5		3.5
HSD	*		*
HSD	0.70		0.48

Means within the same column followed by the same letter are not significantly different from each other

*: significant at 5% level of probability

Table 7.9. Interaction effect between plant population and row spacing on the number of fibre rings of the bottom segment

Number of fibre rings				
Plant population (plants ha^{-1})	Row spacing (m)			Mean
	0.17	0.34	0.50	
300,000	10.0 abcd	9.0 bcd	11.0 a	10
400,000	10.0 abcd	10.8 ab	11.0 a	10.6
500,000	9.5 abcd	10.3 abc	9.0 bcd	9.6
600,000	8.3 d	8.8 cd	9.0 bcd	8.7
Mean	9.5	9.73	10.0	9.73
Pr		*		
HSD		1.99		

Means with the same letter are not significantly different from each other

*: significant at 5% level of probability

Increasing plant population significantly decreased the number of fibre bundles of the middle (Pr < 0.05) and bottom (Pr < 0.01) segments (Tables 7.11 and 7.12). However, no significant effect was observed with regards to the top segment (Table 7.10). Regarding the middle and bottom segments, the lowest plant population had significantly high number of fibre bundles than the highest plant population. Increasing row spacing had no significant effect on the number of fibre bundles of any of the segments (top, middle and bottom segments) (Tables 7.10, 7.11 & 7.12). No significant effect of the interaction between plant population and row spacing was detected on the number of fibre bundles.

Table 7.10. Effect of plant population and row spacing on the number of fibre bundles of the top segment

Plant population (plants ha^{-1})	Number of fibre bundles	Row spacing (m)	Number of fibre bundles
300.000	256.0 a	0.17	230.1 a
400.000	263.2 a	0.34	235.3 a
500.000	210.0 a	0.50	239.1 a
600.000	210.2 a		
Mean	234.8		234.8
Pr	NS		NS
HSD	-		-

Means within the same column followed by the same letter are not significantly different from each other

NS: not significant

Table 7.11. Effect of plant population and row spacing on the number of fibre bundles of the middle segment

Plant population (plants ha^{-1})	Number of fibre bundles	Row spacing (m)	Number of fibre bundles
300,000	639.6 a	0.17	571.6 a
400,000	593.2 ab	0.34	571.6 a
500,000	543.5 bc	0.50	571.6 a
600,000	510.2 c		
Mean	571.6		571.6
Pr	*		NS
HSD	53.71		-

Means within the same column followed by the same letter are not significantly different from each other

NS: not significant, *: significant at 5% level of probability

Table 7.12. Effect of plant population and row spacing on the number of fibre bundles of the bottom segment

Plant population (plants ha^{-1})	Number of fibre bundles	Row spacing (m)	Number of fibre bundles
300,000	1265.2 a	0.17	1101.2 a
400,000	1136.3 ab	0.34	1140.7 a
500,000	1113.6 ab	0.50	1141.8 a
600,000	996.5 b		
Mean	1127.9		1127.9
Pr	***		NS
HSD	71.7		-

Means within the same column followed by the same letter are not significantly different from each other

NS: not significant, ***: highly significant at 1% level of probability

7.4. Discussion

The increase in stem diameter (diameter of segments) of kenaf as observed in the present study is the direct result of an increase in the volume of core and bark regions. Regarding the bark region which was of concern in the present study, the increase in its volume is concomitant to the appearance of new formed concentric fibre rings outside the vascular cambium during secondary growth. Previously formed fibre rings are pushed outward by newly formed rings, causing the dilation of phloem rays to prevent cracking of the stem. This results in an increase in the volume of bark regions, and therefore contributes to the stem diameter. The observation from this study agrees with the findings of Ayre *et al*. (2009), who reported an increase in stem girth of kenaf as a result of the activity of cells of the vascular cambium during secondary growth. The increase in the number of fibre bundles per ring was the result of an increase of the diameter of the core, mainly secondary xylem. The results of this study highlight the fact that the effect of any agronomic practice on the stem diameter of kenaf depends on the responses of the activity of vascular cambium cells. Higher nitrogen fertilization levels probably improved the activity of the cambium cell while, higher plant populations tended to reduce the activity of those cells. Apparently the vascular cambium cells were not sensitive to increase in row spacing, with exception to a few cases. The consequence was that no clear responses of the assessed parameters were observed. However, the increase in the number of concentric rings of the middle segment, and the increase in the thicknesses of the top and bottom segments with increase in row spacing may suggest that increasing the space between planting rows is important for reducing the inter competition between plants. The interaction between plant population and row spacing suggests that growing kenaf at the lowest plant population and wider spacing was a proper agronomic practice for increasing the number of concentric rings, although not necessarily to the fibre production per hectare (chapters 3 and 6).

The increase in stem height with increase in nitrogen levels may be due to the availability, the uptake, and the assimilation of this nutrient by the plants, as well as the effects of this nutrient on cell activity. According to Cechin and De Fatima (2003)

the metabolic processes in the plant is totally dependent upon nitrogen availability. MacAdam *et al*. (1989), and Volenec and Nelson (1981) found an increase in cell elongation with increase in nitrogen supply. The decrease in stem height with increase in plant population might be attributed to the increase in pressure on growth resources reducing the availability of those resources under high plant population.
An increase in height and diameter of kenaf stems with increased nitrogen was also found in previous chapters 4 and 5, and by Kuchinda *et al*. (2001). However, Abdul-Hamid *et al*. (2009) and Danalatos and Archontoulis (2005) reported a decrease in kenaf stem diameter with an increase in nitrogen. Reduction in both plant height and stem diameter of kenaf due to increase in plant population were also observed in chapters 3 and 6 and in other studies (Danalatos & Archontoulis, 2004 a; Acrèche *et al*., 2005). Acrèche *et al*. (2005) also reported an increase in stem height and diameter with increase in row spacing.

It has to be noted that the effects of any agronomic practice on cell activity can indirectly result from their effect on other growth factors including the availability of nutrients, water and light. This was evident by the performance of the plants grown under the same rate of nitrogen, but with different levels of water supply. This illustrates the fact that the availability of nitrogen and other nutrients as well as their absorption by plants vary accordingly to water availability.

Although our results confirmed earlier findings on the effects of agronomic practices on stem height and diameter via diameter of segments, the mechanism of how this occurs was not elucidated. The present study revealed how agronomic practices affect stem diameter through fibre development. The novelty of this study was to investigate the response of fibre development to agronomic practices by using the microscope and the resultant effect thereof on stem diameter. This study revealed that a microscopic study may be an important tool for following the development of fibre. If done throughout the growth cycle it can help to determine the optimal time of harvesting for maximum fibre production. However, other considerations such as the chemical quality (cellulose, hemicellulose, lignin and ash) of fibre and the ease with which the bark can be separated from the rest of the stem must also be taken into account for the harvesting time.

7.5. Conclusions

In general, the agronomic practices used in the present study had various effects on fibre development (number of concentric rings and number of fibre bundles), and in the stem height and thickness. The results of this study showed clearly that the stem thickness of kenaf, apart from the core (pith and secondary xylem) is dependent upon the number of concentric rings forming along the height of the stem. Thus the development of fibre within a single plant may be assessed by considering the number of concentric rings of fibre and fibre bundles along the height of the stem. A further revelation from this study is that the poorer performance of plants grown under rainfed conditions as compared to the plants grown under irrigated conditions, is indeed an indication that optimal fibre development could not be achieved without supplying sufficient water to kenaf.

The use of a microscope in assessing kenaf stem anatomy appears to be a reliable approach to assess the development of fibres at a particular stage of growth. Therefore, if used throughout the growing season the microscopic analysis can assist to determine the correct time of harvesting for optimal fibre production. Further, when growing kenaf for fibre production the aim is to gain a better economic return which can be obtained by producing more fibre per plant/ per unit area. This can be achieved only if more concentric fibre rings and more fibre bundles are developed per individual plant / per unit area. Under local conditions, 150 kg ha^{-1} of nitrogen applied in a split application, 300,000 plants per hectare and 0.50 m row spacing might be the best agronomic practices in terms of fibre development or fibre production per plant. However, for the best economic decision the compensation between the number of plants per unit area and the quantity of fibre produced per plant should be taken into account. This study was conducted on the plants sampled at five weeks before the final harvesting which was done at 25 % flowering as recommended by Agbaje *et al*. (2008). However, these findings need to be confirmed at the final harvest.

To the best of our knowledge, this study constitutes the first step in investigating the effect of agronomic practices on fibre development by the means of microscopic work. Hence, further studies are encouraged to confirm the above findings.

CHAPTER 8.
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1. SUMMARY

Kenaf is a multipurpose crop with various harvestable components; leaves, stems and seeds. It is the third largest fibre crop of economic importance after jute and cotton, and produces high fibre yields with corresponding higher income per hectare as compared to most other pulps. It has been used as an alternative to compensate for the gradual diminishing stocks of hard and soft woods in the world. Kenaf can be grown in a wide range of soil and climatic conditions, and its commercial success has potentially important economic and environmental benefits. In South Africa, kenaf was commercially cultivated up to the 1950's, but production discontinued in the early 1960's, only to restart again in the 2000's as a "new fibre crop". The first kenaf processing factory in the country went into production in 2006 just outside Winterton/Bergville in Kwazulu-Natal. The fibre bales from this factory are mostly exported to the automotive industry in Europe.

The commercial kenaf producers in the Winterton/Bergville were making use of various agronomic practices, which sometimes not only resulted in uneconomic returns but also negative effects on the environment, especially with respect to nitrogen fertilizer. Hence, there was a need to undertake research in order to provide them with guidelines in terms of plant population, row spacing, nitrogen level and water management. Four field trials were carried out under summer conditions between 2008 and 2010 at the Hatfield Experimental Farm of the University of Pretoria. Overall, the effect of nitrogen application level, plant population and row spacing on growth, yield and the chemical composition of fibre (acid detergent fibre, neutral detergent fibre, celluloce, hemicellulose, lignin, ash and crude fibre) and dry matter, fibre development, Water use efficiency, nutrient use efficiency, nutrient removal of the plants and nitrogen contents of leaves and stems were assessed. During the first season (2008/09), a single field trial (trial one) was conducted, applying treatments consisting of a combination of plant population, nitrogen level, and row spacing. However, due to inconsistencies in the response of most of the

parameters to agronomic practices and input (nitrogen), it was decided to split the experiment into two groups during the second season (2009/10). The one trial dealt with N level under rainfed (trial two) and irrigated (trial three) conditions. The final trial (trial four) assessed plant response to the combination of plant population and row spacing under rainfed conditions.

2008/09 Season

Trial 1:

The trial was laid out in a randomized split-split plot design. Three plant populations; 200,000; 300,000 and 400,000 plants ha^{-1}, four N levels; 0; 50; 100; and 150 kg ha^{-1} and three row spacings; 0.17; 0.34; and 0.50 m were assessed under rainfed conditions. The full complement of nitrogen, potassium and phosphorus was applied at planting. Due to adverse conditions in the field, poor germination resulted in 22% missing plots for the total field with the 0.17 m treatment alone accounting for about 56% of missing plots. Hence, this row spacing was left out during further data analysis. Stem diameter, plant height and growth rate were taken at 85, 113 and 126 days after planting (DAP). Biomass production (stems and leaves) as well as the chemical composition of bark fibre (acid detergent fibre (ADF), neutral detergent fibre (NDF), cellulose, hemicellulose, lignin, ash and crude fibre) and dry matter were taken only once at final harvest (126 DAP).

Generally, none of the agronomic practices or inputs resulted in clear effects on different parameters studied. The reason could be the timing and the method of application of nutrients, and also may be related to the missing plots. Regarding the missing plots, it was decided to use the procedures of unbalanced design as indicated in chapter 3. Hence, it was just in some rare cases where the significant effect of either treatment was observed.

2009/10 Season

Trial 2:

The trial was conducted under dryland conditions using the same four nitrogen levels as indicated for trial 1. Nitrogen was applied as two dressings of 0 and 50 kg ha^{-1} each at planting and 0, 50 and 100 kg ha^{-1} at thinning (35 DAP). A plant population of 500,000 plants ha^{-1} and row spacing of 0.50 m was used. Soil water content of each plot was weekly measured with a neutron probe to enable calculation of crop water use. The total amount of irrigation water and rainfall received by the crop was recorded and the water use efficiency was determined for each sampling date. Nitrogen use efficiency (NUE), potassium use efficiency (KUE) and phosphorus use efficiency (PUE), and N, P and K removal by the plants as well as N content in the stems and leaves were determined at the last sampling. The chemical composition of the bark fibre and dry matter content (at final harvest) and fibre development (at 108 DAP) were assessed during the season.

Generally, plant height, stem diameter, leaf area per plant (LA) and leaf area index (LAI) increased with an increase in nitrogen level. As a consequence of the increase in size of individual plants, the biomass yields of both individual plants and total yield per hectare responded positively to nitrogen. The increase in plant height and stem diameter resulted from the availability of nitrogen, which promoted higher vegetative growth. With respect to the chemical composition of the bark fibre, ADF, NDF, cellulose and crude fibre and dry matter tended to increase in response to an increase in nitrogen level, while opposite trends were observed for the hemicellulose, lignin and ash contents. WUE and NUE showed increasing trend in response to an increase in nitrogen level as was the case with stem yield. The nitrogen content of the leaves had a tendency to increase with increase in nitrogen level, while, the stem nitrogen content showed no response. The higher nitrogen content in the leaves in comparison to the stems might be explained by the presence of the mesophyll which is the center of physiological processess.

Trial 3.

This experiment was a duplication of the previous trial (trial 2), except that the plants received supplementary water on a weekly basis from 23 DAP until final harvest via drip irrigation to refill the soil profile to field capacity. The assessment of fibre took place at 96 DAP.

In general, plant height and stem diameter responded positively to increased level of nitrogen over the growth cycle. High nitrogen availability promoted vegetative growth, which had a positive effect on LA and LAI. Biomass yields increased with an increase in nitrogen level. Apart from the ash content, the chemical quality and dry matter content of bark fibres, showed very little reaction to an increase in nitrogen level. High nitrogen level induced an increase in WUE and NUE as the result of increasing stem biomass. Nitrogen content of the stems and leaves were indifferent to nitrogen level, but still the leaves had higher nitrogen content than the stems.

Comparing the two nitrogen trials, it can be seen that the better water regime (irrigated trial), in general, resulted in higher values for the different parameters than the rainfed conditions. The higher NUE under irrigated conditions compared to the rainfed can be ascribed to higher stem biomass production under irrigated conditions.

Trial 4:

Due to an increase in stem dry mass with increase in plant population reported in the 2008/09 season, it was decided to add two higher plant populations, 500,000 and 600,000 plants ha^{-1} and leave out the lowest population, 200,000 plants ha^{-1}. This gave a total of four plant populations; 300,000; 400,000; 500,000 and 600,000 for this study. The row spacings were kept the same as in the first season; 0.17, 0.34, and 0.50m. The details of this experiment are in general similar to those described for trials 2 and 3. Fibre development was assessed at 108 DAP.

Plant population

An increase in plant population negatively affected plant height and stem diameter. At the beginning of the season plant population had a limited effect on these parameters, probably because of a lack in competition between the small plants. However, as the season progressed, so did the effect of the higher plant populations. An increase in plant population negatively affected biomass yields per plant as a consequence of the decrease in plant height and stem diameter. This was probably due to an increase in pressure on environmental resources exerted by higher plant populations. However, opposite trends were observed when using the yields of the same parameters per hectare. The results may indicate that to increase yield per unit area, the emphasis must be on ensuring the number of plants per hectare, rather than on the size of individual plants. NUE increased with increase in plant population as a result of the increase in stem yield per hectare. Increased plant population did not affect the nitrogen content of either leaves or stems, but as with the other trials, the nitrogen content of the leaves was much higher than that of the stems.

Row spacing

Generally, plant height and stem diameter increased with wider rows and consequently the stem and total yields per plant also increased. This may indicate that the increase in space between plants from adjacent rows played a more important role than the reductions in space between the adjacent plants within the same row. The LA increased with an increase in row spacing, probably due to delayed leaf senescence at wider rows. The LAI was not sensitive to manipulation of row spacing from the beginning to the final harvest. The total biomass did not show a consistent trend over the growth cycle. The stem NUE increased with increase in row spacing as a result of increase in stem yield per hectare. No responses of leaf and stem nitrogen content to increases in row spacing were observed.

In general, despite a longer growth season the plants were slightly shorter and thinner than in the 2008/09 season. This could be due to the lower average plant population in the 2008/09 season in comparison with 2009/10.

From chapter 7, various effects of agronomic practices used were observed on fibre development (number of concentric rings and number of fibre bundles). The results of this study showed clearly that the stem thickness of kenaf, apart from the core (pith and secondary xylem) is dependent upon the number of concentric rings forming along the height of the stem. A further revelation from this study is that the poorer performance of plants grown under rainfed conditions as compared to the plants grown under irrigated conditions, is indeed an indication that optimal fibre development could not be achieved without supplying sufficient water to kenaf.

