EFFECT OF CULTIVAR ON THE QUALITY OF FLAX AND HEMP GROWN IN SOUTH AFRICA

LANGA SUNSHINE BLOUW

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EFFECT OF CULTIVAR ON THE QUALITY OF FLAX AND HEMP GROWN IN SOUTH AFRICA

By

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EXECUTIVE SUMMARY

Bast fibrous renewable materials, as commercial crops for the manufacture of textile based and other products, have been used for thousands of years to satisfy certain human needs, such as for shelter, clothing, source of energy and tools, and to sustain the livelihood of many communities in countries, such as in Asia, Europe and Africa. Concern for the environment has led to a number of global initiatives that favour the use of natural fibres. It is forecast that the global fibre demand by 2050 will be 130 million tonnes, which the cotton and synthetic fibre production will not be able to meet. Other than the environmental concerns, the renewed global interest in natural fibres, such as flax and hemp, forms part of a strategy to satisfy the fibre demand.

South Africa, notwithstanding the fact that the flax and hemp industries have long been established for thousands of years in Europe, Asia and Egypt (Africa), has no history of the breeding, growing, processing and production of these cash crops. The renewed global interest in these crops has also stimulated interest from South Africa with respect to the development of a flax and hemp fibre industry so as to address some of the socio-economic challenges confronting the country today in its attempts to bring about real development in the rural areas through the cultivation and complete beneficiation of these fibre crops. In this regard, the relevant stakeholders, namely government, research councils, tertiary education institutions, farmers and communities worked together to investigate whether South Africa has the agronomic and climatic conditions, technical expertise as well as the necessary processing and production infrastructure to support the development of a local flax and hemp agro-industry.

The purpose of this study was firstly to evaluate the performance of EU flax and hemp cultivars grown under different agronomic conditions in South Africa, and their effect on straw biomass yield, fibre yield and total fibre yield per hectare as well as associated fibre

properties, and secondly to undertake mechanical fibre modification trials aimed at producing flax and hemp fibres with fibre diameters close to those of cotton. The minimum fibre diameter targeted being 20µm.

In accordance with the project objectives and work plan, selected dew retted flax and hemp straw samples from the various planting sites selected by the Agriculture Research Council – Institute for Industrial Crops, representing all the agronomic conditions under investigation, were taken to the CSIR for fibre extraction and testing. A relatively inexpensive and easy to operate Russian designed and manufactured machine, the CMT-200M breaker-cum-scutcher, was used for fibre extraction and the resultant extracted fibre bundles were further refined, using a steel comb, to obtain optimal fibre separation before their physical and chemical properties were evaluated.

Results obtained in this research study proved that the climatic and agronomic conditions in South Africa were suitable for the cultivation of flax and hemp, notwithstanding the fact that the fibre yields achieved for hemp were lower than the minimum criteria of 23%, and that for flax only just exceeded the 25% minimum. The lack of local technical expertise on the growing and retting of flax and hemp, contributed to the low fibre yields. The planting parameters which were found to produce good results for the cultivation of hemp were the October planting date, using a row spacing of between 12.5 to 25 cm, with a seeding density of between 80 – 100kg, and the application of 50 – 100kg nitrogen fertiliser. The use of extra artificial lighting and herbicide treatment did not appear to beneficially improve the hemp fibre yields. Similar considerations for flax cultivation in the Southern Cape region, particularly Oudtshoorn and Outeniqua, indicated that May to July planting dates, using inter-row spacing of 25cm and sowing density of 63kg seed.ha^{-1}, produced a fibre yield and total fibre yield per hectare above the minimum values of 25% and 0,8 tonnes per hectare, respectively, quoted in the literature.

Results obtained on the mechanical modification (cottonisation) of the flax and hemp fibres confirmed the effectiveness of the Temafa *Linline* fibre processing line (Lomy, Lin-Star opener and cottoniser) in cleaning, opening and shortening the flax and hemp fibres, thereby creating opportunities for their use in various industrial applications. A single passage of scutched fibre through the Lomy, the Linstar opener and finally the Linstar cottoniser, was sufficient to reduce the fibre diameter of scutched flax fibres to below the targeted 20µm, a fibre diameter reduction ranged between 56.3% for light and 60% for grey colour IDC scutched flax, with total waste (impurities) ranging between 11.8% for light and 11% for grey flax, respectively. For hemp 60.1%, 53% and 47.5% reduction in fibre diameter reduction for locally grown scutched hemp, French nonwoven grade and bleached hemp fibres, was achieved and waste being 21%, 18% and 12% respectively, but the fibres did not meet the minimum fibre diameter target of 20µm. The study revealed that the lack of locally available technical expertise in flax and hemp cultivation and farming management practices needed to be addressed if South Africa is to establish an economically sustainable bast fibre agro-industry.

Future work will focus on strengthening research collaboration between the CSIR and ARC-IIC, instead of analysing data after experimental trials are completed, pre-planning of the experiments based on acceptable experimental design, such as Box Behnken; which will not only limit the extent of experimental work but will also facilitate post-experimental analyses to draw meaningful conclusions, will be adopted to address all the gaps identified in this thesis. Also, there will be a continuation of research by the CSIR on the mechanical and biotechnological modification of flax and hemp fibres for the production of tailor-made fibres, e.g. "cotton-like" for application in the technical textiles and natural fibre composite, as well as the extraction of ultimate or single fibres for high end applications.

ACKNOWLEDGEMENTS

The cultivar selection, procurement, testing of the seed viability, planting site selection and soil preparation to carry out all the flax and hemp cultivation field research trials were led and undertaken by the Agriculture Research Council – Institute for Industrial Crops (ARC-IIC) with the participation of enthusiastic community members, and supported by extension officers of the Eastern Cape Department of Rural Development and Agrarian Reform, and the funding support raised by the House of Hemp. The IDC donated 60 tonnes of the scutched and tow flax fibres to the CSIR for research and production development activities. All the fibre extraction, testing and further processing was carried out at the CSIR – Material Science and Manufacturing (MSM) facilities, a premier research institute, based in Port Elizabeth. This research work was done as part of the national government strategy on advanced materials manufacturing, including biocomposites, to enhance the global competitiveness of local industries, under the new Industrial Policy Action Plans (IPAP 2010-2015).

I am grateful to Professors Lawrance Hunter and Rajesh Anandijwala for their invaluable time and guidance while carrying out this research which embraced disciplines spanning from agricultural plant production to textile science. They wholeheartedly supported my endeavors in carrying out this research which could have a direct impact on the development of sustainable rural communities and creation of new agro-industries based on bast fibres. Notwithstanding many challenges, they allowed me the space and freedom to be part of a group of pioneers which implemented the multi helix (government, industry, academia and the community) based approach to innovation. I am equally indebted to the crop scientists for sharing their expertise as well as to the local rural communities for reinforcing in me the deeply held values of humility, patience, hope and the strength of the human spirit in overcoming adversities. Working with such a fantastic team, was a rare privilege and I would do it again.

Many thanks to the technical staff at CSIR for providing me with the necessary support in carrying out various tasks related to this work. It would have been impossible to undertake this without the support from Cecil, Haydon, Steve, Stephen Smuts (retired), Lydia, Nomvula, Linda and Frances. I want to thank Mr Abisha Tembo, our former competency area manager, for his encouragement and full support for my doctoral studies. A special thank you also goes to Ms Vuyo Mahlati, Mr Bahle Sibisi and Mr Laurie Steenkamp, former employees of the Development Bank of South Africa and the Department of Trade and Industry (the dti), for believing in the initiative and lobbying for funds that made it possible to acquire the new bast fibre processing machines used in carrying out this research. Their funding support established our centre as a leading centre on the African continent on natural fibre research and development. A special thanks to Ms Alicia Mooi, an office administrator, for her continued assistance to the programme to establish the bast fibre industry in South Africa.

I wish to acknowledge the role of my friends, whom I refer to as developmental activists, for being so steadfast, and as a collective, in taking upon ourselves the development of our beautiful country and its people. My whole family, the departed and the living, especially my mother (Mary), wife (Phindiwe) and three sons (Bulumko, Ntlakanipho and Nkazimlo), are dearly acknowledged and thanked for their continued support and prayers for me during my doctoral studies. Without your love, encouragement, understanding and sacrifices, it would have been impossible for me to complete my studies.

Lastly, I thank God the Almighty and my ancestors, for all the unconditional love, blessings and their continued guidance to making me a better person and a good global citizen.

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LIST OF ABBREVIATIONS

i.	AD	: Anno Domino
ii.	ANOVA	: Analysis of Variance
iii.	ARC-IIC	: Agriculture Research Council-Institute of Industrial Crops
iv.	ARC-ISCW	: Agriculture Research Council – Institute for Soil, Climate and Water
v.	ASTM	: American Standard Testing Methods
vi.	BC	: Before Christ
vii.	bn	: billion
viii.	CAGR	: Compound Annual Growth Rate
ix.	CBN	: Cannabinol
x.	CHTA	: Canada Hemp Trade Alliance
xi.	CIS	: Commonwealth Independent States
xii.	CMT	: Cut Make Trim
xiii.	CO_2	: Carbon Dioxide
xiv.	CSIR	: Council for Scientific and Industrial Research
xv.	CV	: Coefficient of Variation
xvi.	DAFF	: Department of Agriculture, Fisheries and Forestry
xvii.	DoH	: Department of Health
xviii.	EDD	: Economic Development Department
xix.	EIHA	: European Industrial Hemp Association
xx.	ELV	: End of Life Vehicles
xxi.	EU	: European Union
xxii.	FAO	: Food and Agriculture Organisation
xxiii.	FAOSTAT	: Food and Agriculture Organisation Statistics
xxiv.	GDP	: Gross Domestic Product
xxv.	HEMP-SYS	: Hemp System
xxvi.	HIA	: Hemp Industries Association
xxvii.	HoH	: House of Hemp
xxviii.	IAF	: Institut fűr Angewande Forschung (Institute for Applied Research)
xxix.	IDC	: Industry Development Corporation
xxx.	INF	: Institute of Natural Fibre
xxxi.	IPAP	: Industrial Policy Action Plan

xxxii.	MDG	: Millennium Development Goals
xxxiii.	NFC	: Natural Fibre Composite
xxxiv.	NaOH	: Sodium Hydroxide
xxxv.	OFDA	: Optical Fibre Diameter Analyser
xxxvi.	p.a.	: per annum
xxxvii.	QoQ	: Quarter on Quarter
xxxviii.	R&D	: Research and Development
xxxix.	rpm	: Revolution per Minute
xl.	SADC	: Southern African Development Community
xli.	SEM	: Scanning Electron Microscope
xlii.	sq km / km^2	: square kilometre
xliii.	STEX	: Steam Explosion
xliv.	STATSA	: Statistic South Africa
xlv.	THC	: Tetrahydrocannabinol
xlvi.	UK	: United Kingdom
xlvii.	UN	: United Nations
xlviii.	US / USA	: United States / United States of America
xlix.	YoY	: Year on Year

CHAPTER 1. INTRODUCTION

1. Introduction and outline of the work

Since the use of stone as a tool by early mankind species to meet their basic needs, scientific research and discovery have defined and influenced every aspect of human existence through the development of new tools or technologies. These enabled products for daily use to be produced, leading to further continuous improvement and the optimisation of manufacturing processes, and the product and its quality. The discovery and use of flax as a textile material around 7000 B.C., demonstrated the ingenuity of humankind in the discovery and development of the extraction technology for fibres and their subsequent conversion into twines and establishing a linen manufacturing sector based on flax and hemp, throughout Europe, Asia and Africa during the middle ages. The widespread use of flax and hemp for the production of textile products lasted until the 18th century, when cotton, which was until then relatively little used, was cultivated in the USA, leading to the mass production of cotton at lower prices. The invention of mechanical cotton spinning technology, replacing hand spinning, resulted in cotton replacing flax as the main traded fibre crop in the world, as it provided textiles for nearly all the end uses previously satisfied by flax and hemp, at a cheaper price due to both cheaper raw materials and processing [1]. Production cost and product quantity and market acceptance became the key determinants in the establishment of economically viable enterprises. The discovery of synthetic fibres, such as polyester in the 1950s, with superior fibre properties, notably for the industrial textile sector, further confined the use of flax to a small market share of niche fashion apparel and industrial textiles [2]. Advancements in the development of high-tech synthetic and cotton fibre processing technologies to produce large volumes of differentiated textile products of high quality at a lower price, together with the lack of development of advanced flax processing technologies, resulted in the market dominance of both synthetic and cotton fibres.

Global fibre production is estimated at 82.0 million tonnes, with manmade fibres accounting for 61.3% of production and cotton for 31.2% [3]. The Asian countries, namely China and India, are the leaders in manmade and cotton fibre production, with China having a global market share estimated at 60% in both the sectors. The global textile and clothing industry is estimated to be worth about US$ 360 bn. The US market is the largest, estimated to be growing at 5% per year, and in combination with the EU nations, accounts for 64% of total clothing consumption in the world. The global textile industry is, however, witnessing the sustained migration of textile and clothing manufacturing activity from the developed nations to developing countries.

The decreasing supply of raw materials, environmental considerations as well as wage equalisation, will in the near future pose a serious challenge to Asia's dominance of manmade and cotton textiles. An increase in the world population, and the recovery of global GDP from the recent economic recession, a growing fibre demand per capita, and the limited availability of arable land due to the competition from food crops for food security, water scarcity, and rising crude oil prices and energy costs, are all important factors that will affect the future production and availability of manmade and cotton fibres. It is estimated [4], that the world demand for textile fibres will experience a Compounded Annual Growth Rate (CAGR) of 3% for the next two decades, and that the increasing capacities in synthetic fibres and manmade cellulose fibre production will not fully meet the anticipated shortfall that will come about from the levelling off of world cotton production. It is further estimated that the total global fibre demand will be 140 million tonnes by 2030, and that manmade fibres will only partially satisfy the gap in cotton applications. The expected gap in cotton fibre is estimated at 22 million tonnes by 2030. This anticipated high demand for raw materials, currently serviced by manmade and cotton fibres, is counteracting the move towards a more sustainable future. Therefore, alternative non-cotton natural fibres resources, such as flax and hemp, could contribute significantly to the sustainability of the textile and allied industries [5]. Natural fibres cover a range of vegetable, animal and mineral fibres, Figure 1 shows a classification of widely used natural fibres from plant origin.

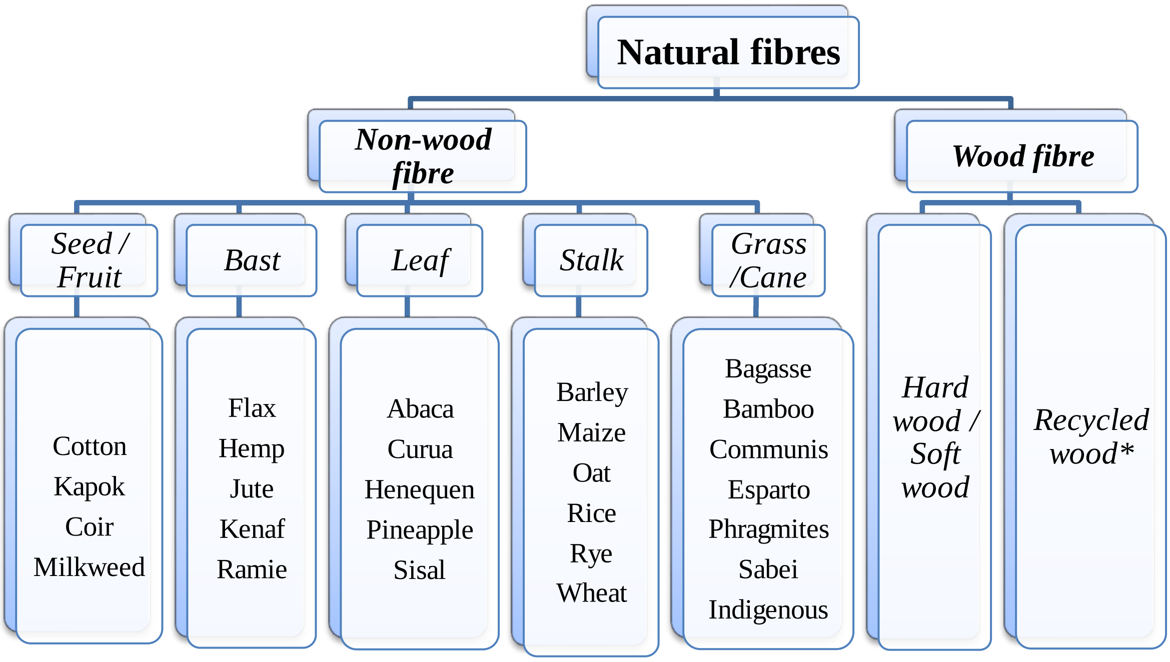

Figure 1. Natural fibres of plant origin [Source: ASTM 07641]
** Recycled wood is derived from tonnes of waste wood and those that were once used as the primary building material. Increase in landfill taxes and haulage cost are the driving force in increase in the amount of waste wood being recycled.*

Natural fibres are a viable choice for textile product development when considering renewable and environmentally acceptable materials. Nevertheless, the wide range of natural fibres and the variation in the physical properties of each fibre makes it difficult to choose the appropriate fibre. Recent advancements in the development of new bast fibre processing technologies and the use of a combination of cultivar breeding techniques and mechanical, chemical and biotechnological approaches in the preparation of fibres with tailor-made properties for various industrial uses, have given the necessary fillip to efforts of establishing a bast fibre industry in various countries, including South Africa.

Other than their potential use in textile product development, natural fibres are increasingly finding application in the lucrative composite sector, driven by increasing environmental awareness. The environmental and performance factors that drive the use of natural fibres in the composite sector are their low cost, low density, acceptable specific properties, ease of separation, enhanced energy recovery, CO_2 neutrality, biodegradability, and recyclable properties, as well as their durability, reliability, lightweight and certain good mechanical properties that are significantly better than those of traditional materials [6]. Figure 2, illustrates those properties that favour the use of natural fibres over their synthetic fibre counterparts.

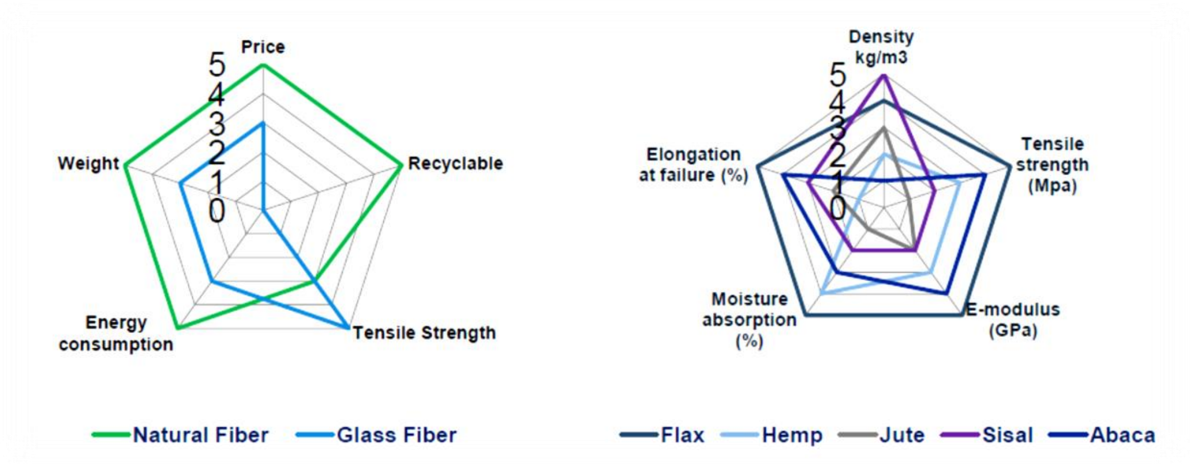

Figure 2. Competitive analysis of natural fibres versus synthetic fibres in composites [6]

In 2010, the total global natural fibre composite material shipments topped some 200 million kilogram, valued at US$289.3 million. It is forecasted that this market will grow to US$531.3 million by 2016, with an 11% compounded growth per year over the next five years [6]. Natural fibre composites (NFC) are used in a variety of markets, such as automotive, construction and electronic components. In the textile sector, nonwoven products are estimated to have a market share of EUR 15 bn, and represent the fastest growing sector, at

7.9% annually [6], with the hygiene, home furnishing, construction and filtration products having a combined estimated share of 82.8% of the total nonwoven products [6].