8.2. CONCLUSIONS

The stem is a valuable component of biomass yield of kenaf due to the use of its fibres for manufacturing of different commodities. Based on the results from the first season, the application of the total amount of nitrogen at planting seemed to have marginal benefits on all the major characteristics of yields. In the second season, the split application of nitrogen in two dressings seemed to be appropriate to increase the profitability of this nutrient. Increasing nitrogen generally increased growth parameters, yields and fibre development. Hence, under conditions similar to those of the experimental site, it is recommended that nitrogen fertilizer be applied in two dressings at a rate of 100 kg ha^{-1} or 150 kg ha^{-1}. Furthermore, according to this study, the benefits from nitrogen fertilization seemed to improve with good management and optimising of other agronomic practices, including water supply. It was also clear that less benefit can be expected under dry land conditions. This is an indication that nitrogen uptake by the crop responds positively to water availability. The results of two seasons of study revealed that the lowest plant population (200,000 and 300,000 plants ha^{-1}) produced big sized stems and a high yield per plant. However, the highest plant population (500,000 and 600,000 plants ha^{-1}) resulted in smaller plants, but higher total biomass yield per hectare. Therefore, a planting density of 500,000 plants ha^{-1} or higher may be recommended for obtaining high stem yield in Pretoria. The results showed that the wider row spacings (0.34 and 0.50 m) may be suitable to increase the profitability of a kenaf crop as it tended to improve both growth and biomass characteristics of the stem.

The use of a microscope, in assessing kenaf stem anatomy appears to be a reliable approach to assess the development of fibres at a particular stage of growth. Therefore, if used throughout the growing season the microscopic analysis can assist to determine the correct time of harvesting for optimal fibre production. Under local conditions, split application of 150 kg $ha^{-1}$of nitrogen, 300,000 plants per hectare and 0.50 m row spacing might be the best agronomic practices in terms of fibre development or fibre production per plant. However, for the best economic decision the compensation between the number of plants per unit area and the quantity of fibre produced per plant should be taken into account. To the best of our knowledge, this study constitutes the first step in investigating the effect of agronomic practices on fibre development by the means of microscopic work. Furthermore, although that the trials were conducted in Pretoria environment we are currently busy developing an assimilation model in order to extrapolate the findings of this study to a various range of soil and climate of South Africa. This will be published as a paper in the forthcoming months.

8.3. RECOMMENDATIONS

Although, further studies are encouraged to validate the findings of this report, the following recommendations may be done;

- ✓ Nitrogen should be applied in two dressings
- ✓ Nitrogen should be applied at the rate of 100 or 150 kg ha^{-1}
- ✓ Irrigation water must be adequately applied in supplement to rainfall
- ✓ Plant population should be in the range of 500,000 or high for stem and biomass yield per hectare
- ✓ The row spacing in the range between 0.34 and 0.50 m is ideal for all aspects of stem yield

- ✓ The fibre development should be assessed through the number of fibre rings and fibre bundles

- ✓ The use of microscope to assess the development of fibre throughout the growing season may be considered to detemine the right time of harvesting

REFFERENCES

ABDUL-HAMID, H., YUSOFF, M.H., AB-SHUKOR, N.A., ZAINAL, B, & MUSA, M.H., 2009. Effects of Different Fertilizer Application Level on Growth and Physiology of *Hibiscus cannabinus* L. (kenaf) Planted on BRIS Soil. *J. Agric. Sci*. 1, 121-131.

ABDUL-KHALIL, H.P.S., IRENA YUSRA, A.F., BHAT, A.H. & JAWAID, M., 2010. Cell wall ultrastructure, anatomy, lignin distribution, and chemical composition of Malaysian cultivated kenaf fiber. *Ind. Crops and Prod.* 31, 113-121.

ACRÈCHE, M., GRAY, L., COLLAVINO, N. & MARIOTTI, J., 2005. Effect of row spacing and lineal sowing density of kenaf (*Hibiscus cannabinus* L.) yield components in the north-west of Argentina. *Spanish J. of Agric. Res.* 3, 123-129.

ADAMSON, W.C. & BAGBY, M.O., 1975. Woody core fiber length, cellulose percentage, and yield components of kenaf. *Agron. J*. 67, 57-59.

ADAMSON, W., LONG, F. & BAGBY, M., 1979. Effect of nitrogen fertilization on yield, composition, and quality of kenaf. *Agron. J.* 71, 11-14.

ADDISON, K., 2013. The biodiesel Bible. http://www.journeyforever.org/biodiesel_yield.htm. Lat date accessed 01 August 2014

ADENIYAN, O.N., AKANDE, S.R., BALOGUN, M.O. & SAKA, J.O., 2007. Evaluation of crop yield of African yam bean, maize and kenaf under intercropping systems. *American-Eurasian J. Agric. & Environ. Sci.* 2, 99-102.

AGBAJE, G., SAKA, J.O., ADEGBITE, A.A. & AEYEYE, O.O., 2008. Influence of agronomic practices on yield and profitability in kenaf (*Hibiscus cannabinus* L.) fiber cultivation. *Afr. J. Biotechnol*. 7, 565-574.

AGBOR, G.A., OBEN, J.E., NGOGANG, J.Y., 2005. Haematinic activity of *Hibiscus cannabinus*. *Afr. J. Biotechnol*. 4, 833-837.

AJI, I.S., SAPUAN, S.M., ZAINUDIN, E.S. & ABDAN, K., 2009. Kenaf fibres as reinforcement for polymeric composites. A review: *Int. J. Mech. Mat. Eng.* 4, 293-248.

ALEXOPOULOU, E., CHRISTOU, M., MARDIKIS, M. & CHATZIATHANASSIOU, A., 2000. Growth and yields of kenaf varieties in central Greece. *Ind. Crops and Prod.* 11, 163-172.

ALONI, R., 1976. Polarity of induction and pattern of primary phloem fiber differentiation in Coleus. *Am. J. Bot. 63,* 877-889.

ALONI, R., 1979. Role of auxin and gibberellin in differentiation of primary phloem fibers. *Plant Physl.* 63, 609-614.

ALONI, R., 1987. Differentiation of vascular tissues. *Ann. Rev. of Plant Physiol*. 38, 179-204.

AMADUCCI, S., AMADUCCI, M.T., BENATI, R. & VENTURI, G., 2000. Crop yield and quality parameters of four annual fibre crops (hemp, kenaf, maize and sorghum) in the North of Italy. *Ind. Crops and Prod.* 11, 179-186.

ANDERSEN, J.R., 1979. Impacts of climatic variability on Australian agriculture; *Rev. Mark. Agr. Econ*. 49, 147-177.

ANNANDALE, J.G., BANADÉ, N., JOVANOVIC, N.Z., STEYN, J.M., DU SAUTOY, N., 1999. Facilitating irrigation scheduling by means of the soil water balance model. *Water Res. Commission Rep*. N0 753/1/99, Pretoria, South Africa.

ANONYMOUS, 1963. PlantFiles: Kenaf, Brown Indian Hemp, Hibiscus cannabinus' Everglades 41'. http://www. Davesgarden.com. Las accessed 25 August 2014

ANONYMOUS, 2008. Pulp and paper project. Available at http://www.gssc.gpg.gov.za/gautengemi/docs/Pulpandpaperprojectdocument April2008draft1.pdf

ARCHONTOULIS, S.V., STRUIK, P.C. & DANALATOS, N.G., 2005. Leaf photosynthesis of kenaf (cv. Everglades 41) as affected by different light intensity and temperature regimes. In: *Proc. of the 14th Europ. Biomass Conf*., 17-21 October, Paris, France, pp. 414-417.

ARKOLL, D.B., 1971. Agronomic aspects of leaf protein production in Great Britain.in Leaf Protein: Its Agronomy, Preparation, Quality, and Use, IBP Handb. No. 20, ed. N. W. Pirie, pp. 9-18. Oxford: Blackwell. In Google books.

ASHORI, A., RAVERTY, W.D. & HARUN, J., 2005. Effect of chitosan addition on the surface properties of Kenaf (*Hibiscus cannabinus*) paper. *Iran Polym J.* 14, 807-814.

ASSOCIATION OF OFFICIAL ANALYTICAL CHEMIST (A.O.A.C), 2000. Official methods of analysis.

AYRE, B.G., STEVENS, K., CHAPMAN, K.D., WEBBER, C.L., DAGNON, K.L. & D'SOUZA, N.A., 2009. Viscoelastic properties of kenaf bast fiber in relation to stem age. *Textile Res. J.* 79, 973-980.

AYUB, M., NADEEM, M.A., TANVIR, A., TAHIR, M. & KHAN, R.M.A., 2007. Interactive effect of different nitrogen levels and seeding rates on fodder yield and quality of pearl millet. *Pakist. J. Agri. Sci.* 44, 592-596.

BALDWIN, B.S. & GRAHAM, J., 2006. Population density and row spacing effects on dry matter yield and bark content of kenaf (*Hibiscus cannabinus* L.). *Ind. Crops and Prod*. 23, 244-248.

BANÕELOS, G.S., BRYLA, D.R. & COOK, C.G., 2002. Vegetative production of kenaf and canola under irrigation in central California. *Ind. Crops and Prod.* 15, 237-245.

BEL-BERGER, P., VON HOVEN, T., RAMASWAMY, G.N. & BOYLSTON, E., 1999. Cotton/kenaf fabrics: a viable natural fabric. *J Cotton Sci*.

BERENDSE, F. & AERTS, R., 1987 Nitrogen-use-efficiency: a biologically meaningful definition? *Funct. Ecol.* 1, 293-296.

BERGER, J., 1969. The world's major fibre crops- their cultivation and manuring. Centre d' etude de l'azote, Zurich, 227-231.

BERTI, M.T., KAMIREDDY, S.R. & JI, Y., 2013. Row spacing affects biomass yield and composition of kenaf (*Hibiscus cannabinus* L.) as a lignocellulosic feedstock for bioenergy. *J. Sustain. Bioen. Syst*. 3, 63-73.

BHANGOO, M.S. & COOK, C.G., 1993. Regional Uniform Kenaf Variety Trial in the San Joaquin Valley, California (1992)," pp. 184-189 in proceedings. Fifth Annual International Kenaf Association Conference, March 3-5, 1993, Fresno CA.

BHANGOO, M.S., COOK, C.G. & SAKOURI, K., 1994. Effect of Soil Salinity and Irrigation Levels on Kenaf Production in the San Joaquin Valley, *California Agric. Technol. Inst*. CATI Publication # 940102.

BHANGOO, M., TEHRANI, H. & HENDERSON, J., 1986. Effect of planting date, nitrogen levels, row spacing, and plant population on kenaf performance in the San Joaquin Valley, California. *Agron. J.* 78, 600-604.

BITZER, M.J. & BRUERNING, B., 1997. Effects of varieties and row width on kenaf yields. In: *Proc. Ninth Ann. Int. Kenaf Assoc. Conf.*, Scottsdale, AZ, March 27-29, pp 67.

BLOCH, D., HOFFMAN, C.M. & MÄRLÄNDER, B. 2006. Impact of water supply on photosynthesis, water use and carbon isotope discrimination of sugar beet genotypes. *Europ. J. Agron*. 24, 218-225.

BONATTI, P.M., CHIARA FERRARI, C., FOCHER, B., GRIPPO, C., TORRI, G. & CSENTINO, C., 2004. Histochemical and supramolecular studies in determining quality of hemp fibres for textile applications. *Euphyt.* 140, 55-64.

BOSSIA, A., 1975. Hemp for refiner mechanical pulp. Paper (World Research and Development Number), pp 37-41.

BOWYER, J.L., 1999. Economic and environmental comparisons of kenaf growth versus plantation grown softwood and hardwood for pulp and paper. In: SELLERS, T. Jr., REICHERT, N., COLUMBUS, E., FULLER, M. & WILLIAMS, K. (eds) 1999. Chemistry of Kenaf: properties and materials Symposium, 323-346. *Mississippi State Univ*.

BOYER, J.S., 1982. Plant productivity and environment. *Science* 218, 443-448

BROADWAY, R., 1990. Scientists find results of kenaf research encouraging. Research Highlights, *Mississippi Agric. And Forestry Exp. Sta., Mis. State, MS*, 53, 7.

BRUECK, H., 2008. Effect of nitrogen supply on water-use efficiency of higher plants. *J. Plant Nutr. Soil Sci*. 171, 210-219.

BRYOM, M.H., 1951. Progress with long vegetable fibers. Crops in Peace and War. The Year book of Agriculture, U.S. Dept. of Agric. pp 472-476.

BURKCY, K. & BISCOE, P.V., 1983. Stickstoff imR¨Ubenblatt und N-Translokation Ausalternden Blattern. In IIRB Winter Congress, Brussels. In NOURI, H; RAZAVI, S.J., AMIN, M.S.M., AIMRUN, W & LEE, T.S., Application of precision farming principles for determination of temporal and spatial variation in a sugar beet field. *EFITA conference* '09.

BURKETT, A.L., GORDON, E.D., PETTIT, V.C., POPE, O.A., WALKER, J.E. & ACUNA, J.B., 1949. Effects of Age of Plant and Retting Procedures on Kenaf, *Hibiscus cannabinus* L., *Fiber Agron. J*. 41, 255-26.

CALDWELL, S.A.G., 1936. Sunn and Bombay hemps. *Textile Mfr.* 62, 455-466

CARBERRY, P. & MUCHOW, R., 1992 a. A simulation model of kenaf for assisting fibre industry planning in Northern Australia. II. Leaf area development. *Aust. J. Agric. Res*. 43, 1515-1526.

CARBERRY, P. & MUCHOW, R., 1992 b. A simulation model of kenaf for assisting fibre industry planning in northern Australia. III. Model description and validation. *Aust. J. Agric. Res.* 43, 1527-1545.

CECHIN, I & DE FATIMA, F.T., 2003 Effect of nitrogen supply on growth and photosynthesis of sunflower plants grown in the greenhouse. Plant Science 166, 1379-1385.

CHAPIN, E.S. 1980. The mineral nutrition of wild plants. *Annu. Rev. Ecol. Syst.* 11, 233-260.

CHEN, C., BAUCHER, M., CHRISTENSEN, J.H. & BOERJAN, W., 2001. Biotechnology in trees: Towards improved paper pulping by lignin Engineering. *Euphyt.* 118, 185-195.

CHENG, Z., 2001. Kenaf research products and applications in Japan. *Plant Fibers Prod.* 23, 16-24.

CHIAIESE, P., RUOTOLO, G., DIMATTEO, A., DE SANTO VIRZO, A., DE MARCO, A. & FILIPPONE, E., 2011. Cloning and expression analysis of kenaf (*Hibiscus cannabinus* L.) major lignin and cellulose biosynthesis gene sequences and polymer quantification during plant development. *Ind. Crops and Prod*. 34, 1072-1078.

CHIANG, V. L., PUUMALA, R.J., TAKEUCHI, H. & ECKERT, R.E., 1988. Comparison of softwood and hardwood kraft pulping. *Tappi J.* 71, 173-176.

CLARK, T.F., NELSON, G.H., NIELSHAG, H.J. AND WOLFF, I.A., 1962. A search for new fibre crops. V. Pulping studies on Kenaf. *Tappi J.* 45, 780-786.

COETZEE, R., 2004. Characterization of kenaf (*Hibiscus cannabinus* L.) cultivars in South Africa. Master's thesis submitted at the University of the Free State. South Africa.

COETZEE, R., HERSELMAN, L. & LABUSCHAGNE, M.T., 2008 a. Genetic diversity of kenaf (*Hibiscus cannabinus* L.) using AFLP (Amplified fragment length polymorphism) markers. *Plant Gen Res Characterization and Utilization*. 7, 122-126.

COETZEE, R., LABUSCHAGNE, M.T. & HUGO, A. , 2008 b. Fatty acid and oil variation in seed from kenaf (*Hibiscus cannabinus* L.). *Ind. Crops and Prod*. 27, 104-109.

COOPER, P.J.M., KEATING, J.D.H. & HUGHUES, G., 1983. Crop evapotranspiration a technique for calculation of its components by field measurements. *Field Crops Res.* 7, 299-312.

COSENTINO, S.L., RIGGI, E., & D'AGOSTA, G., 2004. Leaf photosynthesis in kenaf (*Hibiscus cannabinus* L.) in response to water stress. *Proc. of the 2nd World Biomass Conf.*, 10-14 May, Roma, Italy, pp. 374-376.

CRANE, J.C. 1947**.** Kenaf fibre plant rival of jute. *Econ. Bot.* 1, 334-350.

CRANE, J.C. & ACUNA, J.B., 1945. Effect of Plant Spacing and Time of Planting on Seed Yield of Kenaf, *Hibiscus Cannabinus* L., *Agron. J.* 37, 969-977.

CUNNINGHAM, R. L.; CLARK, T. F.; BAGBY, M. O., 1978: fibre. *Tappi* J. 61, 37-39

CUTLER, D.F., BOTHA, T & STEVENSON, D.W., 2008. Plant anatomy: applied approach. *Ann. Bot.* 102, 48-482.