The combination of two factors, namely the use of natural fibres in the textile sector, e.g. nonwoven and composite production as well as recent achievements made by the global research community in their primary production, i.e., breeding, cultivation, and processing, to produce fibres with specific properties suited for the two areas, are the main driving force that compelled relevant stakeholders (government, research institutes, academia, private sector and communities) in approving a national strategy for the development of the biocomposite sector in South Africa, underpinned by the use of locally grown natural fibres. There is a growing industrial interest in biocomposites in the world, primarily focused on environmental outcomes, such as stringent legislation relating to product recycling and disposal. Research interest in natural fibres has been consistent for well over a decade, resulting in the development of products that have penetrated market sectors, such as textiles, automotive, construction, packaging, renewable energy and general composites production. CSIR is one of the local research and development organizations involved in advancing the local biocomposite strategy based on the development of a number of selected product technology platforms for downstream value addition, as well as strengthening and developing the upstream production of high quality natural fibres and other required raw materials [7]. Product technologies will be prototyped through an industrial scale demonstrator manufacturing facility, with the aim to develop an integrated biocomposite manufacturing industry in the country. An opportunity analysis for South Africa showed that a fully developed local biocomposites industry could result in employment creation estimated at 11000 – 15000 jobs [17] in upstream plant cultivation and fibre extraction/processing, and an additional 2500 – 3000 jobs in downstream manufacturing industries, contributing an estimated R3bn to the SA economy [7].

South Africa, notwithstanding the accolades it is receiving internationally as a stable democratic country, is facing serious challenges, such as high levels of unemployment, underdevelopment in rural areas, and huge inequality gaps between the rich and poor, that undermines the very significant gains achieved to date by the country. The country is regarded as a middle-income, emerging economy, with an abundant supply of natural resources; well-developed financial, legal, communications, energy, and transport sectors; a stock exchange that is the 18th largest in the world; and modern infrastructure supporting a relatively efficient distribution of goods to major urban centres throughout the region. The economy of South Africa is the largest in Africa, with a GDP worth U$ 408.24 bn, an annual growth rate estimated at 2.3%, and inflation expected to be 5.6% for the 2012/13 financial year. Its GDP per capita is estimated at U$3825, with unemployment remaining high at 25.5%, affecting mainly the youth, as a result of both out-dated infrastructure and lack of technical skills amongst the youth, thus constraining growth (see Table 1) [8].

Table 1. SA economic overview [8]

Country	GDP Billion USD	GDP YoY*	GDP QoQ*	Inter-est rate	Inflat-ion rate	Jobless rate	Gov. Budg -et deficit	Debt to GDP	Curr-ent Accoun t deficit	Excha-nge rate R/U$	Popul-ation
South Africa	408	2.30 %	1.20 %	5.00%	5.60%	25.50 %	- 4.80%	38.80 %	-3.30%	8.84	50.59 m

**YoY = Year on Year, QoQ = Quarter on Quarter, m=million*

South Africa has both well-developed and globally competitive commercial agricultural sector as well as subsistence-based and non-competitive farming in the deep rural areas. The country has around 1.2-million square kilometres of land with seven climatic regions - from Mediterranean to subtropical to semi-desert. This huge difference in climate, together with a coastline of 3000 kilometres and seven commercial ports, provide an opportunity for the cultivation and export of a diverse range of agro-based products. The textile industry of South Africa comprises segments; namely fibre production, spinning, weaving, knitting, nonwovens, carpet production and fabric coating. The South African textile and clothing industry plans to utilise all the natural, human and technological resources to make South Africa the preferred region for domestic and international supply of South African manufactured textiles and clothing. With the renewed government support to upgrade the processing and manufacturing technologies used by the local industries, through schemes, such as the competitiveness improvement grant, the local textile production will continue to evolve into a more capital intensive industry, thereby further enhancing the production of manmade textile products. The international recognition of the strength and vibrancy of the local fashion design and the existence of the well-established cut-make-trim (CMT) sub-sectors will play a significant role in ensuring global competitiveness of the local apparel industry. The agro-processing, textile and plastic sectors are the key sectors in the South Africa economy, in terms of employment and contribution to the GDP, and it is estimated that in 2011 they contributed R66.6 bn, R11 bn and R44 bn, in trade-able goods, respectively [9]. The existence of these sectors provides a good foundation on which to establish the natural fibre industry and to apply some of the fibres in existing products without significantly changing the production processes, thereby increasing the biodegradability content of the current products. The development of large-scale commercial cultivation of bast fibres, and their processing, production and manufacturing, will significantly contribute to the establishment of new industries and the associated jobs in both the agro-processing and manufacturing sectors. In this regard, the Industrial Development Corporation (IDC) successfully cultivated flax fibre crops at a commercial pilot, near Brits in the North West Province, producing fibres with properties similar to those of flax fibres grown in the traditional flax growing countries. A linen spinning operation was established at Atlantis, near Cape Town, using imported flax sliver to produce 100% linen yarn by wet spinning, mainly destined for export markets. The lack of a local strategy for the complete beneficiation (short and tow fibre as well as woody core) of the flax crop, made it economically unviable as it focused only on the extraction and use of only long fibres, this was one of the reasons for the discontinuation of the commercial primary cultivation trials by the IDC.

2. Thesis objectives

2.1 Broad objectives

The cultivation and processing of bast fibres, namely flax and hemp, and their use in textiles, represent one of the oldest and the first industrial activity discovered by mankind as early as 7000 B.C. to meet basic human needs, namely food and clothing. Notwithstanding the very old established industrial production process for flax textiles, no associated advancements in fibre processing technologies were made to entrench the dominance of bast fibres in textiles, resulting in their market share dominance being severely diminished by the mass production of cotton and later by manmade fibres, confining bast fibres to a market share of less than 1% of global fibre production. The Kyoto protocol [10], agreed by the community of nations, to drastically reduce the emission of harmful gases released to the atmosphere and the use of high energy intensive production processes, has created a shift towards industries with sustainable production, which involved the selection and the use of environmentally friendly raw material resources and their processing by cleaner production techniques to manufacture textiles [11]. The different fibre processing techniques, such mechanical, chemical and biotechnological, are the subject investigated by numerous R&D organisations resulting in numerous research publications that are, to some extent, covered in the literature review. South Africa has little experience in the cultivation and processing of bast fibres, the only natural fibres grown and processed commercially, to a limited extent, in the country are wool, mohair, cotton and sisal, using totally different technologies for their processing.

This thesis forms part of the broader plan to establish a bast fibre agro-industry in South Africa and is aimed at evaluating the response of European flax and hemp cultivars grown in South Africa under a variety of agronomic conditions and their associated effects on the fibre qualities, to ascertain whether they were comparable to those produced from leading flax and hemp producing countries. In addition, the locally produced flax and hemp fibres were subjected to different mechanical processing treatments to evaluate their potential for producing fibres with the desired properties for subsequent processing on short staple spinning and nonwoven fabric production systems. If these broad objectives could be successfully achieved, they would represent important milestones that could lead towards the full establishment of an economically viable and sustainable bast fibre industry in South Africa.

2.2 Specific objectives

The specific objectives of this research are:

I. To investigate the effect of agronomic parameters on the biomass and fibre yield of European hemp cultivars grown in the Eastern Cape, South Africa.

II. To evaluate the fibre properties of European hemp cultivars grown in the Eastern Cape, South Africa.

III. To investigate the adaptability of European fibre flax (*Linum usitatissimum*) cultivars under South African climatic conditions.

IV. To investigate the cottonisation of flax and hemp fibres by mechanical processing, to produce fibres suitable for processing on short staple spinning and nonwoven systems.

The results of this study could be important to local textile and nonwoven product manufacturers in diversifying their production to incorporate natural fibre based environmentally friendly products without major changes to their existing production set-up.

Material and textile scientists will also benefit from the successful outcome of this study, as it will provide them with a choice of raw material, as well as the opportunities to further explore other fibre treatments that will produce fibres with a unique set of properties which were ideally suited for certain niche applications.

In addition to the above, the research will contribute towards the development of an agro-business model for subsistence farmers in rural areas, to optimally make use of their agricultural land as part of economically viable agro-processing innovation centres based on multiple-crop cultivation approach. This will lead to the creation of new sustainable enterprises and jobs, through optimal productive use of agricultural land.

Based upon the results of this research, recommendations will be made on the best approach, or model, that the country should adopt to ensure that the best agronomic conditions are selected for flax and hemp growing which will produce crops with good fibre yield and quality suitable for various industrial applications leading to new industries and creation of new job opportunities.

CHAPTER 2. LITERATURE REVIEW

2.1 Bast Fibre Overview

Bast fibrous renewable materials, as commercial crops for the manufacture of textile based and other products, have been used for thousands of years to satisfy certain human needs, such as for shelter, clothing, source of energy and tools, and to sustain the livelihood of many communities in various countries, such as in Asia, Europe and Africa [2]. Bast fibres can be grown in moderate climates and need less agricultural input than other natural fibres, such as cotton, to produce high biomass and fibre yields. From the sixteenth to the eighteenth century, flax and hemp were major fibre crops used for the production of fabrics for garments [12]. The emergence in the twentieth century of synthetic materials, derived from fossil based resources, negatively affected the global production and processing of bast fibres. The huge global petrochemical sector sustained by advanced chemical processing technologies ensured advancements in synthetic fibre properties that enabled the mass production of low-cost materials of constant and superior quality and superior properties for various industrial applications, resulting in consumers preferring synthetic products over bast fibre ones. The decline in the fortunes of the bast fibre industry was further compounded by massive reductions in research funding on all aspects of bast fibre beneficiation and the consequent lack in the development of new and advanced bast fibre processing technologies which could compete with those of synthetic materials. Another major reason for the decline in the bast fibre industry was that the world's total production capacity of bast fibres is still largely dependent on small-scale farmers and processors were mainly found in developing countries. To further compound the challenges faced by bast fibre industry is the extent to which it is perceived to be in competition for cultivation land earmarked for food production, the latter being a priority in developing countries [12].

Due to the fact that synthetic materials are derived from a finite resource, are energy intensive during their production and have a negative impact on the environment, and are non-biodegradable when disposed to landfill sites, it was only a matter of time before consensus was reached by various governments and research organisations in the world that urgent steps were necessary to curtail the negative impacts associated with the production, processing and disposal of synthetic materials. The Kyoto Protocol, adopted in 1997 to reduce the 'greenhouse effect' caused by the release of harmful gases into the atmosphere which result in increased global warming, with the potentially devastating effect on our planet, was the first real measure taken by world leaders to restore the atmospheric balance needed to sustain both animal and plant life on earth and entered into force in February 2005 [10]. A total of 195 parties (194 States and 1 regional economic integration organization) ratified the agreement, of which 83 States are the signatories to the Kyoto Protocol (excluding the USA) that commitment to cut their greenhouse gas emissions, such as Carbon Dioxide (CO_2); Hydrofluorocarbons (HFCs); Methane (CH_4); Nitrous oxide (N_2O); Nitrogen triflouride (NF_3); Perfluorocarbons (PFCs) and Sulphur hexafluoride (SF_6) by different percentages relative to 1990 levels, with the exact percentage differing from country to country. The major feature of the Kyoto Protocol is that it sets binding targets for 37 industrialized countries and the European community for reducing greenhouse gas (GHG) emissions [10]. It was realised that if countries do not cut their emissions, it would lead to an ecological and climatic crisis, with devastating consequences to life on earth in all its forms [10]. The Kyoto Protocol is the only legally binding agreement for reducing greenhouse gas emissions worldwide and its first commitment period was between 2008 - 2012. In order to ensure that countries comply with commitments made under the Kyoto Protocol and beyond the first commitment period, the United Nations developed a monitoring and evaluation organisation called the Conference of Parties (COP) to the United Nations Framework Convention on

Climate Change (UNFCCC) - commonly referred to as COP. The COP is the global negotiations platform of all countries aimed at achieving global reductions in Greenhouse Gas (GHG) emissions, which have been scientifically linked to recent changes in climate, specifically rises in global mean temperatures. Major agreements reached under the COP conferences [13-16] to enhance the implementation of the Kyoto Protocol Convention included the following:

- Launching of the comprehensive process to enhance national/international action on mitigation of climate change that is informed by the best available scientific information and supported by the quick deployment, diffusion and transfer of affordable environmentally sound technologies;
- Provision of financial resources and investment to incentivise the implementation of adaptation actions on the basis of sustainable development policies, strategies and actions for both the developed and developing countries;
- That developed countries to provide developing countries with long-term, scaled-up, predictable, new and additional finance, technology, and capacity-building to implement adaptation actions, plans, programmes and projects at local, national, subregional and regional levels aimed at emission reduction;
- Launching of the Green Climate Fund aimed at supporting promoting paradigm shift towards low-emission and climate resilient developed pathways by providing support to developing countries to limit or reduce their GHG emissions; and
- Economic diversification measures taken by countries on their low emission development path depends on their national circumstances;
- Compilation of new international agreements to reduce greenhouse gas emissions which will come into effect in 2020.

Thus, the challenge faced by humanity is to drastically reduce pollution levels and emissions that are harmful to the environment, while simultaneously increasing industrial output to meet the growing needs of an ever increasing population, estimated to reach 11.5 billion by 2050. It has been predicted that there will be a corresponding increase in the demand for fibre (cellulosic, cotton, wool, man-made, others) from approximately 85.9 million tonnes in 2011 to 130 million tonnes per year by 2050 [17]. The market size of 85.0 million tonnes corresponds to an average annual per capita fibre consumption of 12.4 kg fibres. Figure 3 gives a breakdown of the global fibre market in 2011.

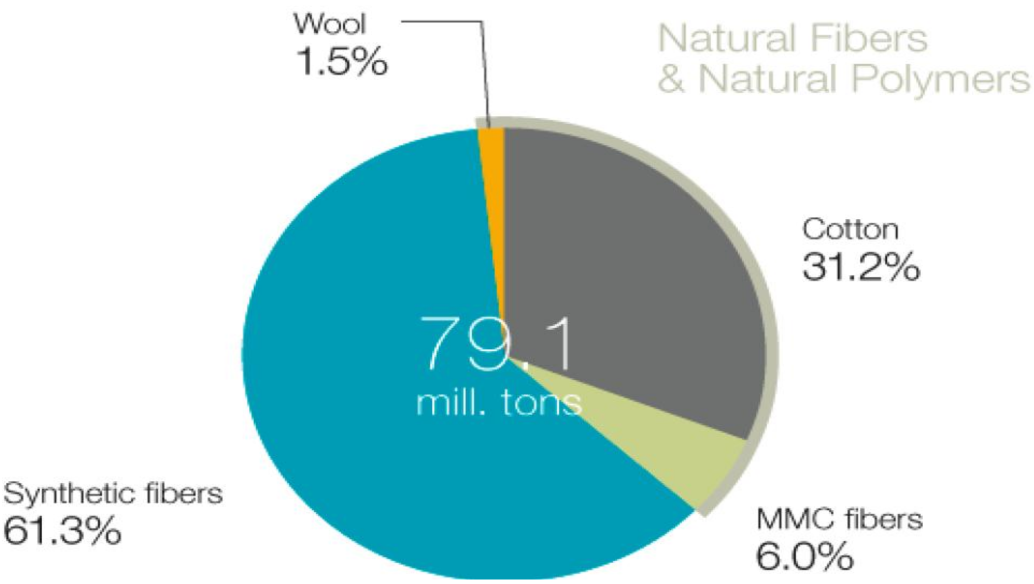

Figure 3. Global fibre market 2011 [Source: The Cellulose Gap. Gherzi, February 2011]

At present, cotton dominates the natural fibre industry and accounts for 80.6% of the worldwide consumption of natural fibres. There is general consensus that current cotton production volumes cannot be doubled to meet the anticipated future market demands for cotton, as water and pesticide requirements for its growing are not environmentally sustainable. These concerns have led to a number of countries embarking on new strategies to investigate the total beneficiation of bast fibre crops, since they are perceived to be more environmentally friendly and sustainable. The passing of tough environmental legislation by many countries to curtail the use of petroleum based synthetic products has renewed interest in the use of natural fibres, for both the manufacture of industrial commodities and niche products with minimal negative impact on the environment. This move towards a bio-based economy and sustainable developments as a consequence of the UNFCCC offers high and new opportunities for natural fibre markets. The inherent benefit on the commercial exploitation of sustainable resources is derived from the potential opportunity of regrowth with an insignificant negative impact on global bio-diversity. These renewable resources are fully bio-convertible and may be reutilised as source for carbon in the form of carbohydrates (sugars), lignin or protein (nitrogen) and minerals. Other reasons for the global acceptance of the increased use of natural fibres relate to their socio-economic benefits, such as social safety, potential for rural economic development (agro-industries), biodegradability, reduction in air pollution and greenhouse gas effects [18, 19].

Regulations on waste disposal and land fill taxes, sweeping legislations in Europe and other countries on plastic products to balance their cost of disposal, have played a significant role in elevating the status of bast fibre crops in industrial applications [20]. These concerns for the environment have led to a number of global initiatives that favour the use of natural fibres.

2.1.1 Morphological Structure

The plant fibre crops that produce bast fibres, i.e. fibres derived from beneath the bark of the plant stalk / stem embedded between the cortex and phloem, include hemp, flax, jute, kenaf, ramie and tobacco. An inventor by the name of Suzanne M. Devall filed a US patent, US20110287681, on 19 May 2010 entitled “Textiles and Process for Making Textiles and Dyes from Tobacco Plants”, in which it is described a process that allows the use of a tobacco plant that is primarily only utilized presently to produce harmful tobacco products and encourages use of that plant for dyes, textiles, essential oils and other non-harmful products [21]. The fibres in the bast plant are found within the inner bark of the stem/stalk of the plant and in the woody core which necessitates a different way of extracting and processing the fibres, to those used, for example, for cotton. The hemicellulose content of these fibres contributes to the properties of breathability and thermal insulation, both of which are excellent features in textiles [22]. Figure 4 shows a cross-section of a flax fibre stalk in different stages of plant maturity, illustrating where fibres are located in the stem [23, 24].