DANALATOS, N. & ARCHONTOULIS, S.V., 2004 a. Potential growth and biomass productivity of kenaf under central Greek conditions: II. The influence of variety, sowing time and plant density. In: Van Swaalj, W.P.M., Fjalistrom, T., Helm, P., Grassi, A. (Ed.), Biomass for Energy, Industry and Climate Protection. *Proc. of the 2nd World Biomass Conf.*, 10-14 May, Roma, Italy, pp 319-322.

DANALATOS, N. & ARCHONTOULIS, S.V., 2004 b. Potential growth and biomass productivity of kenaf under central Greek conditions: I. the influence of fertilization and irrigation. In: Van Swaalj, W.P.M., Fjalistrom, T., Helm, P., Grassi, A. (Ed.), Biomass for Energy, Industry and Climate Protection. *Proc. of the 2nd World Biomass Conf.*, 10-14 May, Roma, Italy, pp 323-326.

DANALATOS, N.G., & ARCHONTOULIS, S.V., 2005. Sowing time and plant density effects on growth and biomass productivity of two kenaf varieties in central Greece. *Proc. of the Int. Conf. on Ind. Crops and Rural Dev.*, 17-21 September 2005, Murcia, Spain, pp. 889-901.

DANALATOS, N. & ARCHONTOULIS, S.V., 2010. Growth and biomass productivity of kenaf (*Hibiscus cannabinus* L.) under different agricultural inputs and management practices in central Greece. *Ind. Crops and Prod.* 32, 231-240.

DE ANDRÉS, E., TENORIO, J. & WALTER, I., 2010. Biomass production and nutrient concentration of kenaf grown on sewage sludge-amended soil. *Span. J. Agric. Res.* 8, 472-480.

DEMPSEY, J.M. 1975. Fiber crops. The Univ. Presses of Florida, Gainesville.

DEOBALD, L. A. & CRAWFORD, D. L., 1997. Lignocellulose biodegradation. In: HURST, C. J., KNUDSEN, G. R. , STETZENBACH, L. D.& Walter, M. V. (Eds) Manual of Environmental Microbiology, pp 730-737. ASM Press, Washington DC, USA.

DODGE, C.R., 1897. A descriptive catalogue of useful fiber plants of the world. U.S. Dept Agr., *Fiber Invest*. Rpt. 9, 358.

EBERBACH, P. & PALA M., 2005. Crop row spacing and its influence on the partitioning of evapotranspiration by winter-grown wheat in Northern Syria. *Plant Soil*. *268*, 195-208.

ECHEKWU, C.A. & SHOWEMIMO, F.A., 2004. Genetic, phenotypic and Environmental variance and character associations in kenaf. *Afr. Crop Sci. J*. 12, 321-326.

EDEEROZEY, A.M. AKIL, H.M., AZAR, A.B. & ARIFFIN, M.I.Z., 2007. Chemical modification of kenaf fibers. *Mater. Lett.* 61, 2023-2025.

El BASSAM, N., 1998. Energy Plant Species. James and James Publishers, London.

ESAU, K., 1965. Plant anatomy. 2nd edn. John Willey & Sons. New York, USA.

ESAU, K., 1977. Anatomy of Seed Plants, (2nd edn.), John Wiley and Sons, New York, USA.

EVANS, L. T., 1980. The natural history of crop yield. *Am. Sci.* 68, 388-397.

FAGERSTROM, T. & LOHM, U., 1977. Growth in scots pine (*Pinus silvestris* L.). Mechanism of response to nitrogen. *Oecologia* 26, 305-315.

FATEMI, S.M., MOHAMED, T.H. & MOHD SOOM, M.A.B., 2011. Proposed model for efficient water management at Razmgan irrigation project, a semi-arid region in Khorasan, Iran. *Aust. J. Agric. Res.* 6, 3203-3216.

FERNANDO, A., DUARTE, P., MORAIS, J., CATROGA, A., SERRAS, G., PIZZA, S., GODOVIKOVA, V. & OLIVEIRA, J.S., 2004. Characterization of kenaf potential in Portugal as an industrial and energy feedstock – Effect of irrigation, nitrogen fertilization and different harvest dates. In: VAN SWAAIJ, W.P.M., FJÄLLSTRÖM, T., HELM, P. & GRASSI, A. (Eds), *2nd World Conference on Biomass for Energy, Industry and Climate Protection*, 10-14 May 2004, Rome, Italy. Vol. I. ETA-Florence and WIP- Munich. Florence, Italy. pp. 169-172.

FIELD, C. & MOONEY, H., 1983. Leaf age and seasonal effects on light, water, and nitrogen use efficiency in a California shrub. *Oecologia* 56, 348-355.

FISHER, G., 1994 a. Kenaf harvesting, processing and products. *IKA Conference Proceedings*. pp 8-12, 1994.

FISHER, G., 1994 b. Manufacturing non-woven kenaf products. *Int. kenaf Assoc. Proc., New Orleans*, LA, 6, 54-56.

FOOD AGRICULTURE ORGANISATION, 1968. Prospects for jute, kenaf and allied fibres in African countries. F.A.O. Working paper1. FAO, Rome.

FOOD AGRICULTURE ORGANISATION, 1998. FAO production year book Vol 3. FAO, Rome.

FOOD AGRICULTURE ORGANISATION, 2002. Fertilizer use by crops. 5th Edition Rome. FAO, Rome.

FOOD AGRICULTURE ORGANISATION, 2003. Consultation on Natural Fibers, The production and consumption of kenaf in China. ESC-Fibers Consultation NO: 03/6. FAO, Rome.

FOOD AGRICULTURE ORGANISATION, 2005. State of the World's Forests. FAO, Rome.

FRANCOIS, L.E., DONOVAN, T.J., & MAAS E.V., 1992. Yield, Vegetative Growth, and Fiber Length of Kenaf Grown on saline soil. *Agron. J.* 84, 592-598.

FREUND, R. J., LITTELL, R. C. & SPECTOR, P. C., 1986. SAS system for linear models. SAS Institute, Can. North Carolina, USA.

FULLER, M.J. & DOLER, J.C., 1994. An economic analysis of kenaf separation. p. 21-22. In: C.E. Goforth, and M.J. Fuller (eds.), A summary of kenaf production and product development research. *Mississippi State Univ. Bul*. 1011.

FULLER, W.H., NORMAN, A.G. & WILSIE, C.P., 1946 a. The Retting of Hemp. I. Field retting of hemp in Iowa. *Iowa Agric. Experiment Station Research Bulletin* 342, 833-891.

FULLER, W.H., NORMAN, A.G. & WILSIE, C.P., 1946 b. The Retting of Hemp. II. Controlled retting of hemp. *Iowa Agric. Experiment Station Research Bulletin* 343, 893-924.

GEUS, J.G., 1967. Fertilizer guide for tropical and subtropical farming, Centre de l'etude de l'azote.

GHADIRI, H. & BAYAT, M. L., 2004. Effect of Row and Plant Spacings on Weed Competition with Pinto Beans (*Phaseolus vulgaris* L.). *J Agric Sci Technol.* 6, 1-9.

GHUMARY, S.R. & BISEN, M.S., 1967. Sunn hemp (*Sunn crotalaria*) has satisfied M.P. farmers. *Indian Fmg*. 161, 17-18.

GOERING, H.K. & VAN SOEST, P.J., 1988. Forage fiber Analyses (Apparatus, reagents, procedures and some applications). Agriculture Handbook No. 379. A.R.S., U.S. Dept. of Agric. ADSRI - JAN 1988.

GOFORTH, C.E. 1994. The evaluation of kenaf as an oil sorbent. p. 25. In: C.E. Goforth, and M.J. Fuller (eds.), A summary of kenaf production and product development research. *Mississippi State Univ Bul*., 1011.

GOLDSMITH, M. H. M. 1967. The polar transport of auxin. *Ann. Rev. Plant Physiol*. 28, 439-478.

GONZALEZ-MORENO, A., DE ANDRES, E.F., WALTER, I. & TENORIO, J.L., 2004. Kenaf responses to irrigation and nitrogen fertilization in central region of Spain. *Proc. of the 2nd World Biomass Conf*., 10-14 May, Roma, Italy, pp 323-326.

GORSHKOVA, T., BRUTCH, N., CHABBERT, B., DEYHOLOS, M., HAYASHI, T., LEV-YADUN, S., MELLEROWICZ, E.J., MORVAN, C., NEUTELINGS, G. & PILATE, G., 2012. Plant fiber formation: state of the art, recent and expected progress, and open questions. *Crit. Rev. Plant Sci.* 31, 201-228.

GROSBACH, J., 2008. The Effect of Row Spacing on the Yield and Plant Growth of Popcorn (*Zea mays*). *Cantaurus* 16, 9-12.

GROWER'S HANDBOOK FOR KENAF PRODUCTION IN THE LOWER RIO GRANDE VALLEY OF TEXAS, USA. 1989. Kenaf International with Rio Farms, Inc., McAllen, TX, 21 pgs.

GULMON, S.L. & CHU, C.C., 1981. The effects of light and nitrogen on photosynthesis, leaf characteristics, and dry matter allocation in the chaparral shrub, *Diplacus aurantiacus. Oecologia* 49, 207-212.

GUTERMA, A. L., 1952. Kenaf in U.S. - an industry's view. *Chem Digest*., 11, 12-13.

GUTTERIDGE, *R.* C., 1988. Alley cropping kenaf *(Hibiscus cannabinus)* with leucaena *(Leucaena leucocephala)* in south-eastern Queensland. *Aust. J. of Exp. Agric.* 28, 481-484.

HALLIDAY, K.J., MARTINEZ-GRACIA, J.F. & JOSSE, E.M., 2009. Integration of light and auxin signaling. Cold Spring Harb Perspect Biol 1:a001586. doi: 10.1101/cshperspect.a001586.

HENDERSON, D.W., HILLS, F.G., LOOMIS, R.S. & NOURSE, E.F., 1968. Soil moisture conditions, nutrient uptake and growth of sugarbeets as related to method of irrigation of an organic soil. *J. of the A.S.S.B.T*. 5, 35-48.

HESSLER, L.E. 1945. Chemical composition and strength differences in dew-retted hemp fiber. *Jour Amer Soc Agron*. 37, 146-155.

HILL, J., NELSON, E., TILMAN, D., POLASKY, S. & TIFFANY, D., 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proc. Natl. Acad. Sci. U.S.A.* 103, 11206-11210.

HOSSAIN, Md. D., MUSA, M.F., TALIB, J. & JOL, H. 2010. Effects of nitrogen, phosphorus and potassium levels on kenaf (*Hibiscus cannabinus* L.) growth and photosynthesis under nutrient solution. *J.of Agric. Sci*. 2, 49-57.

HOSSAIN, M., HANAFI, M., JOL, H. & HAZANDY, A., 2011 a. Growth, yield and fiber morphology of kenaf (*Hibiscus cannabinus* L.) grown on sandy bris soil as influenced by different levels of carbon. *Afr. J. of Biotechnol*. 10, 10087-10094.

HOSSAIN, M., HANAFI, M., JOL, H. & JAMAL, T., 2011 b. Dry Matter and Nutrient Partitioning of Kenaf (*Hibiscus cannabinus* L.) Varieties Grown on Sandy Bris Soil. *Aust. J. crop sci.* 5, 654-659.

HOSSOMI, K., 2000. Utilization dried kenaf leaves to the meal. Proceeding of the 2000. *Int Kenaf Symposium*. Hiroshima, Japan, Oct. 13-14, 171-176.

HOVERMAL, C.H., 1993. Effect of row width and nitrogen rate on biomass yield of kenaf. P. 35-40. *Proc. Fourth Int. Kenaf Conf*., Int. Kenaf Assoc. Ladonia, TX.

HURTER, R.W. & RICCIO, F.A., 1998. Why CEOS don't want to hear about nonwoods-or should they? In: *TAPPI Proceedings*, NA Nonwood Fiber Symposium, Atlanta, GA, USA, pp. 1-11.

HWANG,S.-J., MUHAMMAD H., HO-YOUN K., CHAE-IN N., KIL-UNG K., DONG-HYUN S., SANG-YEOL K. & IN-JUNG L., 2010. Effect of Nitrogen and Silicon Nutrition on Bioactive Gibberellin and Growth of Rice under Field Conditions. *J. Crop Sci. Biotech*. 10, 281-286.

ISTANBULLUOGLU, A., 2009. Effects of irrigation regimes on yield and water productivity of safflower (*Carthamus tinctonius* L.) under Mediterranean climatic conditions. *Agric. Water manage*. 96, 1792-1798.

JEFFRIES, T.W., 1994. Biodegradation of lignin and hemicelluloses, In: Ratledge C (ed.) Biochemistry of microbial degradation. Kluwer, Dordrecht, pp 233-277.

JESSUP, W. & FOWLER, M. W. 1976 a. II. The effect of N source and concentration on nutrient uptake and respiratory activity in cultural sycamore cells. *Planta* 132, 125-129.

JESSUP, W. & FOWLER, M. W. 1976 b. Interrelationships between carbohydrate metabolism and nitrogen assimilation in cultured plant cells. I. Effects of glutamate and nitrate as alternative nitrogen sources on cell growth. *Planta* 132, 119-123.

JONES, M.D, PUENTES, C. & SUAREZ, R., 1955. Isolation of kenaf for seed increase. *Agron. J*. 47, 256-257.

JONOOBI, M., HARUN, J., SHAKERI, A., MISRA, M. & OKSMAN, K., 2009. Chemical composition, crystallinity, and thermal degradation of bleached and unbleached kenaf bast (*Hibiscus cannabinus*) pulp and nanofibers. *BioRessour*. 4, 626-639.

JONOOBI, M., HARUN, J., TAHIR, P.M., SHAKERI, A., SAIFULAZRY, S. & MAKINEJAD, M.D., 2011. Physicochemical characterization of pulp and nanofibers from kenaf stem. *Mater. Lett.* 65, 1098-1100.

JOORDAN, D. L., BARNES, J. S., BOGLE, C. R., MARSHALL, T. M., CORBETT, T., CROZIER, C. R., MCLAWHORN, B. & FISHER, L. 2005. Influence of cultural practices and crop rotation on kenaf yield in North Carolina. Online. Crop Management doi: 10. 1094/CM-2005-0913-01-RS.

JOYNER, J. & WILSON, F., 1967. Effects of row and plant spacing and time of planting on seed yield of kenaf. *Econ. Bot.* 21, 99-102.

KARNANI, R., KRISHNAN, M. & NARAYAN, R., 1997. Biofiber reinforced polypropylene composites. *Polym. Eng. Sci*. 37, 476-83.

KHRISTOVA, P., KORDSACHIA, O., PATT, R., KHIDER, T. & KARRAR, I., 2002. Alkaline pulping with additives of kenaf from Sudan," *Ind. crops and prod.* 15, 229-235.

KILLINGER, G.B., 1967. Potential uses of kenaf (*Hibiscus cannabinus* L.). *Proc. Soil Crop Sci. Soc*. Fl 27, 4-11.

KILLINGER, G.B., 1969. Kenaf (Hibiscus *cannabinus* L), A Multi-use Crop, *Agron. J*. 61, 734-736.

KOBAISY, M., TELLEZ, M.R, WEBBER, C.L, DAYAN, F.E, SHRADER, K.K & WEDGE, D.E., 2001. Phytotonic and fungitoxic activities of the essential oil of

kenaf (*Hibiscus cannabinus* L) leaves and its composition *J. Agric. Food Chem.* 49, 3768-3771.

KOSTER, H. H., COCHRAN, R. C., TITGEMEYER, E. C., VANZANT, E. S., ABDELGADIR, I. & ST JEAN, G. 1996. Effect of increasing degradable intake protein on intake and digestion of low-quality, tall grass- prairie forage by beef cows. *J. Animal. Sci*. 74, 2473-2481.

KUCHINDA, N. C., NDAHI, W. B., LAGOKE, S.T.O. & AHMED, M. K., 2001. The effects of nitrogen and period of weed interference on the fibre yield of kenaf (*Hisbiscus cannabinus* L.) in the northern Guinea Savanna of Nigeria. *Crop Prot*. 20, 229-235.

KUGLER, D.E., 1988. Kenaf Newsprint: A Report on the Kenaf Demonstration Project. Cooperative State Research Service, USDA.

KULKARNI, A. G., MATHUR, R. M., NAITHANI, S., AGARWALL, G. C. & PANT, R. 1985. Newsprint grade pulps from whole mesta plant of *Sabdariffa hibiscus* variety, part II, pilot plant studies on high yield pulp production. *IPPTA*. 22, 45.

KUO, Y-L., LEE, Y-P. & YANG, Y-Z., 2011. Wind effects on stomatal conductance and leaf temperature of three seedlings distributed in various habitats of the Nanzeshan forest, *Southern Taiwan* 26, 1-16.

KURODA, KI, NAKAZAGWA-IZUMI, A., MAZUMDER, B.B., OHTANI, Y., SAMESHIMA, K., 2005. Evaluation of chemical composition of the core and bastlignins of variety Chinpi-3 kenaf (*Hibiscus cannabinus* L.) by pyrolysis-gas chromatography/mass spectrometry and cupric oxide oxidation. *Ind. Crops and Prod.* 22, 223-232.

LAICHE, A. J. & NEWMAN, S. E., 1994. Kenaf core as a container media component for woody landscape plants and greenhouse bedding plants.p30. In: GOFPRTH, C. E., FULLER, M. J., and REMY, H (eds). 1994. Asummary of kenaf production and product development research. Miss. State Univ. Bul. 1011.

LAM, TBT., 2000. Structured details of kenaf cell walls and fixation of carbon dioxide. *Proc. of the 2000 Int. Kenaf Symposium*, Hiroshima, Japan, Oct. 13-14, 81-90.

LEMALIEU, P.J., OPLINGER, E.S. & PUTMAN, D.H., 1991. Kenaf. Alternative Field Crops Manual. St. Paul. University of Minesota.

LEMALIEU, P. J., OPLINGER, E. S. & PUTNAM, D. H., 2003. Kenaf. In: Alternative Field crops Manual. http://www.corn.agronomy.wisc.edu/FISC/Alter natives /Kenaf.htm.

LIN, P., LIN, L., WU, J. & LIN, N., 2004. Breeding of FuHong 4, a kenaf variety with high yielding and resistance. *Plant Fiber Prod*. 26, 1-4.

LIU, Y., 2003. Diallel and stability analysis of kenaf (*Hibiscus cannabinus* L.) in South Africa. Master's Thesis at the University of Free State. South Africa.

LIU, Y. & LABUSCHANE, M.T., 2009. The influence of environment and season on stalk yield in kenaf. *Ind. Crops and Prod.* 29, 377-380.

LIU, J., AN, X., CHENG, L., CHEN, F., BAO, J., YUAN, L., ZHANG, F. & MI, G., 2010. Auxin transport in maize roots in response to localized nitrate supply. *Ann. Bot.* 106, 1019-1026.

LÓPEZ-BELIDO, L., LÓPEZ-BELIDO, R.J. & LÓPEZ-BELIDO, F.J., 2006. Fertilizer nitrogen efficiency in durum wheat under rainfed Mediterranean conditions: Effect of split application. *Agron. J.* 98, 55-62.

MAcADAM, J.R., VOLENEC, J.J. & NELSON, C.J., 1989. Effects of Nitrogen on Mesophyll Cell Division and Epidermal Cell Elongation in Tall Fescue Leaf Blades. Plant Physiol. 89, 549-556

MAITI, R.K., 1973. Comparative study of morphological characters of fibers from various pulps and plants. *Jute Bull*. 36, 1-8. New York.

MALAN, A.S., 2011. Herbicide evaluation for weed control in kenaf (*Hibiscus cannabinus* L.). Master's Thesis at University of Pretoria. South Africa.

MALHERBE, S. & CLOETE, T. E., 2002. Lignocellulose biodegradation: fundamentals and Applications, View in *Env.* Sci. *Bio/Technol.* 1, 105-114.

MAMBELLI, S. & GRANDI, S., 1995. Yield and quality of kenaf (*Hibiscus cannabinus* L.) stem as affected by harvest date and irrigation. *Ind. Crops and Prod*. 4, 97-104.

MANZANARES, M., TENORIO, J. & AYERBE, L., 1997. Sowing time, cultivar, plant population and application of N fertilizer on kenaf in Spain's central plateau. *Biomass Bioenerg.* 12, 263-271.

MASSEY, J.H., 1974. Effects of nitrogen levels and row widths on kenaf. *Agron. J*. 66, 822-823.

MAYBERRY, D. H., 1988. A new source of paper fiber. Washington times Crop, Washington, *DC. The World and July*, pp158-163.

McMILLIN, J.D., WAGNER, M.R., WEBBER, C.L., MANN, S.S., NICHOLS, J.D. & JECH, L., 1998. Potential for kenaf cultivation in south-central Arizona. *Ind. Crops and Prod*. 9, 73-77.

MEINTS, P.D. & SMITH, C.A., 2003. Kenaf seed storage duration on germination. Emergence and yield. *Ind. Crops and Prod.* 17, 9-14.

METWALLY, S.Y. & POLLARD, A. G., 1959. Effects of soil moisture conditions on the uptake of plant nutrients by barley and on the nutrient content of the soil solution. *J. Sci. Food. Agr*. 10, 632-636.

MILFORD, G.F.J., TRAVIS, K.Z., POCOCK, T.O., JAGGARD, K.W. & DAY, W., 1985. Fate of nitrogen from sugar-beet tops. In 57th Winter Congress of IIRB.

MILFORD, G.F.J., TRAVIS, K.Z., POCOCK, T.O., JAGGARD, K.W. & DAY, W., 1988. Growth and Dry Matter Partitioning in Sugar Beet. *J. of Agric. Sci. Camb*. 110, 301-308.

MILFORD, G.F.J. & WATSON, D.J., 1971. The effect of nitrogen on the growth and sugar content of sugarbeet. *Ann. Bot.* 35, 287-300.

MILLER, D.L., 1965. Kenaf: - A potential papermaking raw material. *Tappi* J. 48, 455-459.

MILTHROPE, F. L. & MOORBY, J., 1974. An Introduction to Crop Physiology. Cambridge University Press, Cambridge, U. K. 202 p.

MISHRA, R.K., CHAUDHARY, S., KUMAR, A. & KUMAR, S., 2009. Effects of Multifoliate-pinna, Affila, Tendril-Less and Unifoliata genes on leaf blade architecture in *Pissum sativum*. *Planta* 230, 177-190.

MISRA, A. & TYLER, G., 1999. Infuence of Soil Moisture on Soil Solution Chemistry and Concentrations of Minerals in the Calcicoles *Phleumphleoides* and *Veronica spicata* Grown on a Limestone Soil *Ann. of Bot .* 84, 401-410.

MIYAKE, B. & SUZUTA, I., 1937. *Hibiscus cannabinus* L. *Formosn Agr. Rev*. 368, 591-597.

MOHAMED, A., BHARDWAJ, H., HAMAMA, A. & WEBBER C. III. 1995. Chemical composition of kenaf (*Hibiscus cannabinus* L.) seed oil. *Ind. Crops and Prod. J*. 4, 157-165.

MORRISON, M.J., MCVETTY, P. B. E. & SCARTH, R., 1990. Effect of altering plant density on growth characteristics of summer rape. *Can. J. Plant Sci*. 70, 139-149.

MORRISON, T.A., JUNG, H.G., BUXTON, D.R. & HATFIELD, R.D., 1998. Cellwall composition of maize internodes of varying maturity. *Crop Sci.* 38, 455-460.

MUCHOW, R., 1979 a. Effects of plant population and season on kenaf (*Hibiscus cannabinus* L.) grown under irrigation in tropical Australia I. Influence on the components of yield. *Field Crops Res.* 2, 55-66.

MUCHOW, R., 1979 b. Effects of plant population and season on kenaf (*Hibiscus cannabinus* L.) grown under irrigation in tropical Australia II. Influence on growth parameters and yield prediction. *Field Crops Res.* 2, 67-76.

MUCHOW, R., 1990. Effect of leaf nitrogen and water regime on the photosynthetic capacity of kenaf (*Hibiscus cannabinus* L.) under field conditions. *Aust. J. of Agric. Sci.* 41, 845-852.

MUCHOW, R.C., 1992. Effect of water and nitrogen supply on radiation interception and biomass accumulation of kenaf (*Hibiscus canabinus*) in a semi-arid tropical environment. *Field Crop Res*. 28, 281-293.

MUCHOW, R. & WOOD, I., 1980. Yield and growth responses of Kenaf (*Hibiscus cannabinus* L.) in a semi-arid tropical environment to irrigation regimes based on leaf water potential. *Irrig. Sci.* 1, 209-222.

MURPHY, P.T., MOORE, K.J., RICHARD, T.L. & BERN, C.J., 2007. Enzyme enhanced solid-state fermentation of kenaf core fiber for storage and pretreatment. *Bioresour. Technol.* 98, 3106-3111.

NEILL, S.W. & KURTZ, M.E., 1994. The effect of plant population on kenaf yield. In: GOFORTH, C.E., FULLER, M.J. (Eds), A Summary of kenaf Production and Product Development 1989-1993. *Mississippi Agric. Forestry Exp., Miss. State Bull.* 1011, 535.

NELSON, G. H.; CLARK, T. F.; WOLFF, I. A.; JONES, Q. 1966: A search for new fibre crops: Analytical evaluations. *Tappi J.* 49, 40.

NETO, C.P., SECA, A., FRADINHO, D., COIMBRA, M.A., DOMINGUES, F., EVTUGUIN, D., SILVESTRE, A. & CAVALEIRO, J.A.S., 1996. Chemical composition and structural features of the macromolecular components of *Hibiscus cannabinus* grown in Portugal. *Ind. Crops and Prod.* 5, 189-196.

NIESCHLAG, H.J., NELSON, G.H., WOLFF, I.A., PERDUE, R.E. & JR., 1960. A search for new fiber crops. *Tappi J*. 43, 193-2000.

NISHIMURA, N., IZUMI, A. & KURODA, K., 2002. Structural characterization of kenaf lignin: differences among kenaf varieties. *Ind. Crops and Prod.* 15, 115-122.

OHTANI, Y., MAZUMDER, B.B. & SAMESHIMA, K., 2001. Influence of the chemical composition of kenaf bast and core on the alkaline pulping response. *J. Wood Sci*. 47, 30-35.

ORSENIGO, J.R., 1964. Weed control in kenaf. *Proc. Int. Kenaf Conf*. 2, 177-187.

PAPPAS, C., TARANTILIS, P.A. & POLISSOU, M., 1998. Determination of kenaf (*Hibiscus cannabinus* L.) lignin in crude plant material using diffuse reflectance infrared Fourier transform spectrose. *Appl. Spectrose* 52, 1399-1402.

PARDALES, J.R. & BELMONTE, D.V., 1984. Cultural management studied on upland taro: Effects of population density and planting method on growth and yield. *Philippines J. Crop Sci*. 9, 29-32.

PATE, J.S. 1973. Uptake, assimilation and transport of nitrogen compounds by plants. *Soil Biol. Biochem*. 5, 109-119.

PÉREZ, J., MUЙOZ-DORADO, DE LA RUBIA, T & MARTÍNEZ, J., 2002. Biodegradation and biological treatments of cellulose, hemicellulose and lignin: an overview. *Int. Microbiol*. 5, 53-63.

PETRINI, C., BAZZOCHI, R. & MONTALTI, P., 1994. Yield potential and adaptation of kenaf (*Hibiscus cannabinus*) in north-central Italy. *Ind. Crops and Prod*. 3, 11-15.

PHILLIPS, W., MCCOLLUM, F. & FITCH, G., 1999. Kenaf dry matter production, chemical composition, and in situ disappearance when harvested at different intervals. *Prof. Anim. Sci*. 15, 34-39.

PHILLIPS, W.A., RAO, S.C., FITCH, J.Q. & MAYEUX, D H. S., 2002. Digestibility and dry matter intake of diets containing alfalfa and kenaf. *J. Animal Sci.* 80, 2989-2995.

PHILLIPS, W.A., RAO, S., VON TUNGELN, D.L. & FITCH, G.Q., 1996. Digestibility of freshly harvested, ensiled, and mature kenaf by sheep. *Prof. Anim. Sci*., 12, 99-104.

PRETORIUS, M.M., BOTHA, M.S., LEOKANE, D., RAMUKHESA, R., MTSWENI, P. & SEABELO, W., 2002 (a). Spacing and density of irrigated kenaf. Project

number 508/02. In Kenaf Research - Phase II 2001/2001 season of the Agricultural Research Council- *Inst. for Ind. Crops,* 101-105.

PRETORIUS, M.M., BOTHA, M.S., LEOKANE, D., RAMUKHESA, R., MTSWENI,P. & SEABELO,W., 2002 (b). Spacing and density of irrigated kenaf. Project number 508/02. In Kenaf Research - Phase II 2001/2002 season of the Agricultural Research Council- *Inst. for Ind. Crops,* 116-130.

QUARANTA, E., BELOCCHI, A., BOTTAZZI, P., MONOTTI, M., DEL PINO, A.M. & DESIDERIO, E., 2000. Limited water supply on kenaf (*Hibiscus cannabinus* L.) in central Italy. *Ital. J. Agron*. 4, 1-9.

RADOSEVICH, S.R., 1988. Methods to study crop and weed interactions. (pp. 121-144. In: ALTIERI, M.A., & LIEBMAN, M.L.) Weed management in Agroecosystems: Ecological approaches. CRC Press.

RAJI, J.A., 2007. Intercopping kenaf with cowpea. *Afr. J. Biotechnol.* 6, 2807-2809.

RAMASWAMY, G. N. & BOYD, C.R., 1994. Kenaf as a textile fiber: processing, fiber quality, and product development. In: GOFPRTH, C. E., FULLER, M. J., and REMY, H (eds). 1994. A summary of kenaf production and product development research. *Miss. State Univ. Bul*. 1011, 31-33.

RAMASWAMY, G.N., SOEHARTO, B., BOYD, C.R. & BALDWIN, B.S., 1999. Frost kill and kenaf fiber quality. *Ind. Crops and Prod.* 9, 189-195.

RAUZI, F., 1978. High rates of nitrogen change composition of short grass rangelands in south eastern Wyoming. *J. Range Manage*. 31, 366-370.

REHM, S. & ESPIG, G., 1991. The Cultivated Plants of Tropics and Subtropics. Verlag Joseph Margraf, Priese GmbH, Berlin.

ROBERTSON, J.B. & VAN SOEST, P.J., 1981. The Analysis of Dietary Fibre in Food. Eds James, W.P.T. & Theander, O., Dekker, New York. ADSRI-JAN 1988.

ROCHESTER, T; GENEY, S., MAAS, S., GORDON, R., HANNA, L. & HILL, J. 2009. Monitoring nitrogen use efficiency in cotton crops. *The Australian cotton growers* April-May 2009.

ROSOLEM, C.A. & MIKHELSEN, D.S., 1989. Nitrogen source-sink relationship in cotton. *J. Plant nutr*. 12, 1417-1433.

RYMSZA, A.T., 2004. Vision Paper. The Massachusetts Institute of Technology and Yale University. *J. of Ind. ecology*. 7, 3-4.

SABHARUAL, H.S., AKHTAR, M., BLANCHETTE, R.A. & YOUNG, R.A., 1994. Biochemical pulping of kenaf. *Tappi J.* 77, 105-118.

SADRAS, V.O. & HALL, A.J. 1988. Quantification of temperature, photoperiod and population effects on plant leaf area in sunflower crops. *Field Crops Res.* 18, 185-196.

SAIKIA, C. N.; ALI, F.; DASS, N. N. & BARNAH, J. N. 1991. High alpha-cellulose pulp from fast growing plant materials. IE (I) *J. Chem*. 71, 72-76.

SAIKIA, C.N., GOSWAMI, T. & ALI, F., 1997. Evaluation of pulp and paper making characteristics of certain fast growing plants. *Wood Sci. Technol.* 31, 467-475.

SAKS, Y., FEIGENBAUM, P. & ALONI, R., 1984. Regulatory effect of cytokinin on secondary xylem fiber formation in an in vivo system. *Plant Physiol.* 76, 638-642.

SAMESHIMA, K., 2000. Improvement of kenaf core oil absorption property by heat treatment at 200-500°C. Proceedings of 3rd annual America kenaf society conference, Corpus Christi, TX, February, pp. 64-72.

SAS: Statistical Analysis Software, 2010. Version 9.3. SAS Institute Inc, Cary, NC, USA.

SCOTT, A. 1982. Kenaf seed production: Rio Farms, Inc. Biennial Report for 1980-1981. Monte Alto, TX. 60-63.

SCOTT, A.W. Jr & COOK, C.G., 1995. Growing kenaf for seed in south Texas. Proc. Int. Kenaf Assn. Conf. Irving, TX. 7,133-135.

SCOTT, A.W., Jr & TAYLOR, C.S., 1988. Economics of kenaf production in the lower Rio Valley of Texas. Paper presented at National Symposium on New crops, Indianapolis, IN, Oct. 23-26, 1988, pp 292-297.

SCOTT R.K., JAGGARD KW & SYLVESTER-BRADLEY, R. 1994. Resource capture by arable crops. In: Monteith JL, Scott RK, Unsworth MH, eds. Resource capture by crops. Nottingham, UK: Nottingham University Press, 279-302.

SELLERS, T., MILLER, G.D. & FULLE, M.J., 1993. Kenaf core as a board raw material. *For. Prod. J*. 43, 69-71.

SHARRATT, B.S. & McWILLIAMS, D.A., 2005. Microclimatic and rooting characteristics of narrow-row versus conventional-row corn. *Agron. J.* 97, 1129-1135.