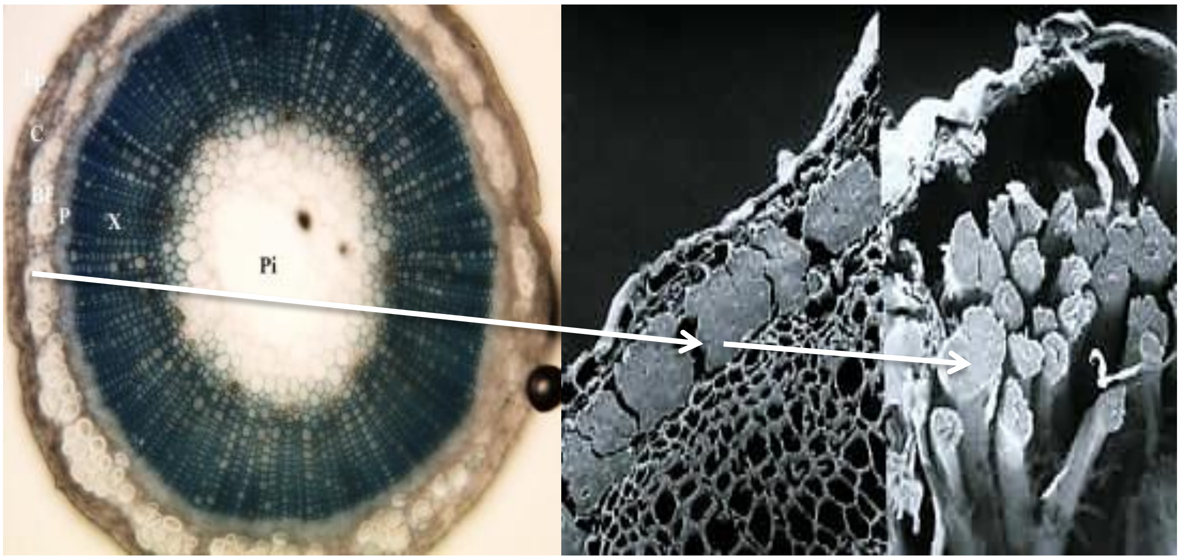

Figure 4. Cross-sections of bast fibres depicting the location of fibres (indicated by white arrow) on plants of different ages, from immature (left), mature and retted (right)[23, 24].
[Ep = epidermis; C = cortex; BF =bast fibres; P =phloem; X =xylem; Pi =pith]

Like any natural agricultural material, bast fibres are inherently variable, within the plant, between plants and between crops, which has a direct effect on the fibre properties and their processing. Climatic conditions, growing site, crop harvesting date, plant maturity and the degree of retting all directly influence the dimensional and mechanical properties of the fibres, and thus affect product properties and application [25].

2.1.2 Flax and hemp stalk pre-treatment processes

The fibres in the flax and hemp stalk occur in the form of bundles or strands on the woody core and act as natural reinforcing elements which help the plant to remain rigid. Matured flax and hemp plants are harvested and subjected to a retting process (dew, water and biotechnological) that aid in the release or loosening of the fibre strands from the plant tissue matrix. These are post-harvesting processes that last between 2 to 6 weeks, whereby either natural bacteria or chemicals are used to break down the fibre binding pectins, and to separate the bast fibre bundles from the inner woody core (shives) [26]. Dew, water, enzymatic or chemical and flash hydrolysis are some of the retting techniques used to loosen the fibre strands from the stalk and which have an effect on fibre properties, such as strength and fineness. The different retting processes are briefly discussed below:

- In <u>*field*</u> or <u>*dew retting*</u> (Figure 5), the plant stems are pulled (flax) or cut (hemp) and left in the field to undergo controlled retting process under human supervision. Pulled flax straws are spread in uniformed layer of rows on the field and are exposed to climatic conditions (dew, rain, wing and sunlight) for several weeks in which during this time the saprophytic fungi found in the soil, such as *Cladosporium herbarum, Mucor stolonifer, Mucor hiemalis, Mucor plumbeus, Aspergillus niger, Fusarium culmorum, Epicoccum nigrum* and *Rhizopus* sp. [27- 29], act on the straw, through microbial action, resulting in change of colour from a golden / yellow and green colours for the newly harvested flax and hemp straws, respectively, to gray (well retted) colour depicting progress in the retting degree process. Constant turning of flax and hemp straw during the retting period ensures that stems are evenly retted.

Figure 5. Field retting of flax and hemp straw [Source: Institute of Natural Fibre and Medicinal Plants, Poland][30]

Constant monitoring of the field retting process by growers is very important to ensure optimum retting and avoid under-or-over retting which would result in poor fibre quality. Correct climatic conditions, such as moisture, humidity and temperature, are necessary to optimise microbial actions which break down the lignin substance binding the fibre strands together and constituents of the middle middle lamella, thereby facilitating ease in separation of fibre strand. This retting method produces strong fibres that are greyish in colour. Dew retting is common in Europe, due to its low cost, and objections against the pollution caused by water retting, the process takes between 3-6 weeks to complete, depending on favourable climatic conditions. The absence of total control of the microbial action of the saprophytic fungi to uniformly breakdown the lignin and components of the middle lamella is the causal effect of variation in mechanical fibre properties across the length of the fibres and in-between the fibres [30].

- The ***water retting*** (Figure 6) process yields fibres of higher and less variability quality than dew retting. It is a labour intensive process using large volumes of water which has a negative environmental impact if not properly treated prior discharging. Stems are immersed in water (rivers, ponds, or tanks) and monitored frequently to produce fibre of high quality, by avoiding straw/stem under-or-over retting occurring.

Figure 6. Water retting of hemp in Yugoslavia [Source: Courtesy of Dr. J. Berenji, Institute of Field and Vegetable Crops, Novi Sad.]

It takes 2-4 weeks before the process is complete. If water retting takes place in tanks, there is a need to treat the water effluent before discharging it to the environment. Only a few bast fibre producing countries [China, Bulgaria and Egypt] use the water retting process due to environmental legislations, such as the water footprint (high pollution) of the bast product, and expensive labour rates. According to Allen, it is spore forming organisms that are responsible for water retting [31]. Light coloured and non-stained fibres are produced by this process. The fibres produced by water retting are characterised by a specific unpleasant smell which is due to the absorption of acids [32].

- *Enzymatic* or *chemical retting* (Figure 7) shortens the retting process and has a direct effect on the strength and colour of the fibres produced. Stalks are immersed in tanks containing solutions consisting of mixtures of enzymes or chemicals. Van Sumere at the behest of the Belgian Flax Association started with the flax retting trials using enzymes produced by *Aspergillus niger* [33]. All the enzyme mixtures involve cellulase, pectinase / polygalacturonase and hemicellulase activities, which cause the degradation of cellulose, pectin and hemicellulose, resulting in the loosening of the fibres. A typical feature of enzymes is their selectivity. Enzyme biocatalysis works in low concentration and is characterised by the mild conditions of the process (temperature, pH, humidity).

Figure 7. Enzymatic/ chemical retting [Source: Institute of Natural Fibres and Medicinal Plants, Poland][30]

Flax straw are immersed in a container containing a solution of endopolygalacturonase pectinases, cellulases and hemicellulases under controlled temperature for a specific time period before they are withdrawn and excess enzymes are washed off or denatured to stop enzyme activities that can cause damage to the cellulose [33, 34].

Enzymatic catalysis selectively focuses on the specific substrate composition. It eliminates the risk of treated substrate damage, thus opening the door for specific technological effects and process unification [35]. The use of enzyme for retting of flax and hemp is still under development phase with some commercial products on flax retting using enzymes already available in the market. Flaxzyme, a mixed-enzyme commercial product of Novo Nordisk from *Aspergillus* sp., was developed earlier and was reported to produce fibers with good yield and quality [36].

In chemical retting, a solution of chemicals, such as sodium hydroxide, sodium carbonate, soaps, and or mineral acids, are used to loosen the fibres within a few hours, but close control is required to prevent fibre weakening due to the harsh nature of the chemical treatments [37, 38]. Drying is necessary to prevent further fermentation and fibre degradation. Both processes are expensive, adversely affecting fibre price and industry viability.

- The *flash hydrolysis* (steam explosion) fibre loosening process is adopted from a technique used in the paper industry that produces finer and shorter fibres, with a lower content of non-cellulosic material. This hydrothermal pre-treatment method subjects the material to high pressures and temperatures for a short duration of time after which it rapidly depressurizes the system, disrupting the structure of the fibrils. Figure 8 shows a simple illustration of the steam explosion pre-treatment for bast fibre separation [39].

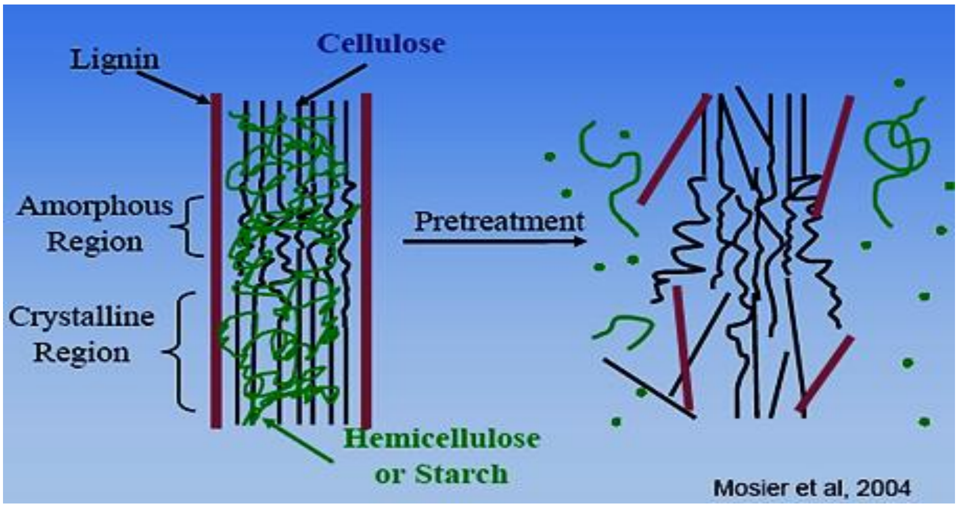

Figure 8. Illustration of steam explosion pre-treatment of bast fibres [39]

In 1986, the Institute of Applied Research in Reutlingen (IAF) in Germany undertook experiments involving the use of steam explosion (STEX) to produce short staple linen fibres that could be processed on a highly productive cotton line in blends with other fibres. This treatment was aimed at hydrolysing (through the steam explosion of the bast straw subjected to saturated steam in a decompressed reaction chamber) the plant cement matrix of the lamella which combines the elementary fibres in technical or vascular bundles. Stalks, pre-treated with NaOH, are immersed in a reaction chamber in which they are subjected to a water vapour treatment at temperatures as high as 200^{0}C or even higher, for a specified time to penetrate the bark of the straw. Strict monitoring of the process is required to limit the degradation in which prolonged stalk treatment would have on the fibres. The process involves four critical and interconnected **phases**, namely; **penetration**, **degumming**, **fibrillation** and **cellulose decomposition**.

This process, like in the paper industry, produces only short staple fibres that can only be used in textiles and technical composites [40, 41]. Steam explosion technology enables the production of special fibres which can be modified according to products or test requirements. Through the adaptation of the process engineering, "tailor-made" fibres can be manufactured, which, for example, can be spun into new types of hemp yarn in cotton spinning. The same applies to the production of special fibres for use in the wool industry (worsted or woolen spinning yarns), or for specific technical uses such as non-woven fabrics, filter elements etc [42].

- The *osmotic degumming* technique (Figure 9) has been investigated by researchers at the Institute of Natural Fibres and Medicinal Plants in Poznan, Poland for the separation of fibres in bast plants, their research leading to the development of a pilot plant.

Figure 9. Pilot scale plant for the osmotic degumming of bast fibres
[Source:Institute of Natural Fibres and Medicinal Plants, Poland][44]

The osmotic degumming method is based on natural physical laws of water diffusion, osmosis and osmotic pressure occurring inside the fibrous plants when they are immersed in water, enabling the easy extraction of fibres without affecting their natural characteristics [43]. Flax and hemp stems are placed in a tank and flooded with water of 15^0C in amount ten-fold exceeding the amount of stems. The leaching process is carried out in continuously flowing water and depends on liquor reaction reduction to pH 5. The degree of retting is determined organoleptically and monitored throughout the whole process. When the straw is degummed, the process is considered completed [44]. Next, the water is removed; straw is pressed to remove excess water, dried and fibre extracted mechanically. Research conducted by Konczewicz and Kozlowski [44] reported the production of fibres of high quality, and established that the temperature and time of osmotic degumming as having an influence in the quality of fibre. They obtained the best results with the degumming temperatures of between 30 and 40^0C and degumming times of between 72 and 96 hours. Figure 9 shows the osmotic degumming pilot plant developed by the Institute of Natural Fibres and Medicinal Plants in Poznan, Poland [30].

2.1.3 Fibre extraction and primary processing technologies

After retting, stalks / stems are mechanically processed to break the woody core, followed by combing processes that ultimately release the fibres from the stalk. This involves a multistep production process, designed to handle the input material of retted straw, to produce fibre as output material which are then processed further through secondary mechanical processes for various industrial applications, and woody core (hurds or shives) and tow as by waste material. Figure 10 illustrates the differentiated product routes possible in the bast fibre beneficiation, achieved by the use of different processing technologies optimised according to the specific target values [45].

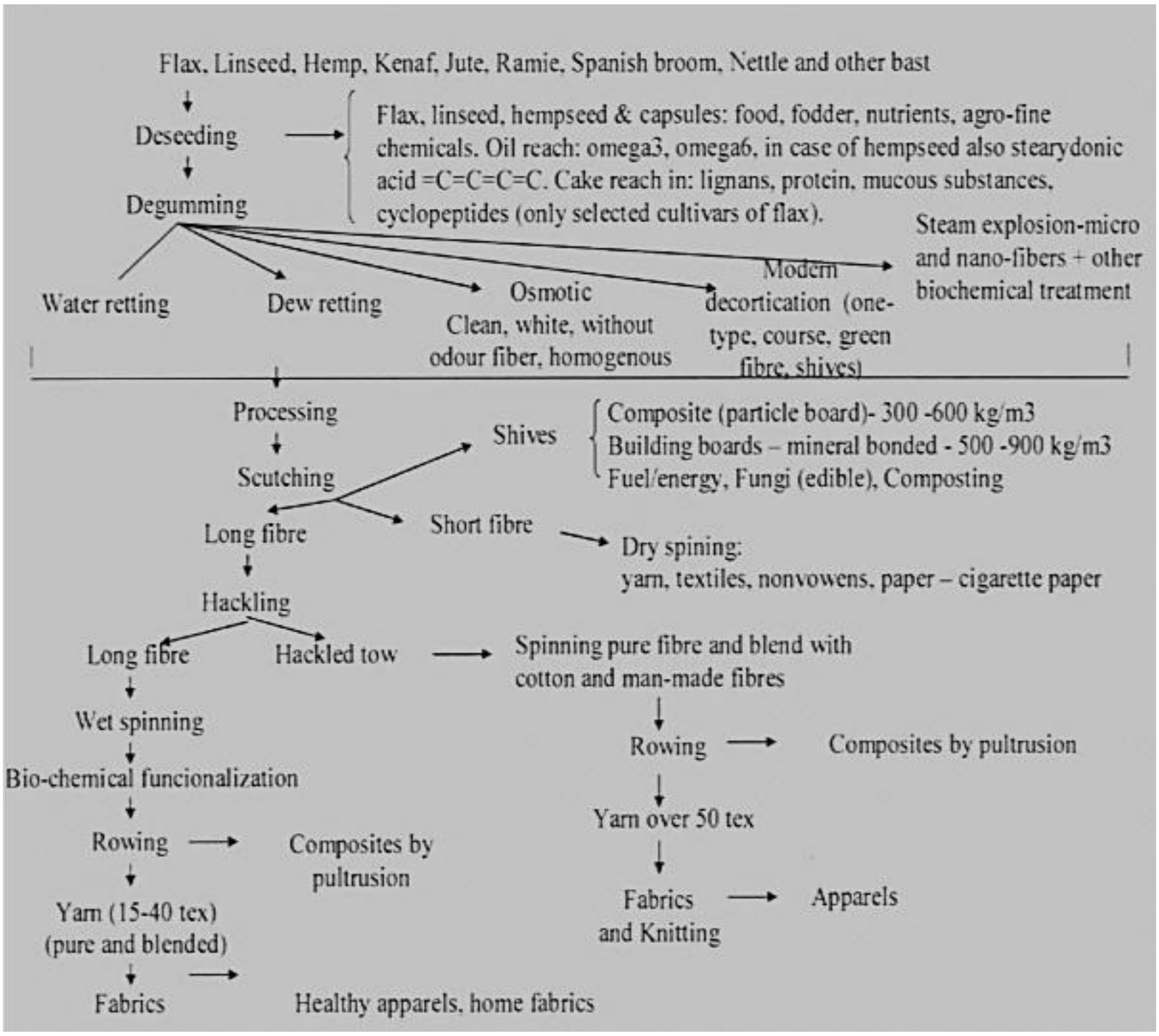

Figure 10. "Road map" of bast fibrous plant processing [45]

The stem of bast fibre producing plants consists of two main components, namely the soft bast fibres located in the stem tissues outside the vascular cambium and the stem tissues inside the vascular cambium containing the hard woody core, as previously shown in Figure 4. After the completion of the retting process, the well retted stalks are generally dried, baled and delivered to a centralised locality for processing. Certain countries, such as China, use a combination of fibre extraction techniques which involves the use of the decorticator to mechanically extract fibres as well as the use of labour intensive practices, whereby the fibre is separated from retted stalks by the use of hands resulting in the creation of considerable employment opportunities for people living in rural areas. With mechanical separation, stalks are passed between fluted rollers to crush and break the woody core into short pieces (called shives) and this activity is known as **breaking** and is followed by a **scutching** process. Scutching is the mechanical beating process in which the broken stalk is subjected to a beating action from the two swinging rotor blades (turbines) rotating in opposite directions for the complete removal of broken shives, releasing long and short fibres (tow) in the process. The machine that combines the breaking and scutching processes is called the decorticator or decortication line [46]. Figure 11 gives a diagrammatic representation and photograph of a flax fibre decortication line.

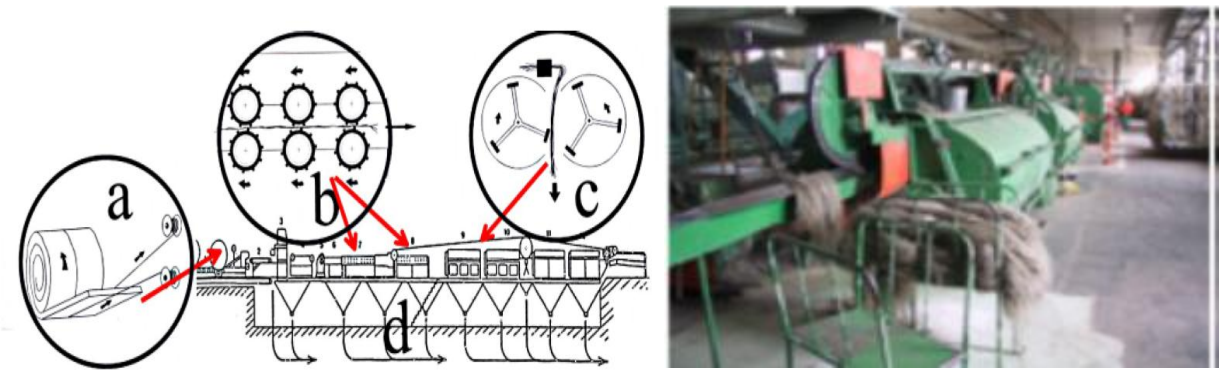

Figure 11. Illustration and photo of the decortication of retted bast stalk, a = retted straw, b=retted stalk breaker, c= scutching , d= decortication and scutching line [Source: Van Dommele, www.vandommele.be]

On the decortication line, the bast fibre stems are transported, pressed in-between two conveyor belts, through the two mechanical fibre separation processes. The parallel-orientated direction of the detached and scutched bast fibres is kept unchanged throughout the process. The clean long fibre, called longitudinal flax or hemp fibres, produced by the process is collected and sorted manually into grades according to quality, length of fibre and colour. The tow, called disordered flax or hemp fibres, and shives drop onto the conveyor under the decortication line for collection and further processing. This type of decortication line is primarily used to produce long fibres for use in subsequent wet spinning processes for the production of yarns.