SHI, B. & PILL, W. 1993. Kenaf as a component of soilless growth media. *Hort. Science* 28, 256. (Abstr.)

SHAW, R.G. & OLDS, T.M., 1993. Anova for unbalanced data: An overview. *Ecology*, 74, 1638-1645.

SOSULSKI, F. W., PAUL, E. A. & HUTHCEON, W. L., 1963. The influence of soil moisture, nitrogen fertilization, and temperature on quality and amino acid composition of thatcher wheat. *Can. J. Soil Sci*. 43, 219-28.

SPARKES, D., 2005. A guide to kenaf production in north Queensland

STRICKER, J.A., PRINE, G.M., & RIDDLE, T.C., 2006. Kenaf – A Possible New Crop for Central Florida. Agronomy Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, No. SS-AGE-68, February 1998 (Reviewed, 2001).

SULLIVAN, P., 2003 a. Intercropping principles and production practices. Agricultural Guide. Appropriate Technology Transfer for rural Areas (ATTRA), http.//attar.ncat.org/attar-pub/pdf/Intercrop.pdf

SULLIVAN, P., 2003 b. Kenaf production. Appropriate Technology Transfer for Rural Areas (ATTRA). National Center for Appropriate Technology, Fayetteville, AR.

SURIYAJANTRATONG, W., TUCKER, R., SIGAFUS, R. & MITCHELL JR, G., 1973. Kenaf and rice straw for sheep. *J. Animal Sci.* 37, 1251-1254.

TAHERI-AGRAMI, M., DANESHIAN, J. & ALIABADI F.H., 2009. Effects of Drought Stress and Planting Density on Quantity and MorphologicalCharacteristics of Chicory (*Cichorium intybus* L.). *Asian J. Agric. Sci.* 1, 12-14.

TAYLOR, C.S., 1984. A systems approach to the commercialization of kenaf. Ph. D. Thesis, University of Missouri-Columbia, Columbia, MO, 111 pgs.

TEULAT, B., MONNEVEUX, P., BORRIES, C., SOUYRIS, I., CHARRIER, A. & THIS, D., 1997. Relationships between relative water content and growth parameters under water stress in barley: a QTL study. *New Phytol.* 137, 99-107.

THEISEN, A.A., KNOX, E.G. & MANN, F.L., 1978. Feasibility of introducing food crops better adapted to environmental stress National Sci. Foundation. Div. Applied Res. NSF/RA., 780289. US Govt. Print Office, Washington, D.C.

THI BATCH, L., T.B.Y., HORI, K. & LIYAMA, K., 2003. Structural characteristics of cell walls of kenaf (*Hibiscus cannabinus* L.) and fixation of carbon dioxide. *J. Wood Sci.* 49, 255-261.

TOBLER, F., 1922. Bimli- Jute. *Faserforschung* 2, 225-232.

TOLIBAEV, K.H., MUKHAMEDOVA, S. & GLUSHENKOVA, A.T., 1986. Phospholipids of the seeds of experimental varieties of kenaf. *Chem of natural compounds.* 22,146-149. http:// www.visionfiber.com

UNITED STATES DEPARTMENT OF AGRICULTURE, 1986. Kenaf -A Promising Crop For Agriculture. Office of critical materials. Washington, D. C.

VAN DER WERF, H.M.G., HARSVELD, J.E., BOUGMA, A.T.M. & TEN CATE, M., 1994. Quality of hemp (*Cannabis sativa* L.) stems as a raw material for paper. *Ind. Crops and Prod.* 2, 219-227.

VERVERIES, C., GEORGHIOU, K., CHRISTODOULAKIS, N., SANTAS, P., SANTAS, R., 2004. Fiber dimensions, lignin and cellulose content of various plant materials and their suitability for paper production. *Ind. Crops and Prod.* 19, 245-254.

VILLAR, J.C., POVEDA, P. & TAGLE, J.L., 2001. Comparative study of kenaf varieties and growing conditions and their effect on kraft pulp quality. *Wood Sci. Technol*. 34, 543-552.

VILLAR, J.C., REVILLA, E., GOMEZ, N., CARBAJO, J.M. & SIMÓN, J.L., 2009., Improving the use of kenaf for kraft pulping by using mixtures of bast and core fibers.: *Ind Crops and prod.* 29, 301-307

VOLENEC, J.J. & NELSON, C.J. 1981. Responses of tall fescue leaf meristems to N fertilization and harvest frequency. Crop Sci 23, 720-724.

WARDER, F.G., LEHANE, J.J., HINMAN, W.C. & STAPLE, W.J., 1963. The effect of fertilizer on growth, nutrient uptake and moisture use of wheat on two soils southwestern Saskatchewan. *Can. J. Soil sci.* 43, 107-116.

WATSON, A.J. & GARTSIDE, B.G., 1976. Using woody fibre from agricultural crops. *Aus. For*. 39, 16-22.

WATSON, A.J., DAVIES, G.W. & GARTSIDE, G. 1976. Pulping and papermaking properties of kenaf. *Appita* 30, 129-134.

WEBBER, C.L. III. 1994. Kenaf (Hibiscus cannabinus L.) response to four grass control herbicides broadcast postemergence. *Weed Technol.* 457-460.

WEBBER C.L. III. 1996. Response of kenaf to nitrogen fertilization. p. 404-408. In: J. Janick and J.E. Simon (eds.), Progress in new crops. Wiley, New York.

WEBBER C.L. III. 1999. Effect of kenaf and soybean rotations on yield components. 316-322. In Janick (ed), Prospectives on new crops and new uses. ASHS Press, Alexandria. VA.

WEBBER, C.L. III & BLEDSOE, R.E., 1993. Production, harvesting, products.416-42. In: J. Janick and J.E. Simon (eds), New crops. Wiley, New York. 416-421.

WEBBER C.L. III & BLEDSOE, V.K., 2002 a. Plant maturity and kenaf yield components. *Ind. Crops and Prod*. 16, 81-88.

WEBBER C.L. III & BLEDSOE, V.K., 2002 b. Kenaf yield components and plant composition. Reprinted from: *Trends in new crops and new uses*. 2002. J. JANICK and A. WHIPKEY (eds.). ASHS Press, Alexandria, VA. 348-357.

WEBBER, C.L. III, BLEDSOE, V.K. & BLEDSOE, R.E., 2002. Kenaf harvesting and processing. 9. 340-347. In: J. Janick and A. Whipkey (eds.), Trends in new crops and new uses. ASHS Press, Alexandria, VA

WEBBER, C.L. III, WHITWORTH, J. & DOLE, J., 1999. Kenaf (*Hibiscus cannabinus* L.) core as a containerized growth medium component. *Ind. Crops and Prod*. 10, 97-105.

WERKER, A.R. & JAGGARD, K.W., 1998. Dependence of sugar beet yield on light interception and evaporation. *Agric.and For. Meteorol.* 89, 229-240.

WHITE, G.A., CUMMINS, D.G., WHITELY, E.L., FIKE, W.T., GRIEG, J.K., MARTIN, J.A., KILLINGER, G.B., HIGGINS, J.J. & CLARK, F.T., 1970. Cultural and Harvesting Methods for Kenaf - An Annual Crop Source of Pulp in the Southeast. *ARS, U.S. Depart. of Agric. Prod. Res. Report*, 113.

WILLIAMS, J., 1966. Influence of row spacing and nitrogen levels on dry matter yields of kenaf (*Hibiscus cannabinus* L.). *Agron. J.* 58, 166-168.

WILSON, F.D., SUMMERS, T.E. JOYNER, J.F., FICHLER, D.W. & SEALE, C.C., 1965 'Everglades 41' and 'Everglades 71', two new varieties of kenaf (*Hibiscus cannabinus* L) for the fiber and seed. *Florida Agri. Exp. Stat*. CIV. S-162, 12. Florida.

WOOD, I.M., 1978. Preliminary experiments on the growth of kenaf (Hibiscus cannabinus) for paper pulp production in the Ord Irrigation Area, Western Australia. *Aust. J. Exp. Agr. Anim Husb.* 18, 97-106.

WOOD, I.M., 2003. Kenaf: the forgotten fiber crop. The Australian New Crops Newsletter 10. http://www.newcrops.uq.edu.au/newslett/ncn10212. htm.

WOOD, I. M. & STERWART, G.A. (Eds), 1981. 'Kenaf as a Potential Source of Pulp in Australia.' (CSIRO: Brisbane.)

WOOLF, L.M., 1993. Alternative crops: Kenaf. Farm Futures. Mid-March, p. 24.

YEUNG, E.C., 1998. A Beginner's Guide to the Study of Plant Structure Department of Biological Sciences, University of Calgary, Calgary, Alberta, Canada.

YOUNG, J., 1992. Kenaf renews drive to become a North American papermaking fiber. *Pulp and Paper* 66, 57-60.

ZHOU, X.B., CHEN, Y.H. & OUYANG, Z., 2011. Effects of row spacing on soil water and water consumption of winter wheat under irrigated and rainfed conditions. *Plant soil environ*. *57*, 115-121.

ZHOU, C., OHTANI, K., SAMESHIMA, M. & ZHENG, M., 1998. Selection of plant population of kenaf (*Hibiscus cannabinus* L.) as a papermaking raw material on arid hillside land in China. *J Wood Sci.* 44, 296-302.

ZHOU, X.B., YANG, M., SUN, S.J. & CHEN, Y.H., 2010. Plant and row spacing effects on soil water and yield of rainfed summer soybean in the northern China. *Plant Soil Environ*. 56, 1-7.

APPENDICES

Appendix A. Table 3.1. ANOVA data of the effect of plant population (Plant P), nitrogen level (N) and row spacing (RS) and their interaction effects on plant height at 85, 113 and 126 days after planting (DAP)

Sampling date	Source	R-square	CV	R-MSE	Mean	HSD	Pr> F
	Plant P	0.510521	12.48866	24.09475	192.9	-	0.0631
	N	0.510521	12.48866	24.09475	192.9	-	0.3920
	RS	0.510521	12.48866	24.09475	192.9	-	0.4138
85 DAP	Plant P x N	0.510521	12.48866	24.09475	192.9	-	0.1555
	Plant P x RS	0.510521	12.48866	24.09475	192.9	-	0.1330
	N x RS	0.510521	12.48866	24.09475	192.9	-	0.8640
	Plant P x N x RS	0.510521	12.48866	24.09475	192.9	-	0.7709
	Plant P	0.701387	9.160305	23.56557	257.3	14.993	0.0115
	N	0.701387	9.160305	23.56557	257.3	-	0.0961
	RS	0.701387	9.160305	23.56557	257.3	-	0.4998
113 DAP	Plant P x N	0.701387	9.160305	23.56557	257.3	52.762	0.0231
	Plant P x RS	0.701387	9.160305	23.56557	257.3	-	0.8632
	N x RS	0.701387	9.160305	23.56557	257.3	-	0.3452
	Plant p x N x RS	0.701387	9.160305	23.56557	257.3	-	0.7601
	Plant P	0.706402	9.268111	25.65711	276.8	16.323	0.0332
	N	0.706402	9.268111	25.65711	276.8	-	0.2887
	RS	0.706402	9.268111	25.65711	276.8	-	0.8306
126 DAP	Plant P x N	0.706402	9.268111	25.65711	276.8	56.957	0.0373
	Plant P x RS	0.706402	9.268111	25.65711	276.8	-	0.5990
	N x RS	0.706402	9.268111	25.65711	276.8	-	0.2564
	Plant p x N x RS	0.706402	9.268111	25.65711	276.8	-	0.3047

Appendix A. Table 3.2. ANOVA data of the effect of plant population (Plant P), nitrogen level (N) and row spacing (RS) and their interaction effects on stem diameter at 10 cm soil level at 85, 113 and 126 DAP

Sampling date	Source	R-square	CV	R-MSE	Mean	HSD	Pr> F
	Plant P	0.689813	14.73038	1.880324	12.76494	-	0.3767
	N	0.689813	14.73038	1.880324	12.76494	-	0.3584
	RS	0.689813	14.73038	1.880324	12.76494	-	0.9412
85 DAP	Plant P x N	0.689813	14.73038	1.880324	12.76494	-	0.2072
	Plant P x RS	0.689813	14.73038	1.880324	12.76494	-	0.4695
	N x RS	0.689813	14.73038	1.880324	12.76494	-	0.7464
	Plant P x N x RS	0.689813	14.73038	1.880324	12.76494	-	0.5003
	Plant P	0.699687	12.78368	2.108851	16.49644	-	0.4008
	N	0.699687	12.78368	2.108851	16.49644	-	0.2438
	RS	0.699687	12.78368	2.108851	16.49644	-	0.9943
113 DAP	Plant P x N	0.699687	12.78368	2.108851	16.49644	-	0.2874
	Plant P x RS	0.699687	12.78368	2.108851	16.49644	-	0.9270
	N x RS	0.699687	12.78368	2.108851	16.49644	-	0.6555
	Plant P x N x RS	0.699687	12.78368	2.108851	16.49644	-	0.3177
	Plant P	0.694551	12.50295	2.136064	17.08448	-	0.7173
	N	0.694551	12.50295	2.136064	17.08448	-	0.3710
	RS	0.694551	12.50295	2.136064	17.08448	-	0.7301
126 DAP	Plant P x N	0.694551	12.50295	2.136064	17.08448	-	0.4391
	Plant P x RS	0.694551	12.50295	2.136064	17.08448	-	0.9730
	N x RS	0.694551	12.50295	2.136064	17.08448	-	0.2290
	Plant P x N x RS	0.694551	12.50295	2.136064	17.08448	-	0.2835

Appendix A. Table 3.3. ANOVA data of the effect of plant population (Plant P), nitrogen level (N) and row spacing (RS) and their interaction effects on stem diameter at 60 cm soil level at 85, 113 and 126 DAP

Sampling date	Source	R-square	CV	R-MSE	Mean	HSD	Pr> F
	Plant P	0.639169	15.79833	1.812268	11.47126	-	0.3295
	N	0.639169	15.79833	1.812268	11.47126	-	0.1842
	RS	0.639169	15.79833	1.812268	11.47126	-	0.4551
85 DAP	Plant P x N	0.639169	15.79833	1.812268	11.47126	-	0.1065
	Plant P x RS	0.639169	15.79833	1.812268	11.47126	-	0.3412
	N x RS	0.639169	15.79833	1.812268	11.47126	-	0.3584
	Plant P x N x RS	0.639169	15.79833	1.812268	11.47126	-	0.5190
	Plant P	0.648817	15.84145	2.004326	12.65241	-	0.4898
	N	0.648817	15.84145	2.004326	12.65241	-	0.2849
	RS	0.648817	15.84145	2.004326	12.65241	-	0.8159
113 DAP	Plant P x N	0.648817	15.84145	2.004326	12.65241	-	0.1951
	Plant P x RS	0.648817	15.84145	2.004326	12.65241	-	0.5117
	N x RS	0.648817	15.84145	2.004326	12.65241	-	0.7882
	Plant P x N x RS	0.648817	15.84145	2.004326	12.65241	-	0.8521
	Plant P	0.689813	14.73038	1.880324	12.76493	-	0.3767
	N	0.689813	14.73038	1.880324	12.76493	-	0.3584
	RS	0.689813	14.73038	1.880324	12.76493	-	0.9412
126 DAP	Plant P x N	0.689813	14.73038	1.880324	12.76493	-	0.2072
	Plant P x RS	0.689813	14.73038	1.880324	12.76493	-	0.4695
	N x RS	0.689813	14.73038	1.880324	12.76493	-	0.7464
	Plant P x N x RS	0.689813	14.73038	1.880324	12.76493	-	0.5003

Appendix A. Table 3.4. ANOVA data of the effect of plant population (Plant P), nitrogen level (N) and row spacing (RS) and their interaction effects on stem diameter at 110 cm soil level at 85, 113 and 126 DAP

Sampling date	Source	R-square	CV	R-MSE	Mean	HSD	Pr> F
	Plant P	0.612392	18.10574	1.594408	8.806092	-	0.5330
	N	0.612392	18.10574	1.594408	8.806092	-	0.1353
	RS	0.612392	18.10574	1.594408	8.806092	-	0.7069
85 DAP	Plant P x N	0.612392	18.10574	1.594408	8.806092	-	0.1746
	Plant P x RS	0.612392	18.10574	1.594408	8.806092	-	0.2398
	N x RS	0.612392	18.10574	1.594408	8.806092	-	0.5693
	Plant P x N x RS	0.612392	18.10574	1.594408	8.806092	-	0.5511
	Plant P	0.643323	17.17577	1.745769	10.16414	-	0.3837
	N	0.643323	17.17577	1.745769	10.16414	-	0.2749
	RS	0.643323	17.17577	1.745769	10.16414	-	0.5318
113 DAP	Plant P x N	0.643323	17.17577	1.745769	10.16414	-	0.2078
	Plant P x RS	0.643323	17.17577	1.745769	10.16414	-	0.4427
	N x RS	0.643323	17.17577	1.745769	10.16414	-	0.6725
	Plant P x N x RS	0.643323	17.17577	1.745769	10.16414	-	0.7286
	Plant P	0.681377	16.55165	1.729122	10.44682	-	0.4709
	N	0.681377	16.55165	1.729122	10.44682	-	0.1925
	RS	0.681377	16.55165	1.729122	10.44682	-	0.2571
126 DAP	Plant P x N	0.681377	16.55165	1.729122	10.44682	-	0.3764
	Plant P x RS	0.681377	16.55165	1.729122	10.44682	-	0.6305
	N x RS	0.681377	16.55165	1.729122	10.44682	-	0.8155
	Plant P x N x RS	0.681377	16.55165	1.729122	10.44682	-	0.5249

Appendix A. Table 3. 5. ANOVA data of the effect of plant population (Plant P), nitrogen level (N) and row spacing (RS) and their interaction effects on stem and leaf dry mass per plant and per hectare at 126 DAP

Variables	Source	R-square	CV	R-MSE	Mean	HSD	Pr> F
	Plant P	0.540637	41.75544	32.74748	78.42686	-	0.5670
	N	0.540637	41.75544	32.74748	78.42686	-	0.1846
	RS	0.540637	41.75544	32.74748	78.42686	-	0.4341
Stem/plant	Plant P x N	0.540637	41.75544	32.74748	78.42686	-	0.1618
	Plant P x RS	0.540637	41.75544	32.74748	78.42686	-	0.4913
	N x RS	0.540637	41.75544	32.74748	78.42686	-	0.5151
	Plant P x N x RS	0.540637	41.75544	32.74748	78.42686	-	0.9938
	Plant P	0.630118	42.10338	9.840645	23.37257	-	0.1782
	N	0.630118	42.10338	9.840645	23.37257	-	0.0918
	RS	0.630118	42.10338	9.840645	23.37257	-	0.8216
Leaves/plant	Plant P x N	0.630118	42.10338	9.840645	23.37257	-	0.4671
	Plant P x RS	0.630118	42.10338	9.840645	23.37257	-	0.0529
	N x RS	0.630118	42.10338	9.840645	23.37257	-	0.6765
	Plant P x N x RS	0.630118	42.10338	9.840645	23.37257	-	0.8818
	Plant P	0.513382	42.57336	9.845995	23.12713	-	0.2465
	N	0.513382	42.57336	9.845995	23.12713	-	0.1906
	RS	0.513382	42.57336	9.845995	23.12713	-	0.9082
Stem/ha	Plant P x N	0.513382	42.57336	9.845995	23.12713	-	0.4341
	Plant P x RS	0.513382	42.57336	9.845995	23.12713	-	0.7746
	N x RS	0.513382	42.57336	9.845995	23.12713	-	0.1596
	Plant P x N x RS	0.513382	42.57336	9.845995	23.12713	-	0.9511
	Plant P	0.452723	34.61213	2.261763	6.534598	-	0.2984
	N	0.452723	34.61213	2.261763	6.534598	-	0.2254
	RS	0.452723	34.61213	2.261763	6.534598	-	0.4029
Leaves/ha	Plant P x N	0.452723	34.61213	2.261763	6.534598	-	0.3129
	Plant P x RS	0.452723	34.61213	2.261763	6.534598	-	0.5643
	N x RS	0.452723	34.61213	2.261763	6.534598	-	0.6118
	Plant P x N x RS	0.452723	34.61213	2.261763	6.534598	-	0.8911

Appendix A. Table 3. 6. ANOVA data of the effect of plant population (Plant P), nitrogen level (N) and row spacing (RS) and their interaction effects on the percentage of stem and leaves at 126 DAP

Variables	Source	R-square	CV	R-MSE	Mean	HSD	Pr> F
Stem	Plant P	0.442890	10.95126	7.450718	68.03529	4.7402	0.0251
	N	0.442890	10.95126	7.450718	68.03529	-	0.5305
	RS	0.442890	10.95126	7.450718	68.03529	-	0.6696
	Plant P x N	0.442890	10.95126	7.450718	68.03529	-	0.7107
	Plant P x RS	0.442890	10.95126	7.450718	68.03529	-	0.2974
	N x RS	0.442890	10.95126	7.450718	68.03529	-	0.7957
	Plant P x N x RS	0.442890	10.95126	7.450718	68.03529	-	0.5865
Leaves	Plant P	0.477655	17.90837	3.719239	20.7682	-	0.1119
	N	0.477655	17.90837	3.719239	20.7682	-	0.1053
	RS	0.477655	17.90837	3.719239	20.7682	-	0.6492
	Plant P x N	0.477655	17.90837	3.719239	20.7682	-	0.5845
	Plant P x RS	0.477655	17.90837	3.719239	20.7682	-	0.1958
	N x RS	0.477655	17.90837	3.719239	20.7682	-	0.5517
	Plant P x N x RS	0.477655	17.90837	3.719239	20.7682	-	0.3165

Appendix A. Table 3. 7. ANOVA data of the effect of plant population (Plant P), nitrogen level (N) and row spacing (RS) and their interaction effects on Acid Detergent Fibre (ADF), Neutral detergent fibre (NDF), dry matter and ash content at 126 DAP

Variables	Source	R-square	CV	R-MSE	Mean	HSD	Pr> F
	Plant P	0.406892	4.481574	2.822160	62.97253	-	0.7264
	N	0.406892	4.481574	2.822160	62.97253	-	0.6421
	RS	0.406892	4.481574	2.822160	62.97253	-	0.8878
ADF	Plant P x N	0.406892	4.481574	2.822160	62.97253	-	0.1638
	Plant P x RS	0.406892	4.481574	2.822160	62.97253	-	0.2330
	N x RS	0.406892	4.481574	2.822160	62.97253	-	0.2428
	Plant P x N x RS	0.406892	4.481574	2.822160	62.97253	-	0.3784
	Plant P	0.498710	4.100754	2.918384	71.1674	-	0.6390
	N	0.498710	4.100754	2.918384	71.1674	-	0.1397
	RS	0.498710	4.100754	2.918384	71.1674	-	0.3923
NDF	Plant P x N	0.498710	4.100754	2.918384	71.1674	-	0.4226
	Plant P x RS	0.498710	4.100754	2.918384	71.1674	-	0.4059
	N x RS	0.498710	4.100754	2.918384	71.1674	-	0.1719
	Plant P x N x RS	0.498710	4.100754	2.918384	71.1674	-	0.1388
	Plant P	0.465459	2.392075	2.140800	89.49552	-	0.3264
	N	0.465459	2.392075	2.140800	89.49552	-	0.0529
	RS	0.465459	2.392075	2.140800	89.49552	-	0.9849
Dry matter	Plant P x N	0.465459	2.392075	2.140800	89.49552	-	0.0979
	Plant P x RS	0.465459	2.392075	2.140800	89.49552	-	0.5712
	N x RS	0.465459	2.392075	2.140800	89.49552	-	0.6418
	Plant P x N x RS	0.465459	2.392075	2.140800	89.49552	-	0.0589
	Plant P	0.517409	16.55634	0.327112	1.975747	-	0.5241
	N	0.517409	16.55634	0.327112	1.975747	-	0.8695
	RS	0.517409	16.55634	0.327112	1.975747	-	0.2769
Ash	Plant P x N	0.517409	16.55634	0.327112	1.975747	-	0.6830
	Plant P x RS	0.517409	16.55634	0.327112	1.975747	-	0.7337
	N x RS	0.517409	16.55634	0.327112	1.975747	-	0.1261
	Plant P x N x RS	0.517409	16.55634	0.327112	1.975747	-	0.6233

Appendix A. Table 3. 8. ANOVA data of the effect of plant population (Plant P), nitrogen level (N) and row spacing (RS) and their interaction effects on cellulose, hemicelulose, lignin and crude fibre content at 126 DAP

Variables	Source	R-square	CV	R-MSE	Mean	HSD	Pr> F
	Plant P	0.364548	8.436278	4.363737	51.72586	-	0.8697
	N	0.364548	8.436278	4.363737	51.72586	-	0.7643
	RS	0.364548	8.436278	4.363737	51.72586	-	0.3686
Cellulose	Plant P x N	0.364548	8.436278	4.363737	51.72586	-	0.1257
	Plant P x RS	0.364548	8.436278	4.363737	51.72586	-	0.7296
	N x RS	0.364548	8.436278	4.363737	51.72586	-	0.1157
	Plant P x N x RS	0.364548	8.436278	4.363737	51.72586	-	0.6127
	Plant P	0.455886	21.86175	1.790223	8.188837	-	0.5396
	N	0.455886	21.86175	1.790223	8.188837	-	0.1986
	RS	0.455886	21.86175	1.790223	8.188837	-	0.3870
Hemicellulose	Plant P x N	0.455886	21.86175	1.790223	8.188837	-	0.9522
	Plant P x RS	0.455886	21.86175	1.790223	8.188837	-	0.9867
	N x RS	0.455886	21.86175	1.790223	8.188837	-	0.2388
	Plant P x N x RS	0.455886	21.86175	1.790223	8.188837	-	0.2446
	Plant P	0.345540	9.75775	2.243345	11.35425	-	0.8757
	N	0.345540	9.75775	2.243345	11.35425	-	0.7395
	RS	0.345540	9.75775	2.243345	11.35425	-	0.2329
Lignin	Plant P x N	0.345540	9.75775	2.243345	11.35425	-	0.1016
	Plant P x RS	0.345540	9.75775	2.243345	11.35425	-	0.8849
	N x RS	0.345540	9.75775	2.243345	11.35425	-	0.1527
	Plant P x N x RS	0.345540	9.75775	2.243345	11.35425	-	0.6884
	Plant P	0.443483	6.352555	3.564543	56.11195	-	0.4007
	N	0.443483	6.352555	3.564543	56.11195	-	0.1053
	RS	0.443483	6.352555	3.564543	56.11195	-	0.4768
Crude fibre	Plant P x N	0.443483	6.352555	3.564543	56.11195	-	0.4059
	Plant P x RS	0.443483	6.352555	3.564543	56.11195	-	0.8502
	N x RS	0.443483	6.352555	3.564543	56.11195	-	0.2415
	Plant P x N x RS	0.443483	6.352555	3.564543	56.11195	-	0.3394

Appendix B. Table 4.1. ANOVA data of the effect of nitrogen level on plant height, stem diameter at at 0, 50 and 100 cm from the soil level cm from the soil level and leaf area index (LAI) at 58, 96, 118 and 136 DAP under rainfed conditions

Variables	Sampling date	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Plant height	**58**	0.9123	2.7806	3.9127	140.71	6.2587	<.0001
	96	0.6584	5.7148	11.8732	207.76	-	0.0527
	118	0.7102	5.3180	12.7846	240.39	20.450	0.0198
	136	0.7949	4.5518	12.6734	278.43	20.272	0.0028
0 cm	**58**	0.7487	7.2743	0.8713	11.9781	1.3938	0.005
	96	0.7348	8.9147	1.2428	13.9413	1.9888	0.014
	118	0.6539	11.1237	1.5967	14.35	2.5541	0.044
	136	0.9015	5.1509	0.7835	15.2113	1.2533	<.0001
50 cm	**58**	0.6312	12.716	1.0368	8.1538	1.6585	0.0258
	96	0.7645	8.8381	0.9304	10.5275	1.4883	0.0076
	118	0.6674	11.3973	1.2256	10.7538	1.9604	0.0353
	136	0.9073	5.1379	0.6269	12.2006	1.0027	<.0001
100 cm	**58**	0.694	14.3795	0.7547	5.2500	1.2073	0.0113
	96	0.7923	9.0417	0.7649	8.4594	1.2235	0.003
	118	0.7749	9.9431	0.8828	8.8788	1.4122	0.0079
	136	0.9515	4.3679	0.4406	10.0869	0.7048	<.0001
LAI	**58**	0.294069	28.04618	0.965840	3.443750	-	0.3685
	96	0.716118	16.03737	0.621348	3.874375	1.3716	0.0093
	118	0.746514	14.62733	0.683370	4.671875	1.5085	0.0050
	136	0.831457	12.18668	0.477337	3.91688	1.0537	0.0009

Appendix B. Table 4.2. ANOVA data of the effect of nitrogen level on stem dry mass (DM) per plant, stem DM per hectare, stem percentage, total DM per plant and total DM per hectare) at 58, 96, 118 and 136 DAP under rainfed conditions

Variables	Sampling date	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Stem DM/ plant	**58**	0.86924	13.1920	1.2835	9.7300	2.8334	0.0008
	96	0.73180	17.4692	5.9266	33.923	13.081	0.0182
	118	0.79891	13.4517	5.6322	41.8700	12.433	0.0025
	136	0.66292	20.1177	10.4486	51.9375	23.065	0.0221
Stem DM/ hectare	**58**	0.87809	14.8981	1.42440	9.5613	3.1444	0.0003
	96	0.72384	18.3333	3.94007	21.491	8.6975	0.0219
	118	0.57616	19.8864	4.00475	20.138	-	0.0606
	136	0.57985	23.95666	6.30674	26.3256	-	0.0540
Stem (%)	**58**	0.29300	7.0701	4.65387	65.7419	-	0.8661
	96	0.48942	3.37223	2.77045	82.1550	-	0.5690
	118	0.05804	4.10408	3.42144	83.3669	-	0.9729
	136	0.85687	9.69786	6.88015	70.9450	11.005	0.0005
Total DM/ plant	**58**	0.906699	9.97939	1.471960	14.7500	3.2498	0.0002
	96	0.729012	16.42713	6.755656	41.1250	14.913	0.0151
	118	0.602928	19.44676	9.820613	50.5000	-	0.0516
	136	0.67957	20.3386	14.8515	73.0213	32.784	0.0156
Total DM/ hectare	**58**	0.92273	9.0239	0.66423	7.3613	1.4662	<.0001
	96	0.74622	17.0610	2.81491	16.4994	6.2137	0.0149
	118	0.62202	22.8650	4.21060	18.4150	-	0.1442
	136	0.60691	21.6057	6.68236	30.9288	-	0.0540

Appendix B. Table 4.3. ANOVA data of the effect of nitrogen level on leaf DM per plant, leaf DM per hectare, leaf percentage at 58, 96, 118 and 136 DAP and reproductive organ DM per plant, reproductive organ DM per hectare and reproductive organ percentage at 118 and 136 DAP under rainfed conditions

Variables	Sampling date	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Leaf DM/plant	**58**	0.78011	14.2236	0.71029	4.99375	1.5679	0.0053
	96	0.59503	15.8043	1.13198	7.1625	2.4988	0.0395
	118	0.34576	18.7104	0.00116	0.00619	-	0.3360
	136	0.34576	18.7104	1.15770	6.1875	-	0.3360
Leaf DM/ hectare	**58**	0.77927	14.2914	0.35675	2.49625	0.7875	0.0057
	96	0.62235	15.1056	0.52643	3.48500	1.1621	0.0305
	118	0.26353	20.3111	0.58775	2.89375	-	0.5402
	136	0.84559	15.2676	0.79397	5.20000	1.7525	0.0009
Leaf (%)	**58**	0.29299	13.5847	4.65387	34.2581	-	0.8661
	96	0.48948	15.5212	2.76966	17.8444	-	0.5684
	118	0.03626	19.2224	2.80455	14.5900	-	0.9772
	136	0.05092	16.4178	2.54598	15.5075	-	0.4814

Appendix B. Table 4.4. ANOVA data of the effect of nitrogen application level on bark percentage, bark-core ratio, bark dry mass per hectare, ADF, NDF, dry matter, cellulose, hemicellulose, lignin, Ash, and crude fibre content at 136 DAP under rainfed conditions

Variables	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Bark percentage	0.32818	8.46534	2.96853	35.0669	-	0.4152
Bark-core ratio	0.42902	11.2962	0.06079	0.53813	-	0.3087
Bark dry mass	0.66830	19.5119	1.78875	9.16750	3.9486	0.0212
ADF	0.78831	1.49119	1.01705	68.2040	2.2451	0.0054
NDF	0.53745	2.23163	1.73296	77.6544	-	0.1480
Dry matter	0.48514	0.78523	0.73484	93.5819	-	0.1609
Cellulose	0.45536	4.38103	2.56646	58.5813	-	0.1836
Hemicellulose	0.25283	20.24547	1.87789	9.27563	-	0.5736
Lignin	0.09045	20.4228	2.00961	9.8400	-	0.8507
Ash	0.30830	12.4633	0.2365	1.8975	-	0.7200
Crude fibre	0.68126	2.61292	1.56367	59.8438	3.4517	0.0179

Appendix B. Table 4.5. ANOVA data of the effect of nitrogen level on thin plants, medium plants and thick plants as measured from 0 cm soil level and leaf area per plant (LA) at 136 DAP under rainfed conditions

Variables	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Thin plants	0.85687	9.69786	6.88015	70.9450	15.188	0.0005
Medium plants	0.84949	24.0557	6.41486	26.6668	14.16	0.0007
Thick plants	0.70933	57.1317	1.33795	2.34188	2.9534	0.0112
Leaf area/plant	0.77676	17.9150	181.423	1012.7	400.48	0.0035