The scutched bast long fibres are still in the form of very coarse fibre bundles which contain impurities and are held together by hemicellulose and remnants of pectin. These fibre bundles consist of the ultimate fibres joined together by non-cellulosic materials. For the subsequent wet spinning process, the long fibre bundles undergo mechanical pre-treatment, known as hackling, a stepwise fibre bundle combing process having the following objectives:

- To disentangle and straighten the fibres,
- To separate the fibre bundles, without destroying the fibre length, and
- To clean the fibres.

Pinned sheets on the hackling machine split the fibre bundles and, through a meticulous combing action, produce parallelised fine fibres. The hackled fibres produced are supplied to wet spinners for the production of pure and blended linen yarns [47].

In recent years, a new generation of bast fibre extraction technologies have been developed in which both retted and unretted bast stalks are processed to produce only 100% short fibres and shives. The short fibres are used in the manufacturing of various textile products, such as in nonwovens and dry spinning, as well as in the production of high value added products, like natural fibre reinforced composites. Figure 12 shows a photo of *Temafa LinLine* [48], as an example of one machine manufacturers' involvement in the development of short fibre production technologies from bast fibre crops.

Figure 12. Temafa short bast fibre processing line [48].

New developments in short bast fibre processing technologies were triggered in the early 1980s by renewed interest from different research institutions and lobby organisations across Europe for the development of alternative renewable resources. Funding was made available to research institutes across Europe to undertake research and development in the field of bast fibres, especially flax and hemp, with a focus on cultivar breeding and plant genetic resources, extraction and processing, biology and biotechnology, economics and marketing, quality and non-textile application that culminated in the establishment of networks or associations to advance the cause of natural fibres, and bast fibres in particular [49, 50]. Kessler *et al* [51], noted that, for the development of a sustainable natural fibre industry, a systematic approach was needed in which a greater co-operation should exist between the grower, fibre producers (processors) and product manufacturers, for novel applications of natural fibres. This institutional co-operation was necessary to ensure the constant supply of high quality fibres for the production of niche products acceptable to the consumers. The objective of fibre preparation was the production of natural fibres with near perfect tailor-made fibre qualities for specific application and to continuously supply fibres that conform to universally accepted standards [52-55], similar to those of man-made fibres.

2.1.4 Bast fibre characteristics

Natural bast fibres tend to be relatively non uniform and inconsistent [56, 24], due to individual plant variations, geographical differences in climate, soil, disease etc., as well as differences in processing batches within and between mills. This inherent inhomogeneity or variation between and along the length of flax and hemp fibres, compounded by a lack of advancement in fibre separation technologies to produce ultimate fibres, pose the greatest challenge to the use of these fibres in the development of high value niche products [24]. Obstacles include the lack of universally accepted standard methods for determining fibre characteristics, such as those for cotton fibres, in all the critical stages of production and processing, where plant and fibre quality can be improved, as well as being able to accurately characterise and classify each fibre lot in relation to its end-use. Furthermore, there are many and diverse technical applications for both hemp and flax fibres, resulting in a variety of demands on fibre quality. Smeder and Liljedahl [57], identified the following classification of key fibre properties for flax, as a foundation towards the development of standard methods for bast fibre crops:

- Fundamental properties (e.g. health aspects, biodegradability, recyclability, renewable resource, preservation of open landscapes, cultural image),
- Performance (overall quality and secondary effects on the end product),
- Functional properties (structure, absorbency, insulation, fire resistance, reinforcement),
- Secondary effects (other than desired effects of using the fibre) and
- Fibre properties (physical and chemical properties of the raw material; strength, dimensions and composition).

The fibre properties identified as most important for technical application include fibre length, diameter and strength, and some of the quality parameters important in the textile industry, namely fineness, uniformity, strength and elasticity, also being among the most desired fibre characteristics for non-textile products [57]. Other than the ASTM standard methods developed for flax [52-55], researchers at the Institute of Natural Fibres and Medicinal Plants [INF] in Poland developed a standard method framework for the measurement of key properties at all the critical stages in bast fibre production and processing for various end-uses, as illustrated in Figure 13 [58].

Name of Process	***Raw Material***	**Product Name** ***Derivative Products***	**Standard No.**
Breeding Cultivation	Seeds	For sowing	PN-R-65023:1978
		Technical	
		Foodstuffs, pharmaceuticals, household	
		Chemicals	
Retting	Straw	Raw	BN-76/7511-08
		Retted	BN-76/7511-09
Breaking Scutching Hackling Carding	Fibre	Long hackled	BN-76/7522-03
		Long scutched	BN-76/7522-03
		Long teamed	BN-76/7522-05
		Short, matted scutched waste fibre	BN-76/7522-04
		Noils	BN-76/7522-04
		Green	BN-76/7511-12
Spinning	Yarn	Raw	BN-85/7521-01
		Carding	BN-86/7521-09
Weaving Improvement	Apparel fabrics	Apparel	PN-P-82450.05:1986
		Shirt	PN-P-82450.02:1986
		Skirt	PN-P-82450.06:1986
	Tablecloth fabrics	Tablecloth	PN-P-82450.9:1996
		Dishcloth	PN-P-82450.10:1986
	Household fabrics	Towel	PN-P-82450.03:1986
		Sheet	PN-P-82450.4:1996
	Decorative fabrics	Curtain and other	PN-P-82450.7:1996
	Technical fabrics	Desk chair and other	PN-P-82450.08:1986
Twisting Knitting	Other technical Products	Threads	PN-P-81101/01:1990
		Ropes	PN-P-85013:1990
		Twines	PN-P-85019:1988
		Fibre hoses	PN-M-51151:1987
		Binder string	BN-54/7596.05
		Nets and others	PN-ISO 1805:1994
By-Products			
De-seeding	Panicles & Leaves	Narcotics	
		Tea	
		Fodder	
Breaking	Shives	Raw material for particleboard	PN-P-80102:1996
		Fuels	
		Fillers	
Cottonisation	Short fibres	Cottonised fibres	ZN-67/MPL.05.032

Figure 13. Illustration of bast plant production and processing standard methods developed at INF [58].

Danny E. Akin working at the Quality Assessment Research Unit, Russell Research Center of the Agricultural Research Service, U.S. Department of Agriculture, is one of the leading experts involved in research in developing standard methods for flax [24]. Also, Drieling et al [59] published a paper on an objective and reliable method for measuring bast fibre physical properties in which they recommended the use of various techniques for use in bast fibre analysis. The techniques include the measurement of fibre strength, fineness and length. The European Commission funded research work, undertaken by a team of researchers from Germany and Italy, to develop an "*innovation production system for hemp fibre for textile destinations: from laboratory results to industrial validations"*, called the HEMP-SYS, to identify and address the problems hampering the production of hemp fibre for textiles in Europe. Their research results led to the following conclusions [60]:

- The semi-industrial validation of the innovative production chain developed within the HempSys Project proved that each processing step of this system is technically feasible, and hackled fibre, suitable for spinning, can be obtained in quantities comparable, or superior, to what can be produced with traditional and other innovative production systems.
- Maximisation of fibre yield can be obtained with a relatively low hemp plant density (120 plants per square metre) and harvesting at full flowering.
- Preliminary results of quality determination on the hackled hemp fibre show that increased homogeneity of quality cannot be obtained by keeping separate the fibre obtained from the bottom to those obtained from the top stem portions, and this will simplify the logistics of hemp stems and fibre handling [60].

2.1.4.1 Physical and chemical properties of bast fibres

Bast fibre characteristics, ease of extraction, processability and product manufacturing are directly related to the chemical composition hierarchy of the fibre. Figure 14 illustrates the complex layered structures of bonded ultimate fibres making up the fibre bundles which comprise hollow cellulose fibrils held together by lignin [61]. It consists of primary and secondary walls with a thick middle layer which play a key role in determining the mechanical fibre properties.

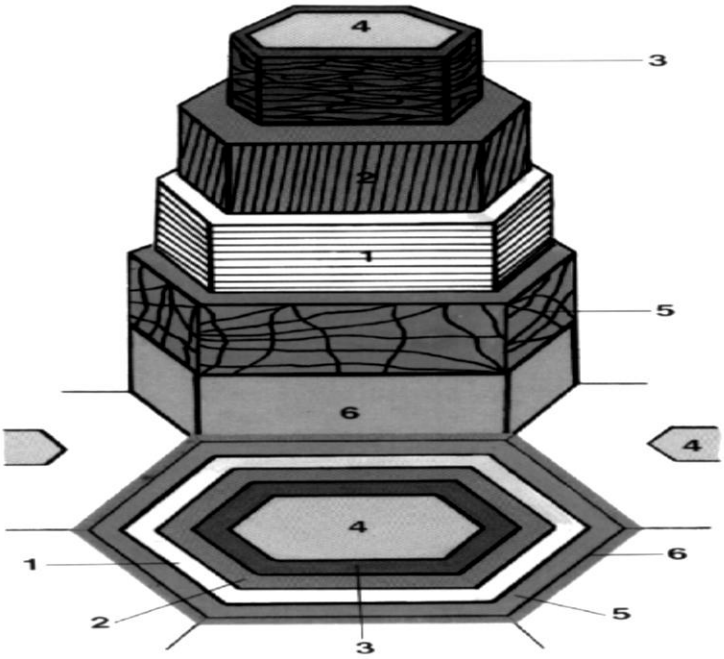

Figure 14. Wall structure of a fibre seen in transverse (bottom) and three-dimensional view (top). Secondary wall (1-3, three different layers with differently orientated cellulose microfibrils), dead lumen (4), primary wall (5) and middle lamella (6)[61].

The natural fibres comprise the main components, such as cellulose, hemicellulose and pectin, in which the hemicellulose is thought to provide the structure to the fibre, as well as waxes. Cellulose is the most important organic compound produced by plants and the most abundant in the biosphere, consisting of glucose units linked together in long chains, which in turn are linked together in bundles called microfibrils. Hemicelluloses are polysaccharides bonded together in relatively short, branching chains, providing hydrophilic properties, and are found in all plant fibres. Lignin is the compound which gives rigidity to the plant, without which the plants could not attain great heights (e.g., trees) or the rigidity found in some annual crops with the least affinity for water. Tables 2 & 3, compare the chemical composition and physical properties flax and hemp fibre bundles and single fibres, respectively [62- 64]. The fibre chemical composition percentage is influenced by flax and hemp agrotechnology which entails the methods or machinery needed for efficient production of the two fibre crops, the harvest time and method of fibre degumming.

Table 2. Comparison of flax and hemp fibre chemical composition [Source: 62- 64]

Fibre type	Cellulose (mass %)	Hemicellulose (mass %)	Lignin (mass %)	Waxes (mass %)
Flax bundle	71	18.6 – 20.6	2.2	1.5
Hemp bundle	68	15	10	0.8
Flax single fibre	64.1	12	2	1.5
Hemp single fibre	68.1	15.1	10.6	-

The technical bast fibre (or bundles of elementary fibres) is made up of overlapping single fibres across the fibre length, bonded together to the middle lamella, which consists mainly of pectin and hemicellulose.

Table 3. Physical properties of flax and hemp fibres [Source: 62- 64].

Fibre type	Tensile Strength in MPa	Young's Modulus in GPa	Elongation at break (%)	Density in (g/cm^3)
Flax	345 – 1035	27.6	2.7 – 3.2	1.5
Hemp	690	70	1.6	1.48

There are variations in the chemical composition and physical properties of both flax and hemp fibres given in the literature, some examples being given below:

- Flax fibre cellulose content ranges between 64.1 and 78.5 %, lignin content between 2 and 8.5 %, and elongation at break between 1.2 and 3.2% [47].
- Hemp fibre lignin content values quoted vary between 10 and 10.6%

The amount of lignin is known to increase at the end of the plant growing period, hence the amount of lignin depends on the crop harvesting time. The discrepancy in the figures for both the physical and chemical properties of bast fibres, quoted by various authors, can be ascribed to the variations due to cultivar type, growing conditions, retting and processing as well as testing conditions.

The combined effects of the three main chemical components of bast fibre plants impart unique fibre properties [65], the most important being:

- **Very good strength**, especially tensile strength. In relation to their weight, bast fibres can attain strengths of between 0.5 – 0.6 N/tex.
- **Very good heat, sound and electrical insulation**
- **Combustibility**. From a waste point of view, combustibility is an advantage. Products can be disposed of through burning at the end of their useful service lives and energy can simultaneously be generated in the process.
- **Biodegradability**. As a result of their tendency to absorb water, fibres will biodegrade under certain circumstances, through the actions of fungi and/or bacteria.
- **Dimensional stability**. As a consequence of the hygroscopicity of the fibres, products and materials based on plant fibres are not dimensionally stable under changing moisture conditions. This can be a serious disadvantage to the industrial use of plant fibres. However, if necessary, this may be controlled at an extra cost by a number of known treatments (e.g., heat treatments or chemical modification procedures, such as acetylation).

- **Reactivity**. The hydroxyl groups present in the cell wall constituents, not only provide sites for water absorption but are also available for chemical modification (e.g., to introduce dimensional stability, durability, or improved oil/heavy metal absorption properties).

The careful technical, mechanical and biotechnological modification of the above mentioned properties (singularly or in combination), is aimed at improving the quality of the fibre, in particular with respect to fibre fineness (total fibre surface area) and surface cleanliness, in order to make them better suited for added value applications in the following three industrial categories :

- Textile Applications (clothing),
- Nonwovens, and
- Technical Textiles

Figure 15 lists a selection of textile and non-textile products and their added value. As can be seen from the graph, textile products usually show higher mass potential and added value than technical applications [50].

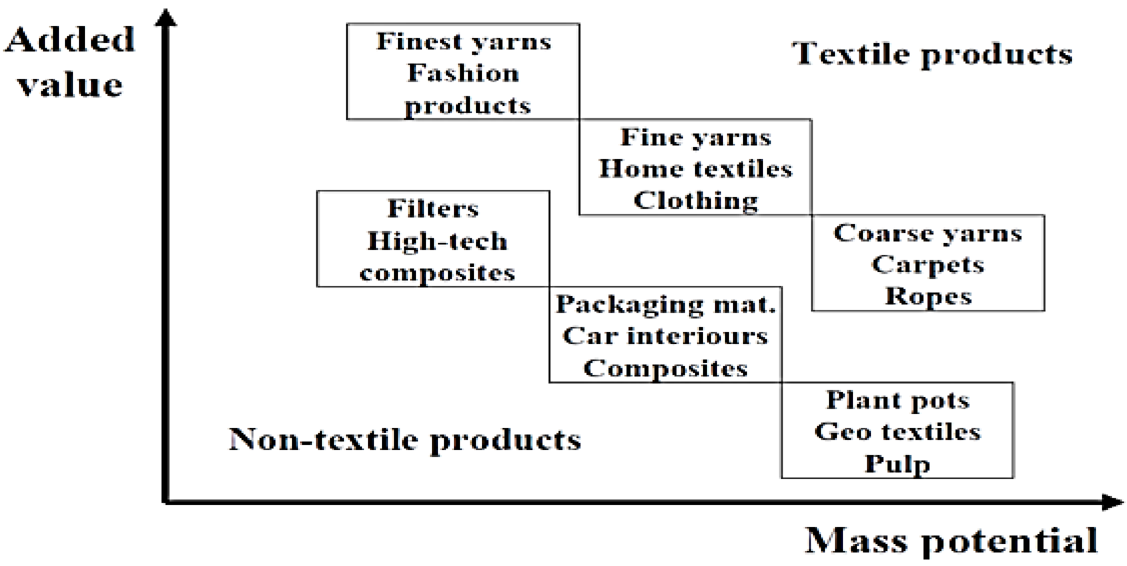

Figure 15: Added value versus mass potential of bast fibre products [50]

2.1.5 Flax and hemp opportunities in various market segments

Flax and hemp fibres are used in a wide range of industrial products, including yarn, textile and fabric; pulp and paper; carpeting, home furnishings; building, construction and insulation materials; mass transportation (automotive, aerospace, rail freight) and composites. The woody-core (shives / hurds) is used in various applications, such as animal bedding, raw material inputs, low-quality paper and composites (e.g. fibre particle density boards). The seed and oilcake are rich in protein, and all the constituent essential amino-acids, as well as omega (3&6) oils, are used in a range of foods and beverages, and can be an alternative food protein source. Oil from the crushed hemp seed is an ingredient in a range of body-care products and also used as nutritional supplements. Hemp seed oil is used for industrial oils, cosmetics and personal care and pharmaceutical applications.

Tables 4 & 5 illustrate the market prices of raw scutched flax fibres and by-products in the EU and the EU bast (flax and hemp) fibre markets, respectively [66].

Table 4. Market prices of raw scutched flax fibres and by-products in the EU [66].

Scutched fibre type and by-product	Quality	Prices in Euro/100kg
Long fibre	Lower	100 – 130
	Medium	130 – 165
	Good	165 – 200
Short fibre	Lower	up to 15.00
	Medium	15.00 – 20.00
	Good	20.00 upwards
By-product	wasted parts of straw	up to 4.00
	by-products from deseeding	2.48
	short scutched fibre waste	8.50
	shives for particle board production	7.50

Table 5. EU flax and hemp fibre markets (2010)[66].

Application and Bast Fibre Type	Total amount consumed / tonnes	Revenue / Million €
A] Textiles		
• Long (line) fibre flax	115 000	183.0
• Short (tow) fibre flax	29 000	10.0
B] Special & Technical Paper		
• Short (tow) fibre flax	25 000	7.5
• Hemp	21 000	7.8
C] Nonwovens		
• Short (tow) fibre flax	2 000	1.0
• Hemp	2 000	1.0
D] Composites		
• Short (tow) flax fibre	17 000	8.5
• Hemp	4 000	2.0
Total	**215 000**	**220.8**

Figure 16, show the flax and hemp price index for the technical short fibres from the European Industrial Hemp Association [67].

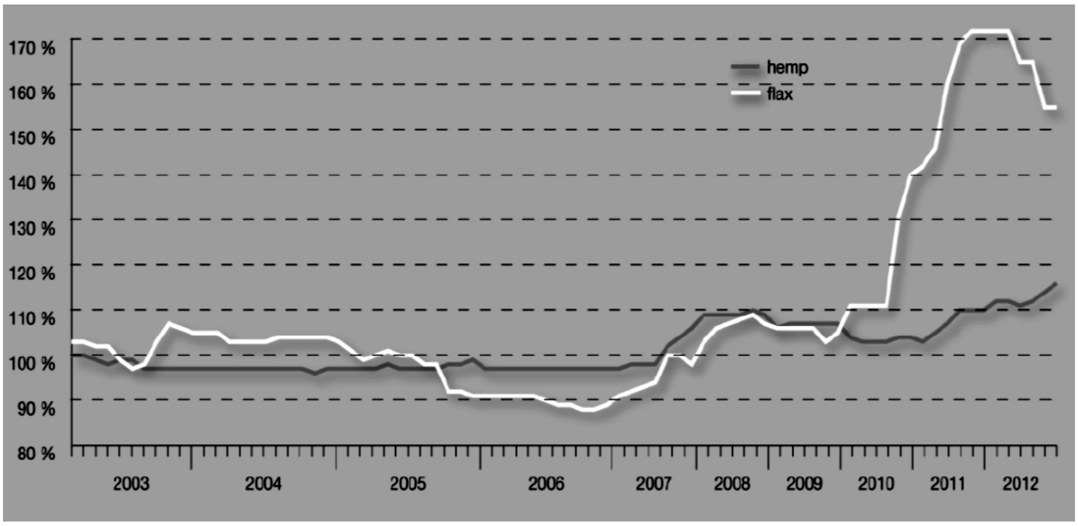

Figure 16. Relative price development for hemp and flax technical short fibres from European production 2003 – 2013(Source: nova 2013) [67].