Appendix B. Table 4.6. ANOVA data of the effect of nitrogen application level on water use efficiency at 58, 96,118 and 136 DAP under rainfed conditions

Sampling date	R-Square	CV	R-MSE	Mean	HSD	Pr> F
58	0.868666	13.18692	0.036701	0.278313	0.081	0.0008
96	0.746120	17.07424	0.120115	0.703563	0.2651	0.0149
118	0.622258	22.82972	0.141587	0.620189	-	0.1436
136	0.57909	24.01235	0.186786	0.777875	-	0.0544

Appendix B. Table 4.7. ANOVA data of the effect of nitrogen application level on N, P and K use efficiency, and N, K, P removal, and leaf and stem N content at 136 DAP under rainfed conditions

Variables	R-Square	CV	R-MSE	Mean	HSD	Pr> F
NUE	0.32293	23.0059	13.6021	59.1244	-	0.4608
KUE	0.59649	22.2298	16.1648	72.7169	35.683	0.0471
PUE	0.61981	26.3486	55.6631	211.26	-	0.0958
N removal	0.96844	2.91235	12.8609	441.596	28.39	<.0001
K removal	0.54559	10.4195	36.9464	354.59	-	0.1171
P removal	0.32211	31.1396	35.5085	114.03	-	0.5265
Leaf N cont	0.18073	26.2935	3.62192	13.775	-	0.8205
Stem N cont	0.65053	11.3244	0.17341	1.53125	-	0.0976

Appendix C. Table 5.1. ANOVA data of the effect of nitrogen level on plant height, stem diameter at 0, 50 and 100 cm from the soil level and leaf area index (LAI) at 58, 88, 118 and 135 DAP under irrigated conditions

Variables	Sampling date	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Plant height	**58**	0.89251	4.07725	5.66893	139.04	12.541	0.0001
	88	0.59332	4.11968	8.45513	205.24	-	0.2667
	118	0.65033	4.53809	13.2807	292.65	-	0.0754
	135	0.61165	5.05752	16.6892	329.99	36.84	0.0430
0 cm	**58**	0.87667	6.71905	0.70376	12.3056	1.5535	0.0002
	88	0.77402	5.56391	0.80552	14.4775	1.7781	0.0074
	118	0.66056	6.96676	1.03996	14.9275	2.2957	0.0361
	135	0.94830	3.36968	0.53268	15.8081	1.1759	0.0533
50 cm	**58**	0.90183	6.93334	0.58747	8.47312	1.2968	<.0001
	88	0.48082	9.96677	1.14536	11.4919	-	0.2391
	118	0.60440	8.40553	0.99905	11.8856	-	0.1080
	135	0.83967	5.33391	0.73548	13.7888	1.6235	0.0007
100 cm	**58**	0.90848	7.40902	0.48900	6.6000	1.0794	<.0001
	88	0.67694	6.91804	0.63088	9.1194	1.3926	0.0197
	118	0.69552	8.38917	0.87950	10.4838	1.9414	0.0376
	135	0.75035	7.61483	0.93853	12.3250	2.0717	0.0061
LAI	**58**	0.54999	16.5406	0.69801	4.22000	-	0.1866
	88	0.84001	11.0986	0.69318	6.24563	1.5301	0.0007
	118	0.87498	7.43050	0.61083	8.22063	1.3484	0.0002
	135	0.84125	10.7159	0.77798	7.26000	1.7173	0.0007

Appendix C. Table 5.2. ANOVA data of the effect of nitrogen level on stem dry mass (DM) per plant, stem DM per hectare, stem percentage, total DM per plant and total DM per hectare at 58, 88, 118 and 135 DAP under irrigated conditions

Variables	Sampling date	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Stem DM/ plant	**58**	0.74278	19.4418	1.84527	9.49125	4.0733	0.0067
	88	0.80383	11.2079	3.67212	32.7638	8.106	0.0027
	118	0.48740	32.2719	17.7693	55.0613	-	0.1703
	135	0.75517	17.9139	12.8416	71.6850	28.347	0.0071
Stem DM/ hectare	**58**	0.74278	19.4418	0.92263	4.74563	2.0367	0.0067
	88	0.80451	11.3163	1.80127	15.9175	3.9762	0.0026
	118	0.644026	19.84642	4.350832	21.9225	-	0.0555
	135	0.75074	18.1172	5.90246	32.5794	13.029	0.0080
Stem (%)	**58**	0.55426	7.56901	4.58342	60.555	-	0.0610
	88	0.48043	3.20063	2.49683	78.0106	-	0.1806
	118	0.20374	4.22578	3.47922	82.3331	-	0.6890
	135	0.24069	3.13615	2.59397	82.7119	-	0.9917
Total DM/ plant	**58**	0.79166	13.4888	2.09110	15.5025	4.616	0.0025
	88	0.84652	8.64395	3.61566	41.8288	7.981	0.0009
	118	0.52318	27.3809	18.1560	66.3088	-	0.1273
	135	0.80302	15.3270	13.2506	86.4525	29.25	0.0025
Total DM/ hectare	**58**	0.79166	13.4888	1.04556	7.75125	2.308	0.0025
	88	0.84595	8.77219	1.78246	20.3194	3.935	0.0009
	118	0.51835	28.2645	9.02379	31.9263	-	0.1350
	135	0.80113	15.3971	6.04952	32.2900	13.354	0.0027

Appendix C. Table 5.3. ANOVA data of the effect of nitrogen level on leaf DM per plant, leaf DM per hectare and leaf percentage at 58, 96, 118 and 136 DAP at 118 and 136 DAP under irrigated conditions

Variables	Sampling date	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Leaf DM/ plant	**58**	0.75563	11.5334	0.69330	6.01125	1.5304	0.0044
	88	0.57899	10.8607	0.98453	9.06500	2.1733	0.0498
	118	0.82516	10.1467	1.04041	10.2538	2.2966	0.0010
	135	0.59256	12.9254	1.27994	9.9025	-	0.5325
Leaf DM/ hectare	**58**	0.75563	11.5334	0.34665	3.00563	0.7652	0.0044
	88	0.57656	11.0247	0.48543	4.40313	1.0716	0.0478
	118	0.60222	12.9897	0.61864	4.76250	-	0.0550
	135	0.83537	9.67440	0.45071	4.65875	0.9949	0.0008
Leaf (%)	**58**	0.55426	11.6198	4.58342	39.4450	-	0.0610
	88	0.48014	11.3542	2.49665	21.9888	-	0.1810
	118	0.13469	23.1392	3.53061	15.2581	-	0.9196
	135	0.45992	15.5001	1.87028	12.0663	-	0.3859

Appendix C. Table 5.4. ANOVA data of the effect of nitrogen application level on bark percentage, bark-core ratio, bark dry mass per hectare, ADF, NDF, dry matter, cellulose, hemicellulose, lignin, Ash, and crude fibre content at 136 DAP under irrigated conditions

Variables	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Bark percentage	0.21887	6.81810	2.36756	34.7200	-	0.5248
Bark-core ratio	0.22254	10.2889	0.05498	0.53438	-	0.5211
Bark dry mass	0.75776	19.3577	2.20291	11.3800	4.8628	0.0063
ADF	0.90151	0.84576	0.59484	70.3313	1.3131	<.0001
NDF	0.68217	1.42050	1.15057	80.9978	2.5406	0.0463
Dry matter	0.47911	2.49696	2.33162	93.3781	-	0.1289
Cellulose	0.38231	3.66261	2.17741	59.4497	-	0.3226
Hemicellulose	0.44455	12.9226	1.37839	10.6665	-	0.2273
Lignin	0.33009	17.4176	1.89530	10.8816	-	0.4814
Ash	0.81437	7.34154	0.13614	1.85438	0.3005	0.0017
Crude fibre	0.69496	3.12087	2.03467	65.1956	4.4914	0.0282

Appendix C. Table 5.5. ANOVA data of the effect of nitrogen level on thin plants, medium plants and thick plants as measured from 0 cm soil level and leaf area per plant (LA) at 136 DAP under irrigated conditions

Variables	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Thin plants	0.77198	18.1803	10.4733	57.6081	23.119	0.0032
Medium plants	0.75184	25.7308	9.70566	37.7200	21.425	0.0052
Thick plants	0.80254	43.7385	2.34020	5.3504	5.1659	0.0064
Leaf area/plant	0.90843	9.59533	161.84	1686.65	357.25	<.0001

Appendix C. Table 5.6. ANOVA data of the effect of nitrogen application level on water use efficiency at 58, 96,118 and 136 DAP under irrigated conditions

Sampling date	R-Square	CV	R-MSE	Mean	HSD	Pr> F
58	0.735871	19.11389	0.025338	0.132563	0.0559	0.0074
88	0.747655	11.34203	0.035593	0.313813	0.0786	0.0127
118	0.519891	19.65265	0.065406	0.332813	-	0.2188
135	0.642331	17.65562	0.074518	0.422063	-	0.0490

Appendix C. Table 5.7. ANOVA data of the effect of nitrogen application level on Nitrogen, potassium and phosphorus use efficiency (NUE, KUE, PUE) and N, K, P removal, and leaf and stem N content at 136 DAP under irrigated conditions

Variables	R-Square	CV	R-MSE	Mean	HSD	Pr> F
NUE	0.55769	17.3180	12.4838	72.0856	-	0.2077
KUE	0.69248	17.9796	14.1963	78.9581	22.708	0.0201
PUE	0.41078	36.2150	98.7269	272.61	-	0.2706
N removal	0.98870	1.81148	8.02931	443.25	12.844	<.0001
K removal	0.25217	11.1047	45.7422	411.92	-	0.4964
P removal	0.13507	33.3287	42.9224	128.79	-	0.9521
Leaf N cont	0.26070	20.7421	3.25132	15.6750	-	0.7491
Stem N cont	0.57407	15.3826	0.27689	1.8000	-	0.6646

Appendix D. Table 6.1. ANOVA data of the effect of plant population and row spacing and their interaction (Plant P x RS) on plant height, stem diameter at 63 DAP at 0, 50 and 100 cm from the soil level, and leaf area index (LAI) at 62 DAP

Variables	Treatment	R-Square	CV	R-MSE	Mean	HSD	Pr> F
	Plant P	0.721917	3.113008	5.607436	180.1292	-	0.1797
Plant height	RS	0.721917	3.113008	5.607436	180.1292	-	0.5980
	Plant PxRS	0.721917	3.113008	5.607436	180.1292	-	0.6142
	Plant P	0.611376	7.845944	1.112865	14.18396	1.5027	0.0204
0 cm	RS	0.611376	7.845944	1.112865	14.18396	-	0.0640
	Plant PxRS	0.611376	7.845944	1.112865	14.18396	-	0.9741
	Plant P	0.743828	7.214628	0.846080	11.72729	-	0.2032
50 cm	RS	0.743828	7.214628	0.846080	11.72729	0.747	0.0023
	Plant PxRS	0.743828	7.214628	0.846080	11.72729	-	0.8346
	Plant P	0.681032	8.856757	0.808179	9.125000	-	0.1142
100 cm	RS	0.681032	8.856757	0.808179	9.125000	-	0.0888
	Plant PxRS	0.681032	8.856757	0.808179	9.125000	-	0.6824
	Plant P	0.685946	17.69916	0.599870	3.338333	-	0.7210
LAI	RS	0.685946	17.69916	0.599870	3.338333	-	0.9820
	Plant PxRS	0.685946	17.69916	0.599870	3.338333	-	0.8926

Appendix D. Table 6.2. ANOVA data of the effect of plant population and row spacing and their interaction (Plant P x RS) on plant height, stem diameter at 90 DAP at 0, 50 and 100 cm from the soil level, and LAI at 89 DAP

Variables	Treatment	R-Square	CV	R-MSE	Mean	HSD	Pr> F
	Plant P	0.615187	6.047328	13.39016	221.4227	-	0.3972
Plant height	RS	0.615187	6.047328	13.39016	221.4227	-	0.1699
	Plant PxRS	0.441239	6.214411	13.39016	221.4227	-	00.9367
	Plant P	0.727700	6.791277	1.041541	15.33646	-	0.1150
0 cm	RS	0.727700	6.791277	1.041541	15.33646	-	0.3599
	Plant PxRS	0.530506	7.604864	1.041541	15.33646	-	0.5839
	Plant P	0.527266	11.29781	1.382475	12.23667	1.2729	0.0376
50 cm	RS	0.527266	11.29781	1.382475	12.23667	-	0.1405
	Plant PxRS	0.434738	10.53560	1.382475	12.23667	-	0.9680
	Plant P	0.484929	14.37234	1.400794	9.746458	-	0.0549
100 cm	RS	0.484929	14.37234	1.400794	9.746458	-	0.1123
	Plant PxRS	0.393070	13.30491	1.296757	9.746458	-	0.9469
	Plant P	0.572575	11.99034	0.552905	4.611250	-	0.1728
LAI	RS	0.572575	11.99034	0.552905	4.611250	-	0.9130
	Plant PxRS	0.572575	11.99034	0.552905	4.611250	-	0.6164

Appendix D. Table 6.3. ANOVA data of the effect of plant population and row spacing and their interaction (Plant P x RS) on plant height, stem diameter at 122 DAP at 0, 50 and 100 cm from the soil level, and LAI at 121 DAP

Variables	Treatment	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Plant height	Plant P	0.757535	4.439008	11.73378	264.333	18.642	0.0101
	RS	0.757535	4.439008	11.73378	264.333	-	0.0568
	Plant PxRS	0.616244	4.762529	11.73378	264.333	18.111	0.9943
0 cm	Plant P	0.500961	6.838223	1.083502	15.84479	0.8905	0.0022
	RS	0.500961	6.838223	1.083502	15.84479	-	0.2235
	Plant PxRS	0.423141	6.269881	1.083502	15.84479	-	0.9813
50 cm	Plant P	0.707360	6.689193	0.849123	12.69396	-	0.1618
	RS	0.707360	6.689193	0.849123	12.69396	-	0.8923
	Plant PxRS	0.490197	7.529341	0.955771	12.69396	-	0.4391
100 cm	Plant P	0.741326	6.389391	0.667239	10.44292	-	0.2536
	RS	0.741326	6.389391	0.667239	10.44292	-	0.3707
	Plant PxRS	0.545222	7.224895	0.754490	10.44292	-	0.4455
LAI	Plant P	0.546367	8.321535	0.492271	5.915625	-	0.4772
	RS	0.546367	8.321535	0.492271	5.915625	-	0.8000
	Plant PxRS	0.546367	8.321535	0.492271	5.915625	-	0.2290

Appendix D. Table 6.4. ANOVA data of the effect of plant population and row spacing and their interaction (Plant P x RS) on plant height, stem diameter at 140 DAP at 0, 50 and 100 cm from the soil level, and LAI at 139 DAP

Variables	Treatment	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Plant height	Plant P	0.705151	4.390714	12.01215	273.5808	16.788	0.0030
	RS	0.705151	4.390714	12.01215	273.5808	-	0.1511
	Plant PxRS	0.572195	4.510321	12.01215	273.5808	17.752	0.5971
0 cm	Plant P	0.690044	7.137871	1.181228	16.54875	-	0.0581
	RS	0.690044	7.137871	1.181228	16.54875	0.8619	0.0389
	Plant PxRS	0.467656	7.977434	1.181228	16.54875	-	0.5381
50 cm	Plant P	0.582815	5.402653	0.706408	13.07521	-	0.2605
	RS	0.582815	5.402653	0.706408	13.07521	-	0.1061
	Plant PxRS	0.359077	5.710765	0.746694	13.07521	-	0.2311
100 cm	Plant P	0.571355	5.208968	0.569470	10.93250	-	0.6635
	RS	0.571355	5.208968	0.569470	10.93250	-	0.9396
	Plant PxRS	0.406711	5.226185	0.571355	10.93250	-	0.2281
LAI	Plant P	0.529569	18.93015	0.798892	4.220208	-	0.2594
	RS	0.529569	18.93015	0.798892	4.220208	-	0.4606
	Plant PxRS	0.529569	18.93015	0.798892	4.220208	-	0.8566

Appendix D. Table 6.5. ANOVA data of the effect of plant population and row spacing and their interaction (Plant P x RS) on thinner, medium and thicker plants as assessed from 0 cm soil level at the final harvest and leaf area per plant (LA) at 140 DAP

Variables	Treatment	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Thin plants	Plant P	0.940017	7.544353	4.815215	63.82542	10.473	<.0001
	RS	0.940017	7.544353	4.815215	63.82542	4.2515	0.0040
	Plant PxRS	0.940017	7.544353	4.815215	63.82542	-	0.0515
Med plants	Plant P	0.886104	15.63259	5.06643	32.4094	9.9361	0.0004
	RS	0.886104	15.63259	5.06643	32.4094	4.4733	0.0076
	Plant PxRS	0.886104	15.63259	5.06643	32.4094	14.739	0.043
Thick plants	Plant P	0.958702	31.48769	1.23366	3.91792	3.2713	<.0001
	RS	0.958702	31.48769	1.23366	3.91792	-	0.2341
	Plant PxRS	0.958702	31.48769	1.23366	3.91792	4.2306	<.0001
LA	Plant P	0.518154	17.29025	174.878	1011.43	-	0.2480
	RS	0.518154	17.29025	174.878	1011.43	154.4	0.0096
	Plant PxRS	0.518154	17.29025	174.878	1011.43	-	0.4991