2.1.5.1 Textile apparel market

In terms of textiles, flax and hemp fibres are found in both apparel and home textile products. China dominates the world market in terms of the production of textiles made from flax and hemp fibres and used in top fashion designs, as shown in Table 6 [68]. Belgium and France export about 80% of their scutched long fibre flax to China for processing into yarns and other products.

Table 6. Production and Processing of various bast fibres in China [68]

Type Bast Fibres	Production in China (tonnes)	Processing amount (tonnes)
Ramie (refined)	113 500	110 000
Flax (scutched)	103 000	258 600
Hemp (refined)	4 000	4 000
Kenaf (retted)	158 000	158 000
Jute (retted)	0	29 000

Although the textile industry experienced a global decline, with a number of companies closing down, as a result of the recent global financial meltdown, in terms of volume and added value this is the most suitable industry for bast fibres. The textile apparel market consumes the greatest percentage of flax and hemp fibres. The economic value of the fibre crop depends on its end-use market and costs of production. Fine and long fibres that can be spun into high counts of yarns are most appreciated and valued. Global flax and hemp markets are growing under a strong influence of linen and hemp fabric products from China, and as a result of the strong fashion appeal of the two products [69]. The growth of the Chinese outlet, which currently accounts for the majority of European sales of textile flax fibres, has in turn led to a considerable increase in the quantity grown and processed by farmers and primary processors in Europe. The European downstream textiles industry – spinning and weaving of the flax – is under considerable pressure given the difference in cost price between Chinese competitors and European manufacturers [70].

2.1.5.2 Nonwovens

Loose fibres, like bast fibres, are bulky and difficult to handle. Therefore, techniques such as needle punching, roller carding and air laying in combination thermo fixation or needle punching, have been developed to aggregate such fibres into nonwoven mats. The mats may be made entirely of plant fibres, or else of a mixture of plant fibres, thermoplastic fibres and resins, in varying amounts, depending on the required properties of the end product. The mats may be the end product in itself, or an intermediate product for the manufacture of composites, as discussed in the next section. From 1997 to 2007, world nonwoven production grew at an average annual rate of 7.9 %. Annual nonwoven production presently stands at some 7.4 million tonnes, as illustrated in Figure 17 [71], which also shows the leading nonwoven product producing countries in the world in 2007.

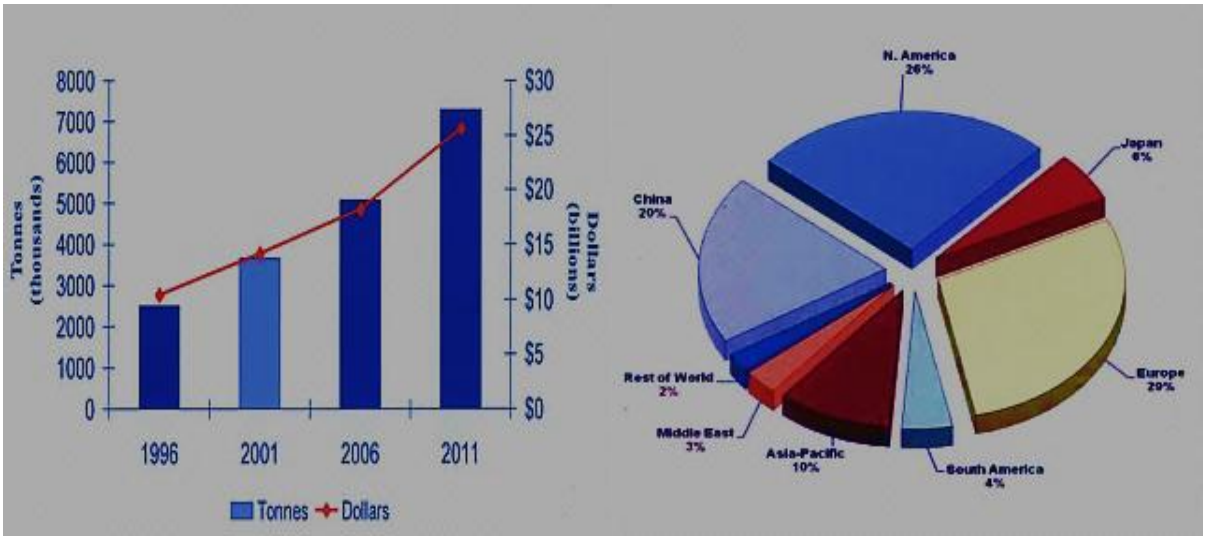

Figure 17. World nonwovens roll goods production and revenue (1996-2011) on the left and bonded nonwoven producing countries in 2007 on the right[71].

In 2010, Europe, North America and Asia accounted for about 87.7% (6.186 million tonnes) of the total world production of nonwovens. The medical textiles (hygiene, medical / surgical and wipes) represented the dominant product produced in 2010, accounting for 44.9% of the total nonwoven production, with the global market estimated at $8 billion, and a growth rate of 9-10% per year. In 2010, worldwide nonwoven production was estimated at 7.05 million tonnes, with the hygiene market having the highest share of 44.9 %, home furnishings 12.8%, construction 18.2%, and furniture and filtration applications both at 6.9% [72].

Cotton and other natural fibres accounted for only 3% of the total nonwoven staple fibre consumed in 2007, as illustrated in Figure 18, the staple synthetic fibre share being estimated at 74%. A potential to increase the natural fibre, particularly bast fibre, share in nonwoven staple fibre consumption exists and is dependent on research breakthroughs in terms of refining the bast fibre physical properties (fineness and strength) through the isolation of the single fibres.

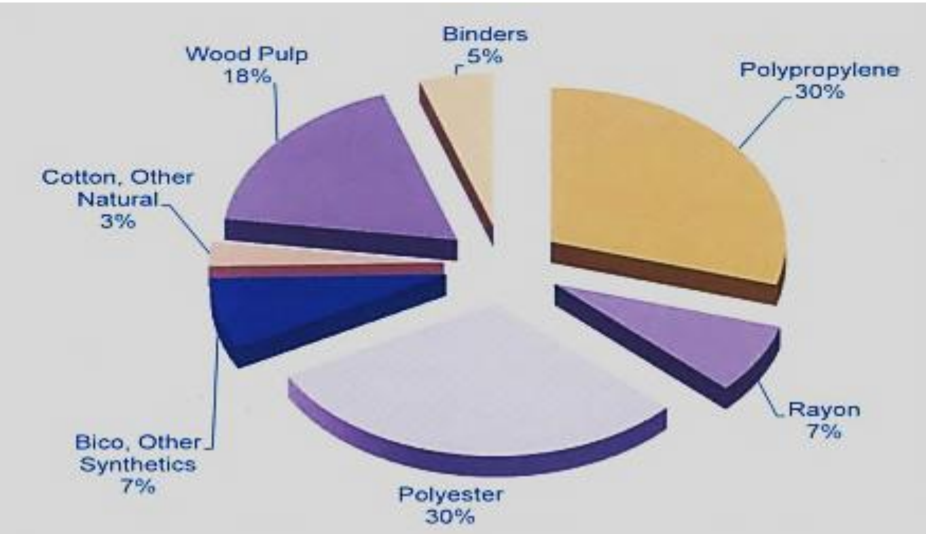

Figure 18. Worldwide nonwoven staple fibre consumption in 2007 [72].

Figure 19 illustrates the market segments for various nonwoven based products and their maturity stage in the market.

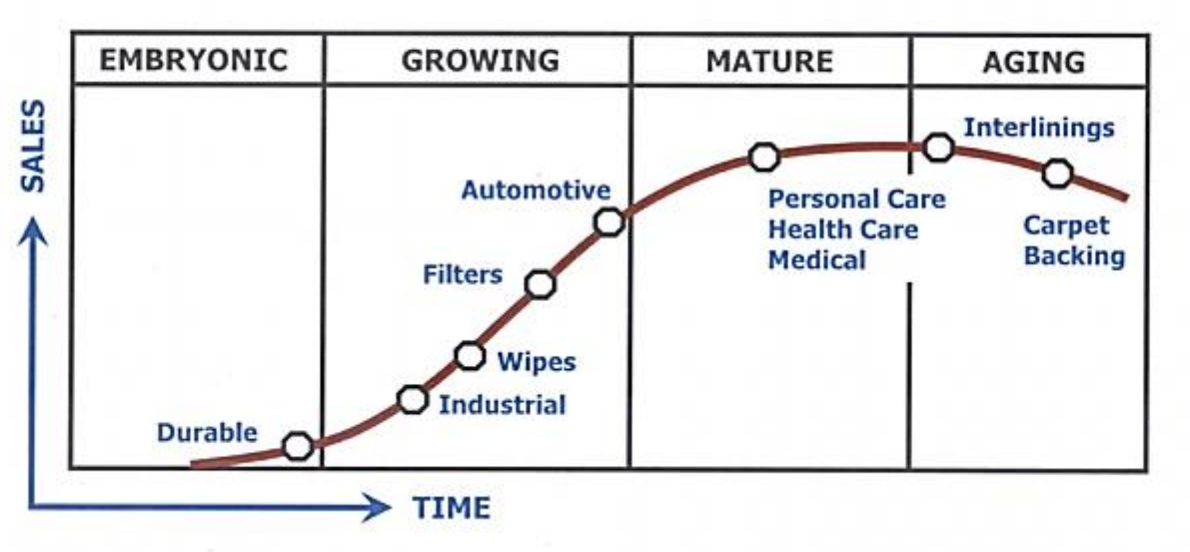

Figure 19. Nonwoven market segments and maturity [72]

Olesen and Plackett [65], in their paper entitled "*Perspectives on the performance of natural plant fibres"*, identified the following opportunities to increase the percentage share of bast staple fibre consumption in the nonwoven sector by converting lower quality shorter and coarser fibres into differentiated nonwoven products such as:

- *Filters:* Filtration is a process of separating solid particles from liquids or gases by passing them through the filter media and trapping those particles whose size are bigger than the fabric pore sizes. Bast fibre surface chemistry and large surface area make them ideal for use in filters. Unmodified plant fibres absorb heavy metal ions, and chemical modification techniques can enhance both their heavy metal and oil absorption properties. Nonwoven fabrics manufactured using flax and hemp fibres are the major media for dry and wet filtration applications. Applications could include clean-up of polluted drinking water, industrial run-off water, and various other waste waters. Opportunities also exist for use of plant fibre filters in capturing volatile emissions from industrial processes, such as in coal fired power stations.
- *Growth media:* Artificial substrates, synthetic binder twines, plastic clips and plant pots are extensively used in the modern horticultural production in greenhouses and nurseries.

For the growers the plastics products and substrates for soilless production (e.g. mineral wool) are forming increasingly a problem of disposal. Nurseries use different types of growth media for the production of flowers and grass mats, mats based on plant fibres appearing to be ideal for such uses. At present, mineral fibre mats are used over large areas in greenhouses, but not without problems. The water absorption is uneven (too dry on the top and too wet at the bottom), they have to be disinfected after a certain period, and at the end of their service life, they create waste problems when disposed at the landfill sites, since these mats are difficult to burn nor easily biodegradable.

- *Insulation:* Plant fibre mats may have a promising future as insulation materials within the building industry. One of the major challenges with this application is the provision of fire retardancy. However, this is technically feasible and the first insulation materials based on plant fibre mats are already on the market in France and Germany. The market potential for partial replacement of glass and mineral fibre mats for insulation purposes is huge.
- *Geotextiles:* Geotextiles is a market that is experiencing a growth rate of 18% per annum (the highest growth category) in Eastern Europe, Africa, and Asia, with bast fibres making a large impact. Plant fibre geotextiles are already available as industrial commodities for the control of soil erosion and weeds. The natural biodegradation of the lignocellulosic fibres can be considered to be an advantage in temporary civil engineering applications. In many cases on slopes and waterfronts, natural rooting of plants takes over the reinforcing role of the geotextile. The use of natural fibre based geotextiles in civil engineering offers large environmental advantages by the fact that these are fully biodegradable and no synthetic polymers remain in the soil after its functional lifetime.

Figure 20 illustrates the nonwoven technologies used in 2010 by the different regions of the world for the production of nonwoven products, with the needle-punch technique the dominant technology of choice followed by the spun melt system. The predominant fibres currently used in the production of different nonwoven products are derived from synthetic fibres owing to their tailor-made specific functional properties for each application, guaranteed fibre supply as well as price.

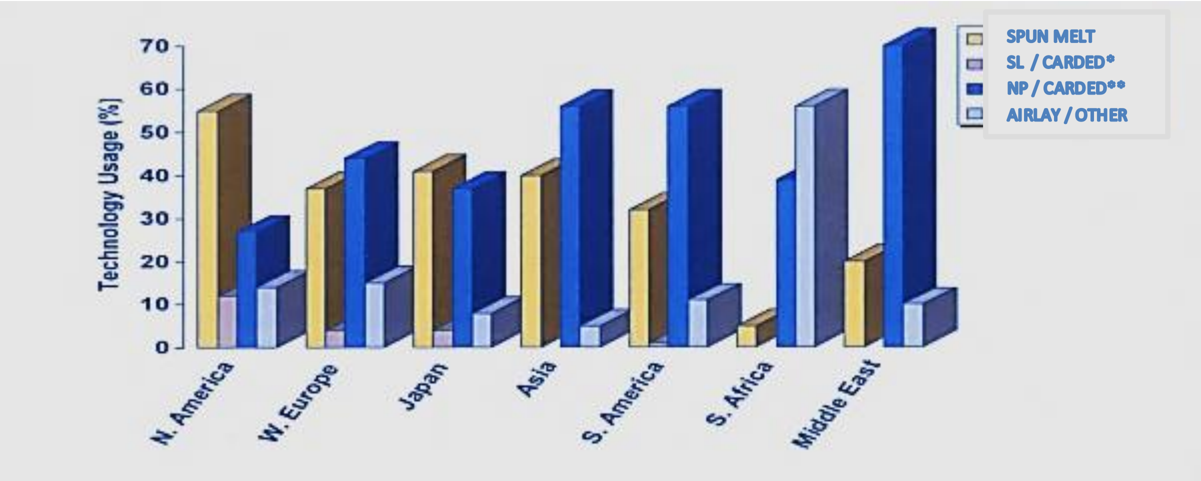

Figure 20. World nonwoven technology usage [72]
*(*SL = Spunlace ; ** NP = Needle-punched)*

Advancement in the pretreatment of flax and hemp fibres discussed in Section 2.1.2 aimed at the production of fibres with lower non-cellulosic content at cost effective manner for the development of high quality products with excellent technical performance function provides an opportunity for enormous increase in flax and hemp fibre volumes in the production of nonwoven products through spunlace, needle punched and airlay nonwoven production techniques.

2.1.5.3 Composites

Composite materials, reinforced with natural fibres, such as flax, hemp, kenaf and jute, and generally referred to as biocomposites, are gaining increasing importance in the mass transportation sector (automotive, aerospace, rail freight transportation), packaging, construction and other industrial applications, owing to the specific performance improvements they impart to the final product, including lightweight; specific strength and stiffness; improved energy recovery; carbon sequestration; ease in handling and flexibility of manufacturing as well as environmental friendliness [73].

A resurgent in interest in industrial application of flax and hemp fibres utilization in composite product development is in the automotive sector in the production of inner panels and is driven by environmental legislation and policies in Europe. In this case, a plant fibre-based composite is able to successfully compete with the more traditional glass-fibre-reinforced component, as a result of the low price of plant fibres and their beneficial properties (low weight and good thermal and sound insulation) [73]. The manufacturing techniques employing fibre mats and moulds for three-dimensional products, such as car panels, can also, in principle, be extended to other product areas within the building, furniture, transportation and packaging industries. For bast fibre plants to compete fully with synthetics, new approaches to research and development are currently being explored by a number of research organisations worldwide, which focus on improvements in fibre mechanical properties, such as tensile, bending and impact resistance, to match those of synthetics [74 , 75].

The global composites market registered double-digit growth in 2010 but levelled off in 2011 due to the financial meltdown experienced by major world economies, and according to Lucintel [76] it is estimated that the value of the global composites market in 2012 will be about $30bn. Notwithstanding the economic downturn in the developed countries, it is expected that the emerging and developing markets in the Middle East, Africa, Asia and South America will contribute to the increase in the demand for composites.

In 2010, the total global natural fibre composite material market shipments topped some 200 million kilogram, valued at US$289.3 million. The market is expected to grow to US$531.3

million in 2016 with an 11% per annum increase in the next five years [76]. Natural fibre composites (NFCs) are used in a variety of markets, such as automotive, construction and electronics components. Europe was the top continent in terms of total NFC consumption; Asia is emerging as a big market for NFCs due to the rapidly increasing demand in China and India. Lucintel [76] predicts that, in the future, there will be higher market fragmentation due to emerging economies. Future markets are anticipated to be highly competitive and companies with innovative capabilities will thrive and gain market share [6]. Figure 21 illustrates the external driving forces that shape the future of the natural fibre composite industry and thus its long-term economic sustainability [6].

Figure 21. External forces shaping the natural fibre composite industry [6]

Figure 22 illustrates the market distribution for fibre reinforced composites according to application [76].

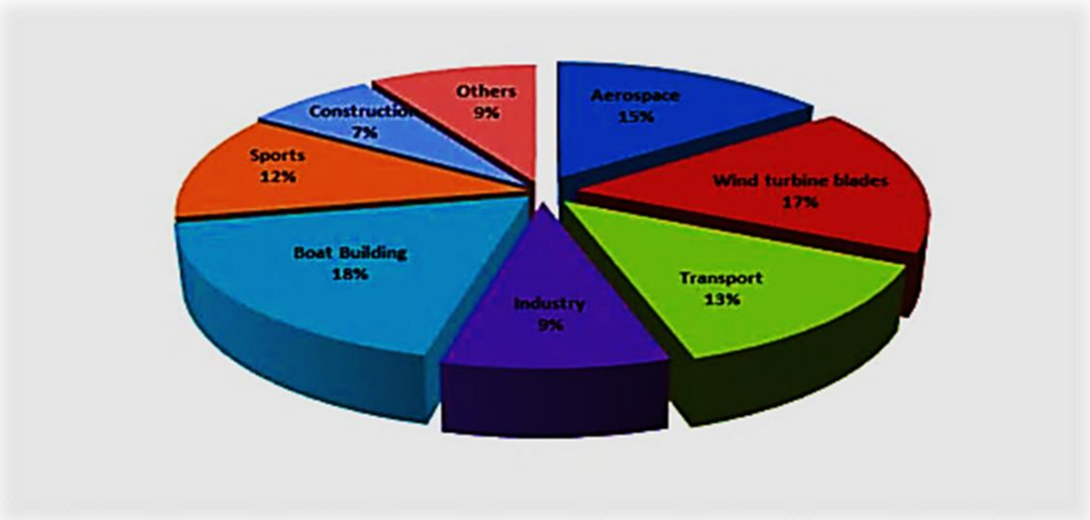

Figure 22. Market distribution of fibre reinforced composites [76]

Wide ranging national policies and voluntary agreements by major automobile manufacturers have been developed concerning the environmental impact of vehicles over their lifetime. Throughout their life cycle, vehicles impact the environment in several ways, including energy and resource consumption, waste generation during manufacturing and use, and disposal at the end of their useful lives. About 75% of the mass of end-of-life vehicles, mainly metals, is recyclable in the European Union. The rest (~25%) of the vehicle is considered waste and generally goes to landfills. At the end of 1999, ten E.U. member countries (Austria, Belgium, France, Germany, Italy, the Netherlands, Portugal, Spain, Sweden, and the United Kingdom) had specific regulations and/or industrial voluntary agreements addressing end of life vehicles (ELV) [77]. These countries represent almost 96% of ELV estimated to be in the European Union. Environmental legislation of the European Union requires the reduction of the remaining 25% vehicle waste going to landfill to a maximum of 5% by 2015. The European Parliament and Council have promulgated national policies and voluntary agreements, aimed at harmonizing the existing rules and to push the E.U. governments and automobile industry to comply fully with the directive to put only 5% of ELV residues (ASR) into landfills [78]. This directive re-ignited the interest amongst international research institutes worldwide to conduct relevant research and development in the use of natural fibres in the manufacture of lightweight and environmentally friendly composite products for a sustainable automotive sector. Figure 23 illustrates the growth in the use of natural fibres for composites in the German automotive industry (1999-2005) [79].