Appendix D. Table 6.6. ANOVA data of the effect of plant population and row spacing and their interaction (Plant P x RS) on stem DM, total DM per plant, total DM per hectare, and stem percentage at 63 DAP

Variables	Treatment	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Stem	Plant P	0.516529	15.75278	5.197565	32.99458	-	0.2106
DM/ plant	RS	0.516529	15.75278	5.197565	32.99458	-	0.4582
	Plant PxRS	0.516529	15.75278	5.197565	32.99458	-	0.4176
Stem	Plant P	0.815720	16.46400	1.785110	10.84250	2.8599	0.0005
DM/ hectare	RS	0.815720	16.46400	1.785110	10.84250	-	0.1859
	Plant PxRS	0.815720	16.46400	1.785110	10.84250	-	0.2566
	Plant P	0.673284	4.88925	3.21513	65.75917	4.7463	0.0221
Stem (%)	RS	0.673284	4.88925	3.21513	65.75917	-	0.3056
	Plant PxRS	0.673284	4.88925	3.21513	65.75917	-	0.8607
Total	Plant P	0.701430	13.72396	5.203140	37.18417	-	0.1283
DM/ plant	RS	0.701430	13.72396	5.203140	37.18417	-	0.0912
	Plant PxRS	0.452087	15.85480	5.895476	37.18417	8.4813	0.0340
Total DM	Plant P	0.796852	16.10264	2.646972	16.43813	2.2303	0.0018
DM/ hectare	RS	0.796852	16.10264	2.646972	16.43813	-	0.0874
	Plant PxRS	0.664342	17.65178	2.901622	16.43813	4.1743	<.0001

Appendix D. Table 6.7. ANOVA data of the effect of plant population and row spacing and their interaction (Plant P x RS) on stem DM, total DM per plant, total DM per hectare, and stem percentage at 90 DAP

Variables	Treatment	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Stem	Plant P	0.637973	15.05025	3.649247	24.24708	-	0.2960
DM/ plant	RS	0.637973	15.05025	3.649247	24.24708	-	0.2100
	Plant PxRS	0.637973	15.05025	3.649247	24.24708	-	0.1594
Stem	Plant P	0.769132	19.94588	2.688289	13.47792	2.8358	<.0001
DM/ hectare	RS	0.769132	19.94588	2.688289	13.47792	-	0.8220
	Plant PxRS	0.769132	19.94588	2.688289	13.47792	-	0.8696
	Plant P	0.603262	4.079294	3.29891	80.86958	-	0.5341
Stem (%)	RS	0.603262	4.079294	3.29891	80.86958	-	0.8574
	Plant PxRS	0.603262	4.079294	3.29891	80.86958	-	0.4789
Total	Plant P	0.517582	16.97361	7.45467	43.91208	-	0.2599
DM/ plant	RS	0.517582	16.97361	7.45467	43.91208	-	0.9131
	Plant PxRS	0.383346	16.36560	7.186467	43.91208	-	0.6688
Total DM	Plant P	0.793510	17.71686	3.253737	18.36521	2.7415	<.0001
DM/ hectare	RS	0.793510	17.71686	3.253737	18.36521	-	0.8379
	Plant PxRS	0.744099	16.81986	3.089002	18.36521	4.4439	<.0001

Appendix D. Table 6.8. ANOVA data of the effect of plant population and row spacing and their interaction (Plant P x RS) on stem DM, total DM per plant and total DM per hectare, and stem percentage at 122 DAP

Variables	Treatment	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Stem	Plant P	0.625825	11.74809	6.757086	57.51646	-	0.2593
DM/ plant	RS	0.625825	11.74809	6.757086	57.51646	-	0.7548
	Plant PxRS	0.625825	11.74809	6.757086	57.51646	-	0.1978
Stem	Plant P	0.913682	11.11453	2.600429	23.39667	4.9476	<.0001
DM/ hectare	RS	0.913682	11.11453	2.600429	23.39667	-	0.6509
	Plant PxRS	0.913682	11.11453	2.600429	23.39667	-	0.0755
	Plant P	0.612153	3.479315	3.024982	86.94188	-	0.8567
Stem (%)	RS	0.612153	3.479315	3.024982	86.94188	-	0.4189
	Plant PxRS	0.612153	3.479315	3.024982	86.94188	-	0.8779
Total	Plant P	0.701649	10.72209	7.638395	71.23979	-	0.2541
DM/ plant	RS	0.701649	10.72209	7.638395	71.23979	-	0.7830
	Plant PxRS	0.503142	11.79995	8.406263	71.23979	-	0.2000
Total DM	Plant P	0.927396	9.987658	2.887390	28.90958	2.4329	<.0001
DM/ hectare	RS	0.927396	9.987658	2.887390	28.90958	-	0.6294
	Plant PxRS	0.852270	12.06896	3.489087	28.90958	5.0195	<.0001

Appendix D. Table 6.9. ANOVA data of the effect of plant population and row spacing and their interaction (Plant P x RS) on stem DM, total DM per plant, total DM per hectare, and stem percentage at 140 DAP

Variables	Treatment	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Stem	Plant P	0.725670	11.60498	7.197191	62.01813	-	0.7405
DM/ plant	RS	0.725670	11.60498	7.197191	62.01813	-	0.7095
	Plant PxRS	0.725670	11.60498	7.197191	62.01813	-	0.1968
Stem	Plant P	0.88826	12.78296	3.21947	25.18563	5.2245	<.0001
DM/ hectare	RS	0.88826	12.78296	3.21947	25.18563	-	0.6282
	Plant PxRS	0.88826	12.78296	3.21947	25.18563	-	0.5666
	Plant P	0.454008	8.682584	6.554935	75.49521	-	0.1636
Stem (%)	RS	0.454008	8.682584	6.554935	75.49521	-	0.0515
	Plant PxRS	0.454008	8.682584	6.554935	75.49521	-	0.8311
Total	Plant P	0.685418	11.53730	8.217392	71.22458	-	0.7648
DM/ plant	RS	0.685418	11.53730	8.217392	71.22458	-	0.8568
	Plant PxRS	0.417456	13.38906	9.536300	71.22458	-	0.6366
Total DM	Plant P	0.893272	12.37732	3.588211	28.99021	3.0234	<.0001
DM/ hectare	RS	0.893272	12.37732	3.588211	28.99021	-	0.7521
	Plant PxRS	0.842367	12.82801	3.718866	28.99021	5.3500	<.0001

Appendix D. Table 6.10. ANOVA data of the effect of plant population and row spacing and their interaction (Plant P x RS) on leaf DM per plant and per ha and contribution at 63 DAP

Variables	Treatment	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Leaf	Plant P	0.745975	16.41460	2.102779	12.81042	1.7718	0.0349
DM/ plant	RS	0.745975	16.41460	2.102779	12.81042	1.5344	0.0420
	Plant PxRS	0.533094	18.97824	2.431191	12.81042	3.4976	0.0085
Leaf	Plant P	0.715294	18.38294	1.026534	5.584167	0.8694	0.0344
DM/ hectare	RS	0.715294	18.38294	1.026534	5.584167	-	0.0502
	Plant PxRS	0.516242	20.43523	1.141137	5.584167	1.6417	0.0138
	Plant P	0.687615	9.165235	3.142072	34.28250	2.6475	0.0221
Leaf (%)	RS	0.687615	9.165235	3.142072	34.28250	-	0.2940
	Plant PxRS	0.515143	9.737642	3.338307	34.28250	4.8026	0.0324

Appendix D. Table 6.11. ANOVA data of the effect of plant population and row spacing and their interaction (Plant P x RS) on leaf DM per plant and per hectare, and leaf percentage at 90 DAP

Variables	Treatment	R-quare	CV	R-MSE	Mean	HSD	Pr> F
Leaf	Plant P	0.506331	36.79998	4.032818	10.95875	-	0.2688
DM/ plant	RS	0.506331	36.79998	4.032818	10.95875	-	0.1366
	Plant PxRS	0.355258	35.86506	3.93062	10.95875	-	0.4549
Leaf	Plant P	0.480122	38.85805	1.748/369	4.499375	1.4731	0.0311
DM/ hectare	RS	0.480122	38.85805	1.748/369	4.499375	-	0.1649
	Plant PxRS	0.377738	36.25481	1.631240	4.499375	-	0.2485
	Plant P	0.417715	28.22911	6.928541	24.54396	-	0.1291
Leaf (%)	RS	0.417715	28.22911	6.928541	24.54396	-	0.0706
	Plant PxRS	0.324477	25.92974	6.364185	24.54396	-	0.2995

Appendix D. Table 6.12. ANOVA data of the effect of plant population and row spacing and their interaction (Plant P x RS) on leaf and reproductive organ DM per plant, leaf and reproductive organ DM per hectare, and leaf and reproductive organ percentage at 122 DAP

Variables	Treatment	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Leaf	Plant P	0.661865	19.27726	2.143712	11.12042	-	0.3507
DM/ plant	RS	0.661865	19.27726	2.143712	11.12042	-	0.7020
	Plant PxRS	0.451106	20.94562	2.329240	11.12042	-	0.3707
Leaf	Plant P	0.826407	16.55679	0.736432	4.447917	0.6205	0.0026
DM/ hectare	RS	0.826407	16.55679	0.736432	4.447917	-	0.9769
	Plant PxRS	0.697002	18.65432	0.829728	4.447917	1.1937	<.0001
	Plant P	0.567984	15.65006	2.429020	15.52083	-	0.5640
Leaf (%)	RS	0.567984	15.65006	2.429020	15.52083	-	0.5016
	Plant PxRS	0.403926	15.67708	2.433214	15.52083	-	0.3330

Appendix D. Table 6.13. ANOVA data of the effect of plant population and row spacing and their interaction (Plant P x RS) on leaf and reproductive organ DM per plant, leaf and reproductive organ DM per hectare, and leaf and reproductive organ percentage at 140 DAP

Variables	Treatment	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Leaf	Plant P	0.397422	29.58706	1.646520	5.565000	-	0.8097
DM/ plant	RS	0.397422	29.58706	1.646520	5.565000	-	0.9210
	Plant PxRS	0.170346	29.60687	1.647622	5.565000	-	0.9624
Leaf	Plant P	0.692922	29.97940	0.684842	2.284375	0.577	0.0057
DM/ hectare	RS	0.692922	29.97940	0.684842	2.284375	-	0.8859
	Plant PxRS	0.526492	31.74757	0.725234	2.284375	1.0433	0.0048
	Plant P	0.402820	26.19931	2.051679	7.831042	-	0.8478
Leaf (%)	RS	0.402820	26.19931	2.051679	7.831042	-	0.8912
	Plant PxRS	0.142907	26.76700	2.096135	7.831042	-	0.7240

Appendix D. Table 6.14. ANOVA data of the effect of plant population and row spacing and their interaction (Plant P x RS) on Bark DM per hectare, bark percentage and bark-core ratio at 140 DAP

Variables	Treatment	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Bark DM per hectare	Plant P	0.882126	13.91009	1.387097	9.971875	1.1687	0.0003
	RS	0.882126	13.91009	1.387097	9.971875	1.0122	0.0152
	Plant PxRS	0.773494	16.44406	1.639781	9.971875	2.359	<.0001
Bark (%)	Plant P	0.511101	10.49754	4.123191	39.27771	-	0.5161
	RS	0.511101	10.49754	4.123191	39.27771	-	0.1653
	Plant PxRS	0.511101	10.49754	4.123191	39.27771	-	0.4963
Bark ÷ core	Plant P	0.506489	17.68583	0.115584	0.653542	-	0.5967
	RS	0.506489	17.68583	0.115584	0.653542	-	0.2101
	Plant PxRS	0.506489	17.68583	0.115584	0.653542	-	0.4833

Appendix D. Table 6. 15. ANOVA data of the effect of plant population and row spacing and their interaction (Plant P x RS) on NUE, KUE and PUE, N removal, K removal and P removal, leaf nitrogen content and stem nitrogen content at 140 DAP

Variables	Treatment	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Leaf N	Plant P	0.550949	16.43098	3.094159	18.83125	-	0.8659
	RS	0.550949	16.43098	3.094159	18.83125	-	0.7540
	Plant PxRS	0.225924	18.39740	3.464460	18.83125	-	0.7356
Stem N	Plant P	0.577768	23.15657	0.464579	2.006250	-	0.8960
	RS	0.577768	23.15657	0.464579	2.006250	-	0.5510
	Plant PxRS	0.334709	24.78865	0.497322	2.006250	-	0.3049
NUE	Plant P	0.832074	15.3682	8.373376	54.50063	7.0553	0.0019
	RS	0.832074	15.3682	8.373376	54.50063	-	0.8468
	Plant PxRS	0.674647	18.23753	9.939568	54.50063	14.299	<.0001
KUE	Plant P	0.824926	18.97233	15.31826	80.74000	12.907	0.0001
	RS	0.824926	18.97233	15.31826	80.74000	13.525	0.0372
	Plant PxRS	0.753590	19.19501	15.49805	80.74000	22.296	<.0001
PUE	Plant P	0.674164	24.68526	54.74214	221.7604	46.125	0.0293
	RS	0.674164	24.68526	54.74214	221.7604	-	0.5078
	Plant PxRS	0.489314	26.35506	58.44508	221.7604	84.08	0.0341

Appendix E. Table 7.1. ANOVA data of the effect of nitrogen application level on the number of fibre rings and fibre bundles from the top, middle and bottom segments under rainfed and irrigated conditions

Variables	Segment	R-Square	CV	R-MSE	Mean	HSD	Pr> F
Rainfed							
Fibre rings	**Top**	0.58396	13.7653	0.16436	1.19375	-	0.0789
	Middle	0.41631	6.34661	0.19437	3.0625	-	0.1951
	Bottom	0.35988	4.91638	0.38532	7.83750	-	0.9094
Fibre bundles	**Top**	0.72195	6.76762	12.1540	179.563	19.438	0.0110
	Middle	0.86040	9.47172	41.8709	442.063	66.976	0.0004
	Bottom	0.73322	11.3033	73.1111	646.813	116.95	0.0066
Irrigated							
Fibre rings	**Top**	0.17968	21.8199	0.26048	1.19375	-	0.6425
	Middle	0.73917	4.13360	0.13184	3.31875	0.2194	0.0235
	Bottom	0.87819	3.44782	0.28186	8.17500	0.4509	0.0002
Fibre bundles	**Top**	0.86871	9.21884	16.57663	179.8125	26.516	0.0003
	Middle	0.84113	11.0327	45.0823	408.625	72.113	0.0007
	Bottom	0.97179	5.12038	33.0038	644.1250	52.792	<.0001

Appendix E. Table 7.2. ANOVA data of the effect of plant population and row spacing and their interactions on the number of fibre rings from the top, middle and bottom segments

Segments	Source	R-square	CV	R-MSE	Mean	HSD	Pr> F
Top	Plant P	0.42772	39.0321	0.57735	1.479167	-	0.6450
	RS	0.42772	39.0321	0.57735	1.479167	-	0.4556
	Plant PxRS	0.235469	38.47370	0.569090	1.479167	-	0.5448
Middle	Plant P	0.65052	14.5326	0.51167	3.520833	-	0.0663
	RS	0.65052	14.5326	0.51167	3.520833	0.3734	0.0049
	Plant PxRS	0.464113	15.34684	0.540337	3.520833	0.7986	0.0175
Bottom	Plant P	0.79738	7.9138	0.76830	9.708333	0.6474	0.0033
	RS	0.79738	7.9138	0.76830	9.708333	-	0.1380
	Plant PxRS	0.696067	8.265665	0.802458	9.708333	1.1544	<.0001

Appendix E. Table 7.3. ANOVA data of the effect of plant population and row spacing and their interactions on the number of fibre bundles from the top, middle and bottom segments

Segments	Source	R-square	CV	R-MSE	Mean	HSD	Pr> F
Top	Plant P	0.74296	12.2497	28.7663	234.833	24.338	0.0312
	RS	0.74296	12.2497	28.7663	234.833	-	0.6786
	Plant PxRS	0.495988	14.62813	34.35172	234.833	49.419	0.0197
Middle	Plant P	0.80381	6.5553	37.4703	571.604	31.572	0.0002
	RS	0.80381	6.5553	37.4703	571.604	-	1.0000
	Plant PxRS	0.710734	6.77187	38.80156	571.6042	55.821	<.0001
Bottom	Plant P	0.70349	9.82139	110.773	1127.875	93.498	0.0097
	RS	0.70349	9.82139	110.773	1127.875	-	0.5938
	Plant PxRS	0.517788	10.6827	120.4714	1127.875	174.27	0.0063