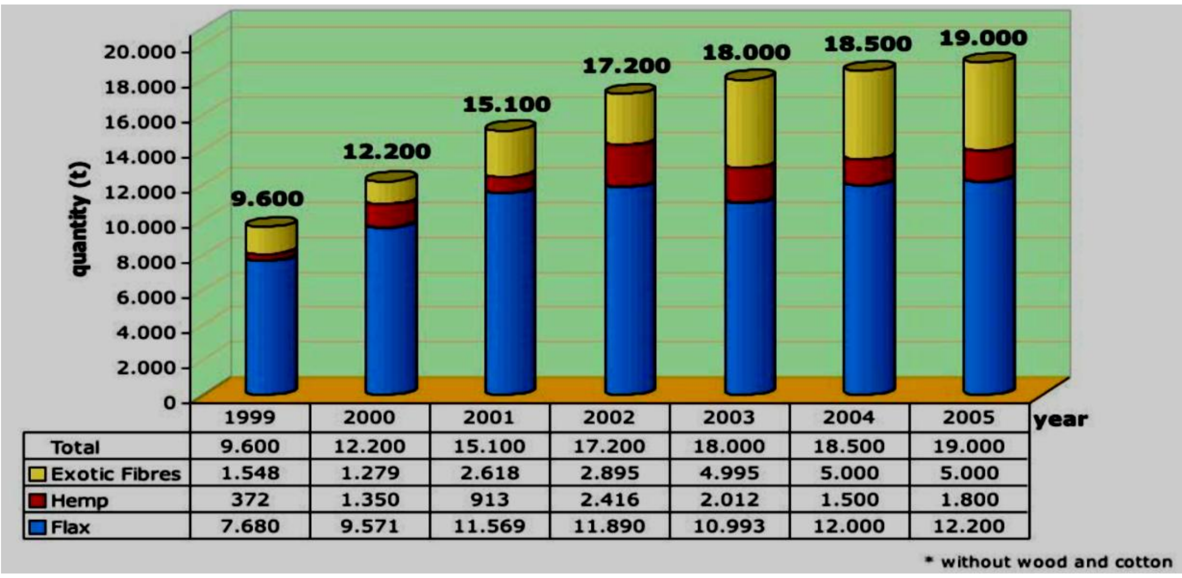

Figure 23. Use of natural fibres for composites in German automotive industry (1999-2005) [79]

The global passenger car industry is expected to experience modest growth and reach an estimated $1394 billion in 2017, with a compounded annual growth rate (CAGR) of 3.4% over the next five years. Demand for electric and hybrid vehicles, and development of other emerging technologies, indicate a bright outlook for the global passenger car industry. Despite economic slowdown, significant opportunities exist for composites in the European automotive market. According to Lucintel [76], the European automotive industry output will expand significantly, owing to the rapid growth in auto production, with composite material demand in European market being forecast to increase by 6.87% per year. Several automobile models, first in Europe and then in North America, feature natural fibre reinforced thermosets and thermoplastics in door panels, package trays, seat backs and trunk liners. The application of natural fibre composites has increased and is gaining preference over glass fibre and carbon fibre due to stringent environmental policies in the EU as well as the low-cost and low-weight of products, with European-based natural fibre composite moulders and supplier of interior parts, such as headliners, side and back walls, seat backs, and rear deck trays to GM, Audi, and Volvo, among others [78].

2.2 Industrial Hemp (*Cannibis sativa* L.) Overview

Industrial hemp, *Cannibis sativa* L, is a cash crop that has been grown and used for many centuries for the manufacturing of products which satisfied the human needs of the time, such as cordage, clothing, food, lighting oil, and medicine. According to the literature it appears that China was the first country to cultivate hemp for the production of ropes and fishnets, as early as 4000 BC [80]. Through the trade route, hemp, grown for its fibre, was introduced to western Asia, Japan and Egypt, and subsequently to Europe, somewhere around 500 BC [81]. Cultivation in Europe became widespread after 500 BC, products produced from hemp included rope, sail cloth, sacking, work clothes, etc, and hemp continued to be cultivated in Central Europe throughout the ensuing centuries. By the 5th Century AD, hemp was a well-established crop, with cultivation spread throughout Europe, including the Germanic, Anglo-Saxon, and Norse regions, for making products such as paper, sails, fishing nets, lines, waterproofing and ropes. More than fifty plants of other genera are referred to as "Hemp", including Manila hemp (*Musa textilis*), commonly known as Abaca, and sunn hemp (*Crotalaria juncea* L.) [82]. While these have some useful fibre qualities for producing twine or matting, they do not yield high-quality textiles, nor do they have the antimicrobial or rot-resistant properties of industrial hemp [83]. Literature is rich of studies on antibacterial activity of compounds extracted from high-THC hemp types, which are known to contain powerful antibacterial agents, and some recent findings demonstrate that non-psychotropic cannabinoids and their precursors are most likely antibacterial agents [83, 84].

In 1537, hemp was classified in the family *Moraceae* [85]. In 1753, the famous Swedish botanist and father of taxonomy, Carl Linnaeus, recognized and named the species *Cannabis sativa* (*C.sativa*), meaning cultivated as a crop, in his principle work on the classification of living things, *Systema Naturae*, and the official taxonomy used today being *Cannabis sativa*

L., where the L refers, to Linnaeus himself [86, 87]. In the 1970s, according to Schultes et al [88], almost all botanists agreed that the genus Cannabis should be classified in the family *Cannabaceae* rather than in the family *Moraceae*. Figure 24 shows a drawing, made by Schlechtendal *et al*, in 1882 [89], of the cultivated and seed hemp, for which the name *Cannabis sativa* was generally approved. By definition, industrial hemp refers to those strains of *Cannabis sativa L* containing less than 1% of Δ^9 tetrahydrocannabinol (THC), a psychoactive component [90, 91]. Cultivation in industrialized countries was more or less halted in the early 20th century, when hemp became intrinsically linked with marijuana, the species other phenotype, which contains larger quantities of the psychoactive compound, THC [92]. This type of Cannabis sativa is unlike the type for seed and fibre, which cannot in anyway be used as a recreational drug [93]. Other than the THC, the other main cannabinoids found in *Cannabis sativa L.* are cannabidiol (CBD) and cannabinol (CBN).

Figure 24. Sketch of Cannabis sativa L [89]

The following equation, based on the percentage concentration of cannabionoids, known as the Cannabis-phenotype-ratio, to determine whether the *Cannabis* plant bred or grown is the industrial hemp (THC levels of ≤1%) or its high THC variety that is illegal (THC level range of 5-20%) was developed [94]:

$$Phenotype\ ratio = \frac{(THC+CBN)}{CBD}$$

Cannabis sativa L., was banned internationally in 1961 under the United Nations' Single Convention on Narcotic Drugs [95].

2.2.1 Environmental benefits

Due to its vigorous growth, hemp is regarded as a pioneer plant that can be used for land reclamation purposes. Studies have shown that hemp is suitable for reclamation of land polluted by heavy metals (phytoremediation), the resultant straw biomass being used for industrial applications, such as raw material for composites, pulp and paper and chemical industries [96]. Unlike many crops, hemp can be grown in most locations and under most climatic conditions, with only moderate water and fertilizer requirements.

Industrial hemp has been identified as a renewable resource, and the following combination of events has strengthened the case for the cultivation of hemp. Firstly, unsustainable agriculture, associated with high-input high-impact crops, is a global problem [97]. Secondly, the use of non-renewable resources has been linked with global climate change and a reduction in both water and air quality [98]. Furthermore, the growing world population and ever increasing resource demands make the depletion of non-renewable resources inevitable, thereby increasing the current global dependence on such a renewal resource and new agricultural systems of production that do not diminish the productive capacity of agricultural land and quality of the environment. Hemp has a deep root system that improves the soil structure and limits the presence of nematodes and fungi, whilst enhancing the soil nutrients. Hemp crop economic benefits are derived by commercially exploiting both its upstream and downstream production opportunities for rural farming communities and stakeholders involved in its value-addition, such as in processing, manufacturing, distribution and retailing of hemp based products [99].

A study conducted in 1999 to assess the biodiversity friendliness of 23 crops in terms of 26 biodiversity parameters, which included both hemp for fibre and seeds and flax, found that hemp for seed and fibre, as well as flax crops performed better than all major crops, such as wheat, maize or rapeseed (see Figure 25) [100].

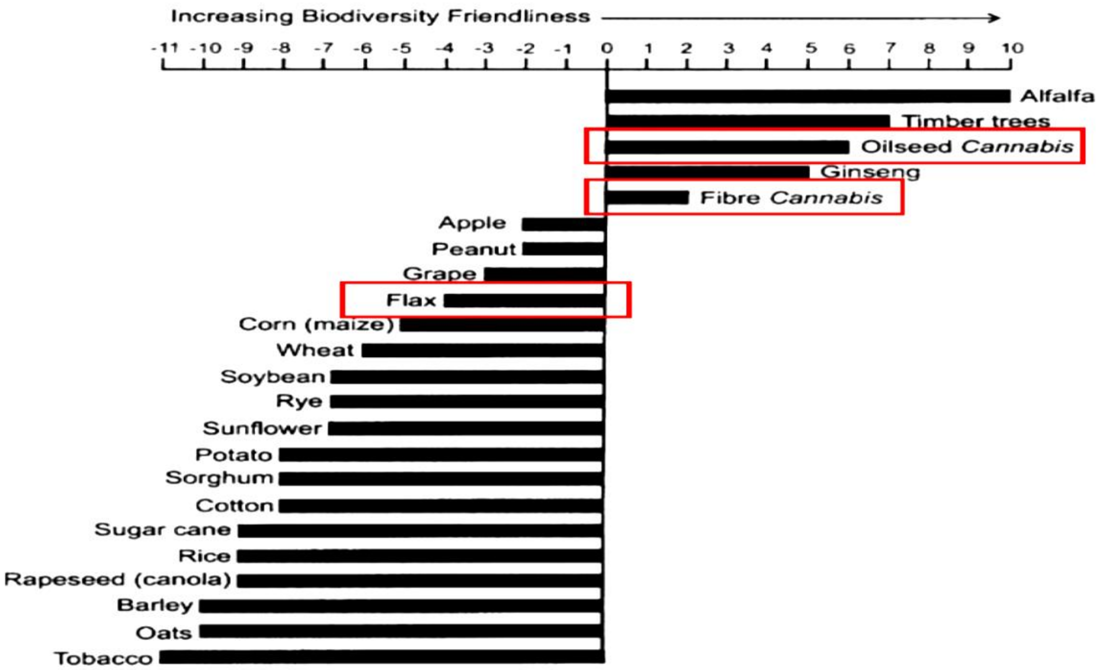

Figure 25. Crude mean evaluation of biodiversity friendliness of selected major crops and fibre and oilseed Cannabis (Source: Montford and Small 1999)[100].

As a study by the European Environmental Agency (EEA 2007) on the ecological effects of different crops proved, both flax and hemp exhibit excellent ecological credentials in their cultivation and performed much better in the study compared to most other major crops. Not only the cultivation itself, but also the products made of hemp and flax entail significant environmental benefits, for example hemp based reinforced plastics show energy and greenhouse gas (GHG) savings in comparison with their fossil based counterparts [101].

2.2.2 Cultivation practices

The hemp plant needs a sufficiently deep, well-aerated soil, with abundant organic matter, and should be planted in rotation with other crops. It requires a mild, temperate climate, a humid atmosphere and sufficient annual rainfall, particularly during the vegetative growing stage. According to the literature, the hemp crop can tolerate temperatures of between 2^0C and 35^0C for its germination, with the optimal temperature being about 24^0C [102-104]. Important soil nutrients that are needed to ensure proper hemp growth, are nitrogen, potassium and phosphorus, as defined in the Good Agricultural Practice (GAP) for successful fibre hemp crops, including the anticipation of fertilization needs. A good seedbed is important, since hemp seedlings are tender during emergence, and to accelerate germination and emergence, a fine and level seedbed is necessary to ensure good contact of the seed with the soil. Depending upon the specific cultivar variety being grown, it takes between 80 and 150 days for the hemp plant to reach maturity for fibre harvesting [105]. Most of the hemp cultivars currently grown in major hemp growing countries are bred in Europe and are essentially suitable for the northern latitudes and temperate climates [106].

Seeding rates for hemp vary widely, and in most hemp growing countries a seeding rate of 100 to 140kg of seed per hectare is used, producing between 500 and 700 plants per square metre. The high seeding rate and plant density used result in the production of hemp straw with smaller diameter and high fibre content, with the fibre properties being very suitable for textile use. In addition, the dense growth, due to the high seeding rates, creates conditions not favourable for the proper growth of weeds, since hemp out-competes them during growth. Sparse seeding rates with large row-spacing, result in the production of hemp straw with coarse fibres which are less attractive for textile application.

2.2.3 Global production data

Hemp cultivation was never prohibited in the majority of the Eastern European countries, the Commonwealth Independent States (CIS) (formerly Soviet Union) and in the Asian Pacific, when other countries, such as in Europe and North America, made it illegal to grow the crop. It was only in the 1990s that the commercial production (including cultivation) of industrial hemp was legalized in Canada and Europe, under a permit system, which clearly set out the necessary guidelines, on THC content (≤0.3%), of hemp that could be cultivated. It is estimated that there are presently more than 30 nations growing industrial hemp as an agricultural commodity, which is sold on the world market. It is grown as a fibre, seed or dual purpose crop [107]. China, Canada and Europe are the main hemp cultivation areas in the world. The continued efforts by hemp breeders towards breeding hemp cultivars with no traces of THC will go a long way in restoring the legal credibility and acceptability of hemp as an agricultural cash crop worldwide.

2.2.3.1 Major producing countries

Figure 26, shows the agricultural database provided by the Food and Agricultural Organization (FAO) of the United Nations (UN), on hemp fibre and seed production for the periods 2001-2010 (FAOSTAT data, 2010)[108]. The figure shows that the world hemp fibre and tow production declined over the two-year period from 2006 to 2008, falling from over 109 500 tonnes in 2006, to just under 66 700 tonnes in 2008, after which it increased marginally. The hemp seed production increased steadily from 2005 to 2007, dropping markedly in 2008, and then increasing sharply in 2009.

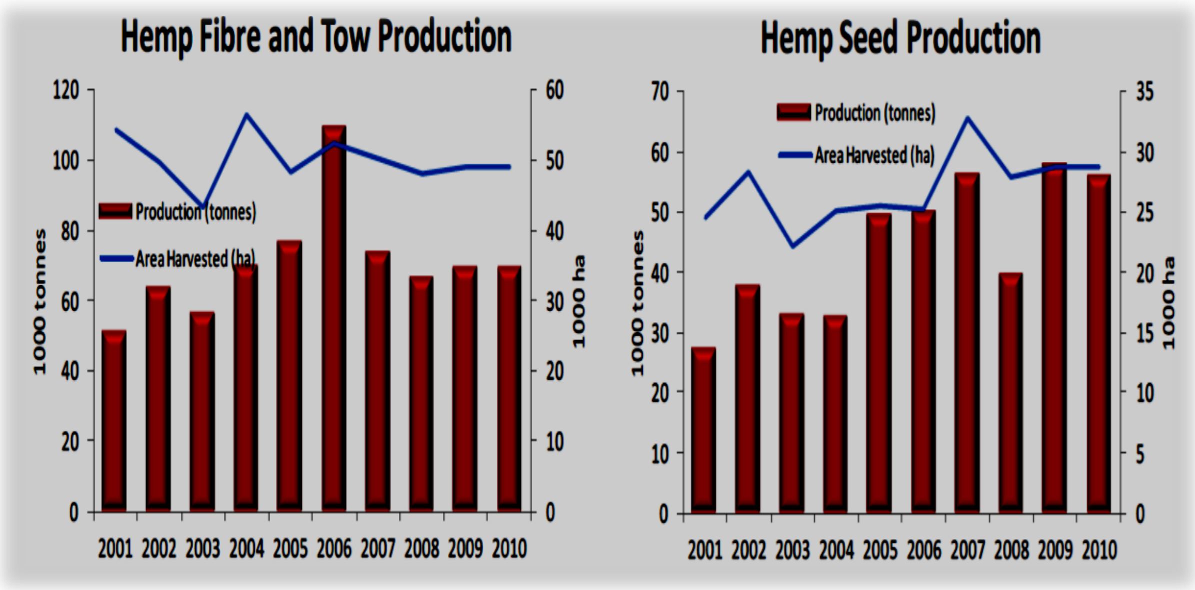

Figure 26: Hemp fibre, tow and seed production, 2001 to 2010 data [Source FAO][108]

Figure 27 shows the 2009 production data provided by the Food and Agricultural Organization (FAO) of the United Nations (UN), for hemp fibre and tow, as well as hemp seed for the largest hemp producing countries.

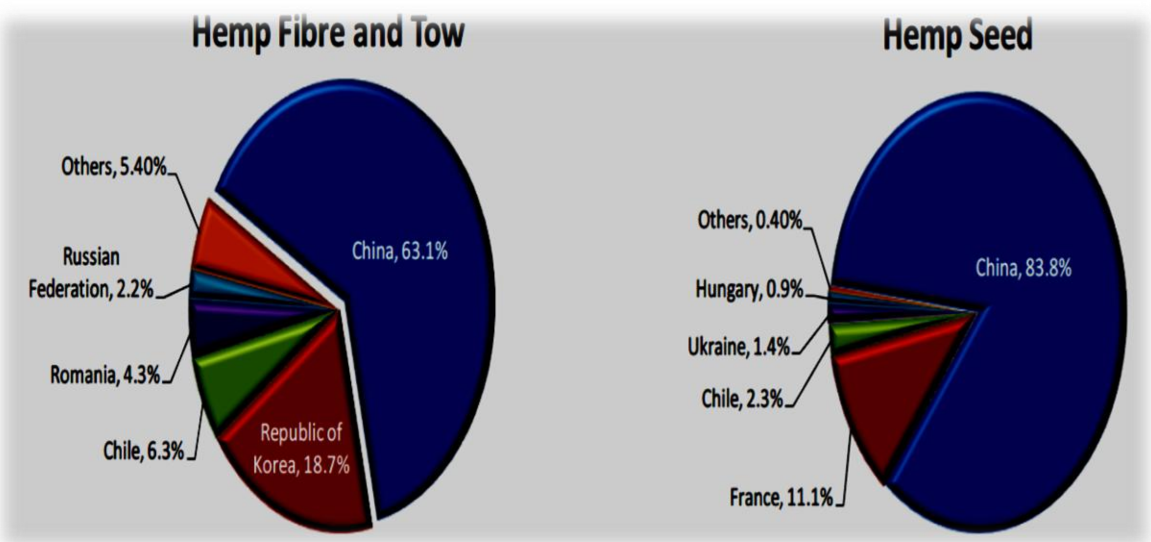

Figure 27: Hemp fibre, tow and seed production of leading hemp producing countries in 2009 [Source: FAO][108]

As illustrated in Figure 27, China dominates both hemp fibre and seed production, accounting for 63.1% and 83.8%, respectively, and is the world's largest producer of the two hemp commodity products. The Chinese government aims to increase the current hemp growing areas from an estimated 300 000 to 1.33million hectares producing about 2 000 000 tonnes of fibres for the China textile industry, and employing labour intensive methods of growing and harvesting to create around 3 million new job opportunities in the rural areas. The implementation of this plan will entrench China's dominance of the hemp industrial sector as well as the global markets for hemp products [109].

Figure 28 illustrates the global hemp seed production in 2011, from which it can be seen that France was the largest hemp seed primary producer in the EU, owing to the fact that hemp cultivation was never prohibited in France, as was the case in other EU countries. France produced approximately 3 700 tons of hemp seed, while the Ukraine produced around 700 tons of hemp seed during the same period [108].

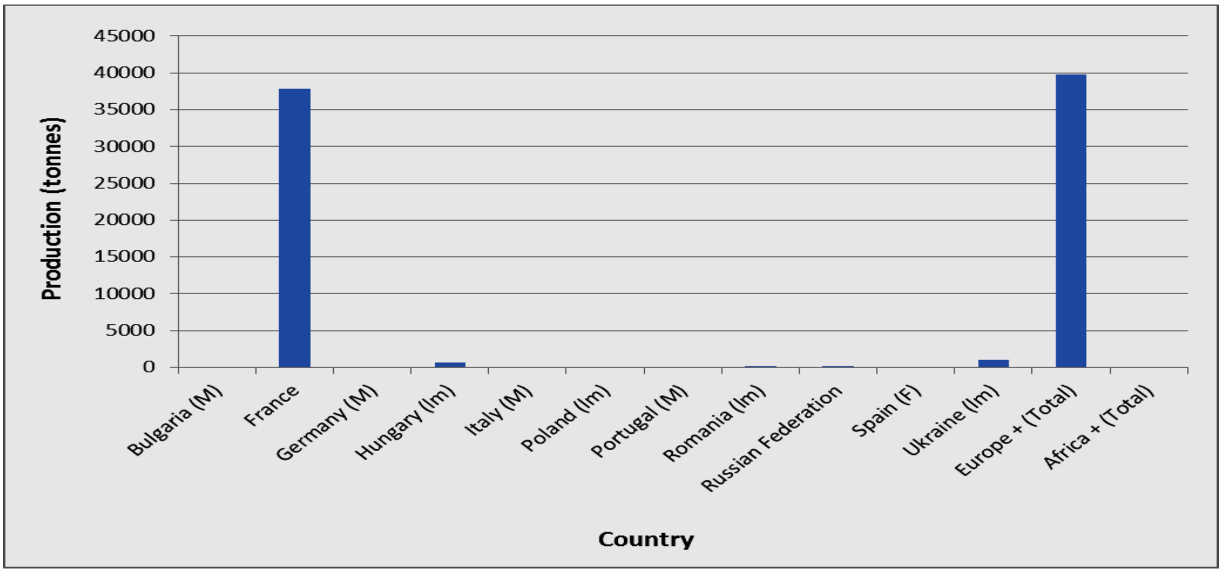

Figure 28: 2011 FAO global hemp seed production data [Source FAO][108]

[ ] = Official data | A = Aggregate, may include official, semi-official or estimated data | F = FAO estimate | Im = FAO data based on imputation methodology | M = Data not available

The above figures show that none of the African countries produced hemp seed in 2011, largely due to legislative issues which prohibits the production of hemp, especially in South Africa.

Figure 29, shows the land areas under hemp cultivation in Canada, from which it can be seen that there was an increase in area under cultivation from 2002, reaching a peak of 19 458 hectares in 2006 [110].

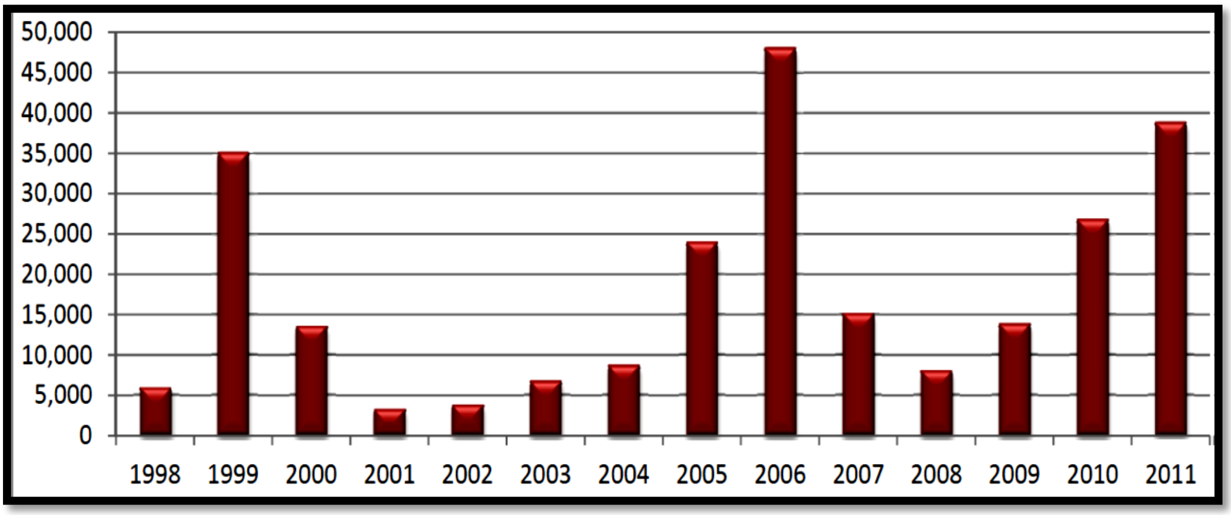

Figure 29: Hemp production area (ha) in Canada [Source Health Canada][110]

South Africa and Africa in general are losing out on the socio-economic benefits arising from the commercial cultivation of flax and hemp can follow the Canadian example in establishing a vibrant hemp industry based on seed production and industrial uses of fibres after seed harvesting.

2.2.3.2 Markets

According to most hemp advocates, the variety of applications for hemp as raw material is seemingly endless, with some estimating that the global market for hemp consists of more than 25 000 products in about nine submarkets, such as agriculture; textiles; recycling; automotive; furniture; food/nutrition/beverages; paper; construction materials; and personal care (see Figure 30) [81]. Nevertheless, hemp is not, and will not necessarily be, the best material of choice for many products, although there are some niche areas where hemp products have definite advantages and have been successful. New applications for hemp as a raw material are constantly being researched, tested and developed.

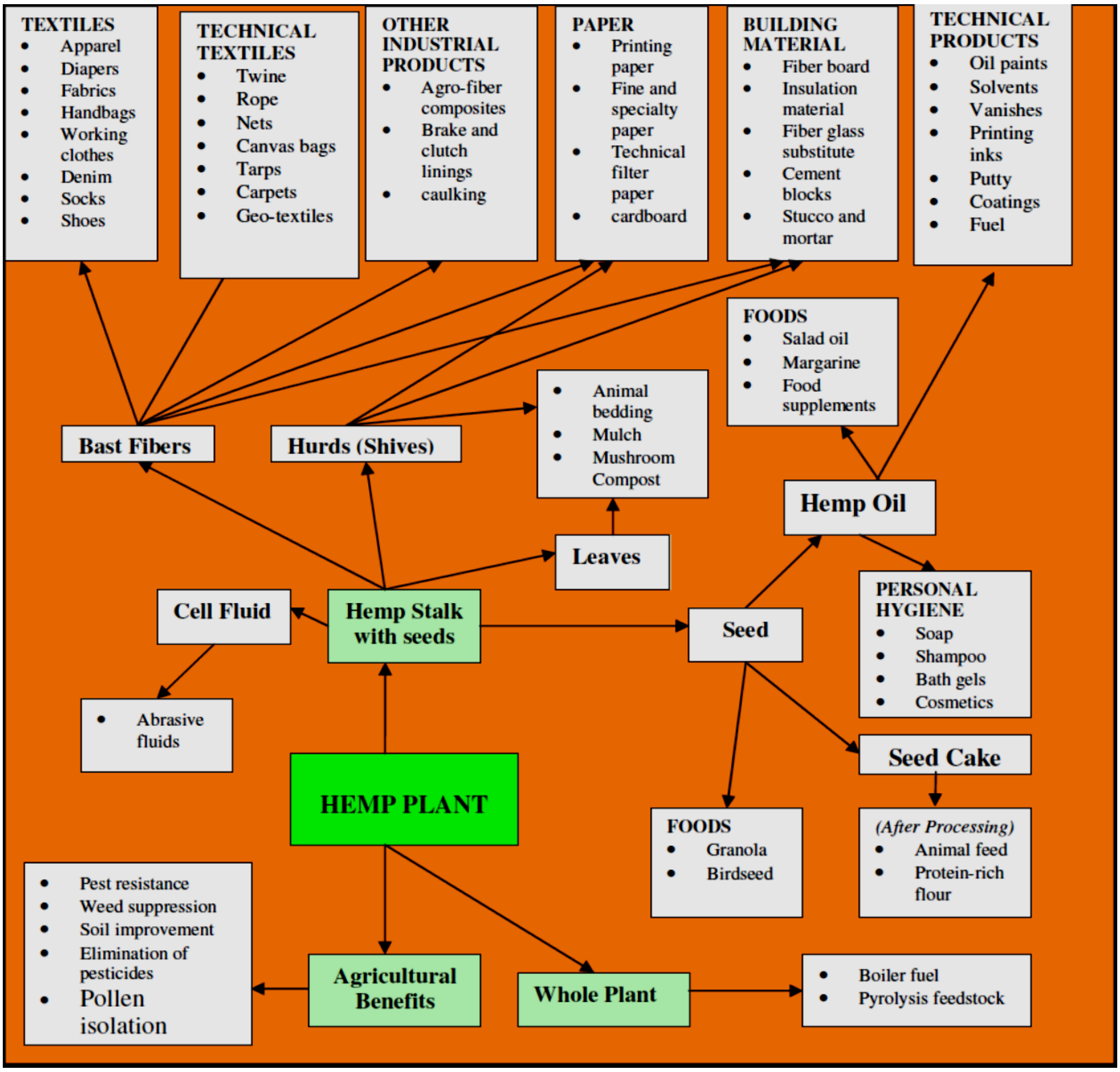

Figure 30. The Roulac hemp value chain tree, demonstrating its industrial usage [81].

The potential use and markets of hemp include, but are not limited to, the following differentiated product lines [90]:

- High value-added opportunities, such as the oil and health food markets; woven and knitted textiles, such as carpets and apparel, moulded or pressed textiles; medium to low value added products, such as pulp and paper, building materials, beverages, livestock feed and bedding and biomass fuels.
- The use of all the parts of the hemp plant for the manufacturing of various industrial products. For example, the whole stalk of the hemp plant can be used to make environmentally friendly paper, packaging material, cardboard, cigarette papers, filters and newsprint.
- The production of large amounts of biomass, which can be converted into ethanol for use as fuel that is an environmentally friendly alternative to toxic petrochemicals. The by-products from this process include food, animal feed, bio-chemicals and various materials, making it a much attractive option to oil refineries.
- The woody core of the stalk (hurds) can be used as building materials, insulation material and fibreboard. Hemp applications in the building industry range from a strong, light and durable cement, when mixed with lime, to environmentally friendly insulation, to an input for fibre-board. It can be used for animal bedding, mulch, boiler fuel and chemical absorbent.
- The fibre can be used to make fabrics, apparel, bags, shoes, socks and carpets. Due to its high absorbency rate and quick decomposition, hemp fibre has also several applications as industrial product.
- Hemp seed contains up to 25% high quality protein, with all eight essential amino acids being present. It can be used to make bread, granola, ice cream, protein, powder and oil. After pressing hemp seed for oil, the remaining seed cake solids are still very nutritious for both humans and animals, and can be processed into protein-rich flour and animal

feed. Hemp oil can also be used to manufacture cosmetics, soap, shampoo, hand cream, salad oil, margarine, oil paints, leather care and printing ink.

2.2.3.3 Analysis of International trade

According to FAOSTAT data, only 6.8% of the hemp fibres produced, were traded internationally in 2009, a clear indication that not all of the hemp fibre producing countries were exporting hemp, but rather using it for domestic consumption. Figures 31 & 32 illustrate the graphical representation of the hemp fibre and seed collectively exported internationally by hemp producing countries in 2009 [110].

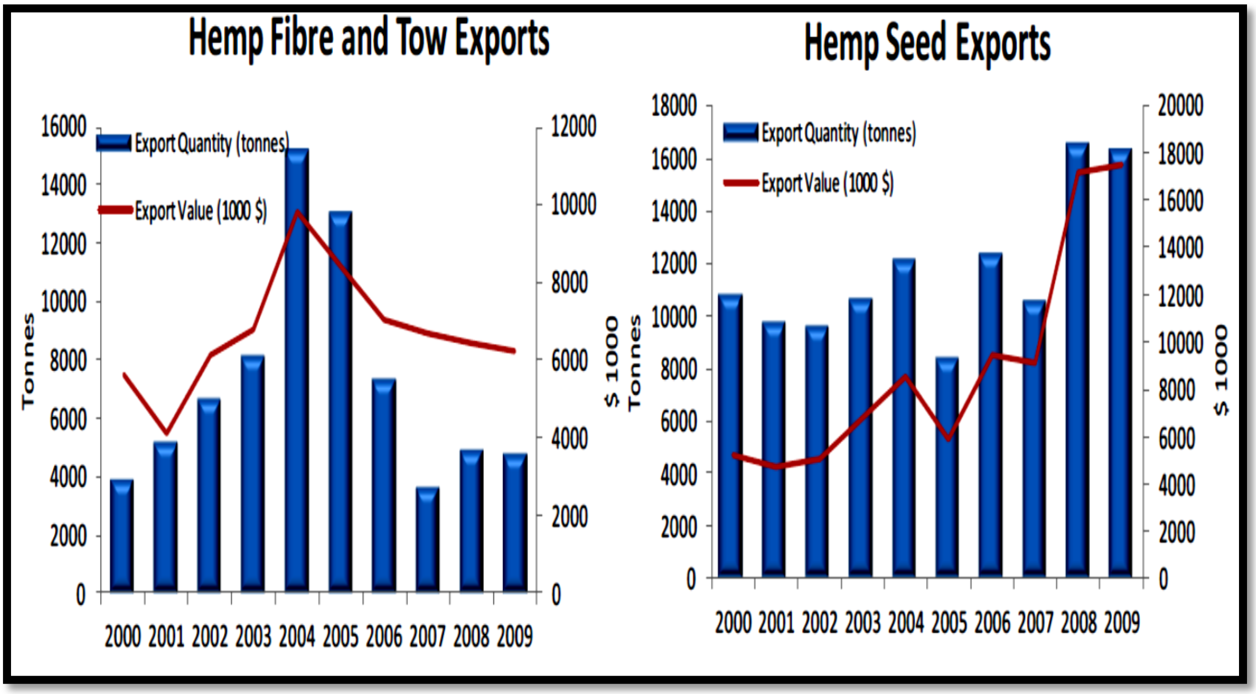

Figure 31. World hemp fibre and seed export data (quantity and value) from 2000 to 2009[FAOSTAT][110]

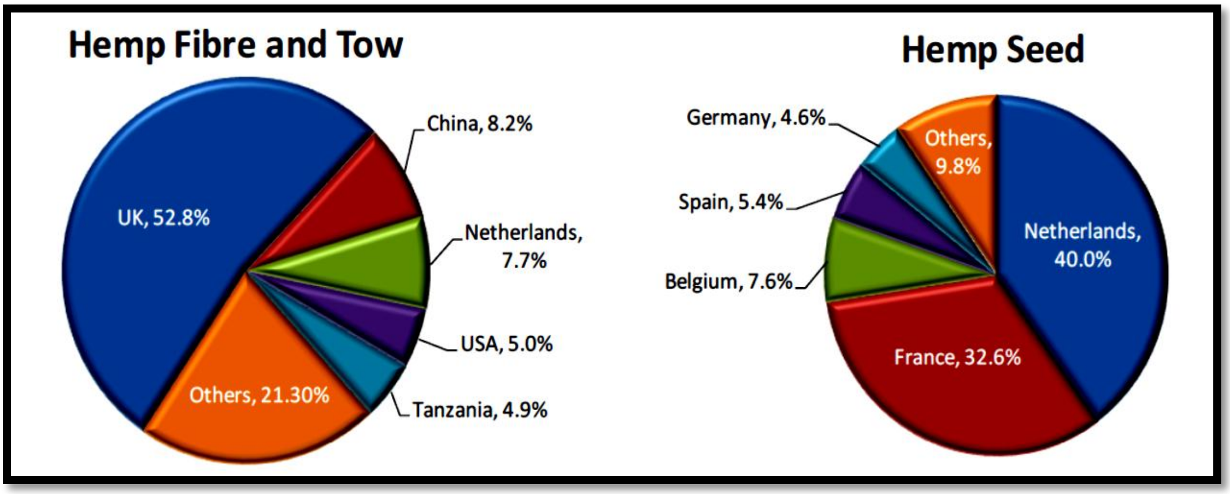

Figure 32. The top hemp fibre and seed exporters for 2009 [FAOSTAT][110]

Whilst China accounted for more than 60% of the global hemp production in 2009, it only exported 8.2% of the hemp fibre it produced, and none of its seed. The UK, which did not feature in the world hemp fibre production data given in Figure 27, for 2009, was the biggest hemp fibre exporter that year, whilst the Netherlands was the biggest hemp seed exporter, followed by France. Tanzania is not known as a hemp fibre producing country, but still accounted for 4.9% of hemp fibre traded internationally in 2009 [79]. This anomaly points to shortcomings in countries producing hemp not submitting their production data to the FAO for collating.

Figure 33 shows the top hemp fibre and seed importing countries, with Spain topping the list, whilst the Netherlands leads the list in terms of seed importation. It can be seen that the major hemp fibre and seed importing countries were in Europe in 2009. The Netherlands is an important player in international hemp trade, processing technology development and logistics management, hence their dominant position in hemp seed trade.

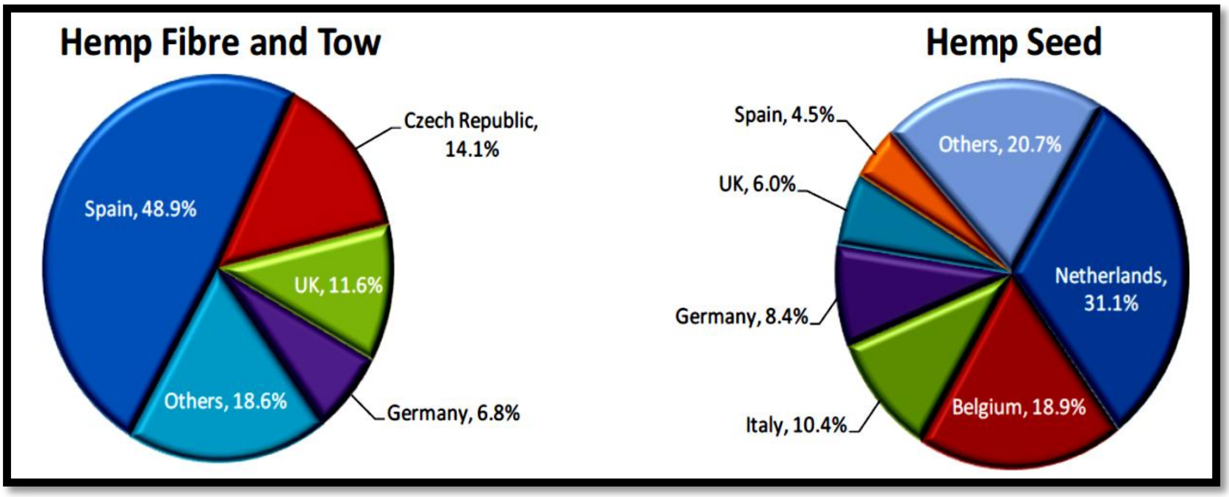

Figure 33. Hemp fibre and seed importing countries for 2009 [Source FAO][110]

The FAO hemp fibre and seed production data for 2009 indicate that the size of the hemp industry was still fairly small compared to that of cotton. Notwithstanding its size, the global hemp commerce still managed to become a multi-million dollar industry, as indicated by the export value data in Figure 31.

Figures 34 & 35, as a way of example, depict the markets for the hemp fibre and hurds produced in the European Union in 2006. The fibre and woody core waste production ranged between 22 000 and 24 000 tons and between 40 000 and 44 000 tons, respectively, and was used by various sub-markets, as illustrated in the figures [111].

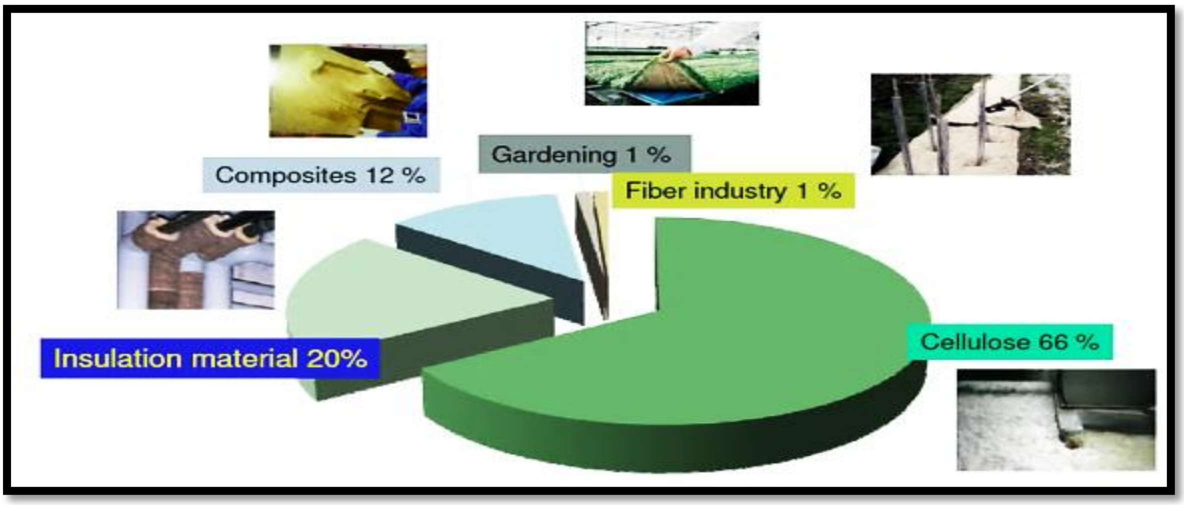

Figure 34. Markets for the hemp fibre harvested in the EU in 2006 [111].

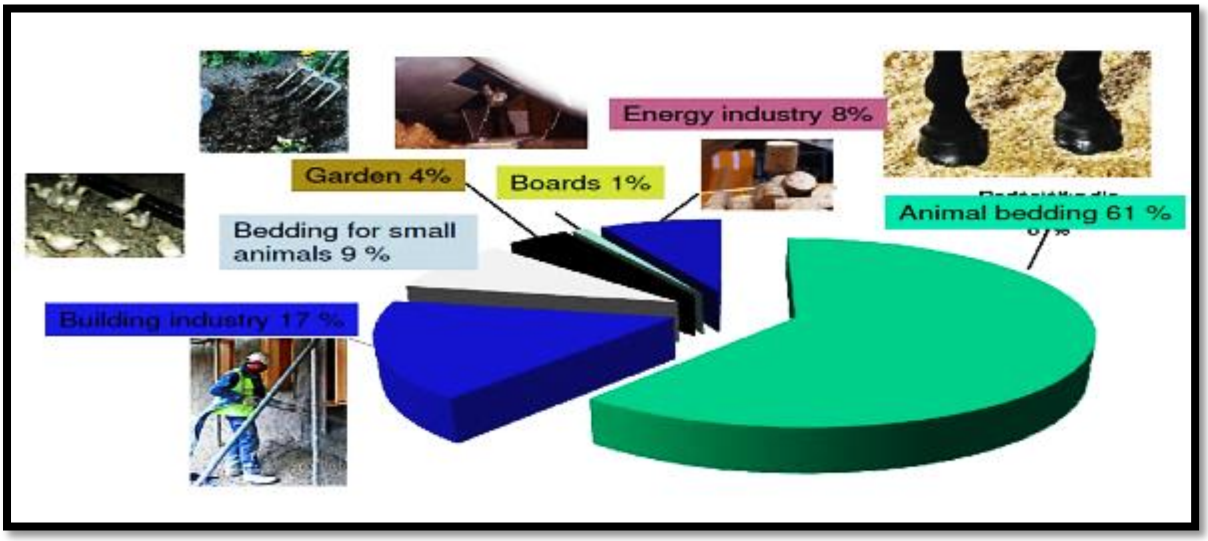

Figure 35. Markets for the hemp woody core in the EU for 2006 [111].

2.2.4 Hemp Industry Associations

The resurgence, in the early 1990s, of interest in allowing commercial cultivation of industrial hemp as a renewable resource in response to the Kyoto Protocol which is aimed at reducing the greenhouse effect resulting from a fossil fuel based economy, led to several countries forming hemp industry associations. This was with a view to exploring commercial cultivation of hemp for new industry development. Some of the hemp industry associations, formed to actively pursue the establishment of global hemp industries, are listed and described below:

2.2.4.1 The European Industrial Hemp Association (EIHA)

Founded in 2005, the European Industrial Hemp Association (EIHA) in 2010 had 70 members from 24 different countries, seven Regular members (hemp processors) and 63 Associate members (companies, associations, institutes, private persons) [112]. The EIHA was originally formed to give members a voice at the European Commission in Brussels to lobby for the EU financial support and subsidies to hemp growers, processors and research institutions, with an interest in the commercial potential of the hemp crop. It has grown quickly into a respected organisation that represents an excellent bank of information and a real support for the fast developing hemp industry. Each annual EIHA conference allows members and non-members alike to exchange views and important developments with their colleagues within the EU and elsewhere in the world. The European Hemp industry is a relatively young and modern industry, with new and improved harvesting and fibre processing technologies.

2.2.4.2 Hemp Industries Association

The mission of the Hemp Industries Association (HIA) (www.thehia.org), a 501(c)(6) membership-based non-profit trade group, is to represent the interests of the hemp industry and to encourage the research and development of new products made from industrial hemp, low-THC oilseed and fibre varieties of Cannabis. It is based in Summerland, California, USA and its activities include:

- Educate the public about the exceptional attributes of hemp products.
- Facilitate the exchange of information and technology between hemp agriculturists, processors, manufacturers, distributors and retailers.
- Maintain and defend the integrity of hemp products.
- Advocate and support socially responsible and environmentally sound business practices.

Members of the HIA support ethical business practices, including accuracy in labelling, use of environmentally friendly technologies, sustainable and organic agriculture, high quality products and concern for human rights.

2.2.4.3 The Canada Hemp Trade Alliance (CHTA)

The Canada Hemp Trade Alliance (CHTA) (www.hemptrade.ca) is a national organization that promotes Canadian hemp and hemp products globally. Established in 2003, the CHTA represents those involved in Canada's hemp industry. Members include farmers, processors, manufacturers, researchers, entrepreneurs and marketers. The key functions of the Alliance are to disseminate information, promote the use of nutritional and industrial hemp and coordinate research.

2.2.4.4 China Hemp Industry Association

The China Hemp Industry Association is a representative body of all Chinese stakeholders (government, academia, farmers, processors, machine manufacturers and hemp product producers) with a focus on ensuring that China continues to dominate the global hemp industry. Its short term goal is to cultivate more than 1 million hectares of hemp crop, produce more than 2 million tonnes of fibre and create job opportunities for 3 million rural farm labourers.

2.2.4.5 Others

Other countries with hemp industry associations include Australia and New Zealand, with South Africa trying to revive its National Hemp Foundation which was formed in 2000.

2.3 Flax (*Linum usitatissimum* L) Overview

Flax, known commonly as linen in the fabric form, is one of the oldest fibres used in textile production, the plant being used also for other products, such as flax seed for consumption. According to the archaeological excavations, people in Switzerland cultivated flax seed and used the fibre for twines and fish net production as early as around 7000 BC [113]. The first well documented application of flax is by the Egyptians who wrapped their mummies with linen fabrics before 5000 BC. This proved that the Egyptians had the technical know-how for fibre extraction and its conversion into yarns, which were used for the production of fabric for various uses, such as clothing, sails for ships and tents, during Medieval times [114]. The use of flax was not only confined to the Mediterranean region and countries to its immediate East, studies showed that it was also extensively used in Central and Northern Europe [114]. A discovery reported in 2009 of spun, dyed and knotted wild flax fibres in a prehistoric cave in the Republic of Georgia indicated that the plant was already in use by humans in the country as long ago as 3 000 BC [115]**.** The first cultivated form of flax was a biennial type *Linum angustifolium* Huds**.** The annual flax cultivated nowadays is *Linum usitatissimum L.*, which has been grown in Mesopotamia for at least 4000 years [84]. Flax is primarily cultivated for textile fibres in Northwest Europe (traditionally northern France, Belgium, and Holland), Eastern Europe, Belarussia, Russia, China, Egypt, and in small quantities in other countries, such as Brazil and Chile. In North America, flax was introduced by the Puritans.

The genus *Linum* belongs to the family *Linaceae*, which consists of nearly 200 species, its distribution being in the temperate and warm temperate zones of the northern hemisphere, mostly in Europe and Asia [116] . *Linum usitatissimum* is the only member of the family *Linaceae* that is important for fibre production [117]. Figure 36 shows drawings of the cultivated and seed flax (*Linum usitatissimum*) [118]. The Latin species name *usitatissimum* means most useful, pointing to the several traditional uses of the plant and its importance for human life [119].

Figure 36. Diagrammatic illustration of Linum usitatissumum [118]

Linum usitatissimum can be bred with an emphasis on seed (see Linseed) or fibre production, the classification of a variety depends on the market at which the plants are aimed and classified according to the following three cultivated types [116]:

- Crops grown for fibre are known as ‘flax,’ ‘fibre flax’ or ‘textile flax’ (EU) and are cultivated in temperate regions throughout the northern hemisphere, especially in the region of the former Soviet Union,
- Crops grown for seed, which are known as ‘linseed’ (UK and India), ‘flaxseed’ (Canada),'oil flax’ or ‘seed flax’ (EU), linseed, i.e. oil flax or seed flax, being

cultivated in warm regions, especially in Argentina, Uruguay, India, United States, Canada and the former Soviet Union, and

- Crops grown for both seed and fibre, and which are known as ‘dual-purpose flax’ or ‘flax grown for fibre flax seed’ (EU), being cultivated in the same places as fibre flax and linseed, but both seeds and stems are utilized.

As a nutritional supplement, one hundred grams of ground flax seed supply about 450 kilocalories, 41 grams of fat, 28 grams of fibre, and 20 grams of protein. During the Middle Ages, the growing of fibre flax and other natural fibre resources was greatly supported, resulting in their dominance over cotton growing [2]. However, the invention of the cotton gin in 1793 and the establishment of huge cotton plantations in the Southern States of America, which produced large volumes of cotton at competitive prices for export to both Europe and to the Northern American States, resulted in a massive decline in flax production [120]. Competition from man-made fibres in the 1950s further eroded the market share of flax fibre, essentially confining its long fibre use to linen fabric production for the fashion industry. The inherent quality variability along the length of flax fibres and lack in advancement of processing technology made it difficult for it to compete with standardized blends of cotton and man-made fibres. In recent years, owing to environmental challenges and interest in eco-friendly sustainable and renewable products, flax fibre has enjoyed renewed attention as a natural alternative to petrochemicals and other non-renewable raw materials in various industrial products. This has led to numerous research institutions worldwide becoming involved in research in such areas as cultivar breeding, development of new fibre processing technologies and different fibre treatment approaches, all of which being largely aimed at improving flax fibre quality in terms of its fineness, uniformity and strength [121].

2.3.1 Environmental benefits

Transition to a more sustainable bio-based economy, as a political consequence of the Kyoto protocol on global climate change [10], includes a shift of feedstock for energy and chemical industries from petrochemical to renewable resources. Flax is a natural food source and industrial material that needs fewer pesticides, chemical fertilisers and water than most other comparable industrial crops. The utilisation of residues and waste for generation of energy, or other value added outlets, substantially enhances the overall ecological performance of the flax fibre crops. A comparison of the production phase of fibre crops with synthetic products or glass fibres shows that the score of the fibre crops, in terms of CO_2 and greenhouse gas emission levels, consumption of fossil energy and resources, is much better [121].

The crude mean evaluation of biodiversity friendliness of selected major crops, discussed under the Hemp Literature Review section, shows that flax outperforms most of the commonly known industrial crops [100]. The production of linen fabrics uses five to twenty times less water and energy than the production of similar cotton and synthetic fabrics [100]. By-products from the processing of natural flax fibre are recyclable and linen fabrics are biodegradable and recyclable, unlike most of the synthetic fibre by-products and products [101]. There is a worldwide increase in the number of consumers with strong environmental and social values who base many of their purchasing decisions accordingly in support of goods or products produced in a manner that does not cause irreversible damage to the ecosystem, flax being one such favoured product [122].

2.3.1 Cultivation practices

The soils most suitable for flax, besides the alluvial kind, are deep loamy soil that contain a large proportion of organic matter and have a pH ranging between 5 and 7. Heavy clays are unsuitable, as are soils of a gravelly or dry sandy nature. Flax exhibits better yields on medium to heavy textured and fertile soils, and because of its shallow rooting character, flax extracts 95% or more of its water from the top 71 cm of soil. Farming flax requires not much fertilizers or pesticides. Recommended nitrogen levels are currently 40kg/ha. High levels of nitrogen cause lodging. It is advisable to reduce nitrogen application in the year prior to sowing. Nitrogen levels in soil will vary depending on the previous crop. Measurement of nitrogen levels prior to sowing is important to allow for adjustment in application rates. Recommended levels of phosphorus and potassium are currently 50kg/ha each of P_2O_3 and K_2O. Fertiliser levels should be reduced if organic manure is applied. Flax is moderately tolerant to salinity, provided that fertility levels are suitable and adequate moisture is available during its germination. Fibre flax cultivars grow best in cool and moist climates and should be sown shallowly, 2.5 to 4.0 cm deep, in rows 15 to 20 cm apart, and a seeding rate of 30 to 45 kg/ha being recommended. [123].

Within 8 weeks of sowing, the plant will reach 10 to 15 cm in height, and will grow several centimetres per day under its optimal growth conditions, reaching 70 to 80 cm within fifteen days (Figure 37).

Figure 37. Flax plants grown at Tarkastad, Eastern Cape, South Africa [Source: own photo]

Flax is harvested for fibre production after approximately 100 days, or a month after the plant flowers and two weeks after the seed capsules form. When the base of the plant begins to turn yellow, it indicates the time is right for straw harvesting for fibre production. If the plant is still green, the seed will not be useful, and the fibre will be underdeveloped. The fibre degrades once the plant is brown, resulting in brittle stems that produce short fibres not suitable for processing. Flax is considered to be fully mature when 75% of the bolls have turned brown. After this stage has been reached, the crop may be swathed [124]. Fibre flax is harvested by a special pulling machine or may be pulled by hand. The flax is left in the field until dry, when the seed is threshed in such a way as to prevent breaking of the straw.

2.3.2 Global flax fibre production data

The global production of textile fibres was roughly 82 million tonnes in 2011, comprising about 44 million tonnes of synthetic, petroleum-based fibres; 5 million tonnes of manmade regenerated cellulose (wood) fibres (such as viscose); and 33 million tonnes of natural fibres. Within the natural fibre category, cotton represented about 27 million tonnes and the various types of flax fibre about 500 000 to 700 000 tons. Jute, wool, ramie, kenaf, silk, hemp, sisal, and coir represented the majority of other natural fibres within this total. These totals do not include wood fibres used to make paper (250 million to 300 million tonnes) or glass fibres of about 5 million tons [125, 126].

2.3.2.1 Major flax producing countries:

Figure 38, shows the agricultural database provided by the Food and Agricultural Organization (FAO) of the United Nations (UN), on flax production for the periods 1973-2011 (FAOSTAT data, 2011)[108]. The figure shows that the cultivated area for flax production declined from about 1 550 000 hectares in 1993 to more than 200 000 hectares in 2011.

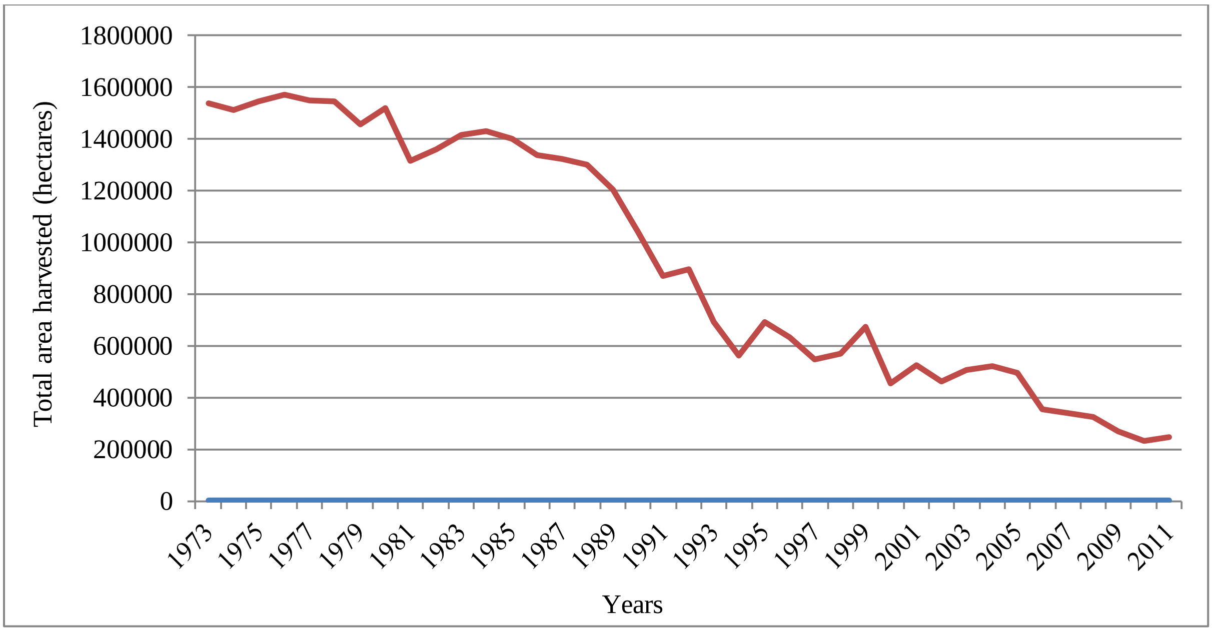

Figure 38. Global flax cultivation in the world in hectares [Source: FAOSTAT | © FAO Statistics Division 2013 | 13 March 2013 http://apps.fao.org][108]

Figures 39 and 40 show the 2002-2012 flax cultivated areas in hectares of leading flax producing countries in the world as provided by the Food and Agricultural Organization (FAO) of the United Nations (UN), with France, Belgium and The Netherlands being the top flax producers in Europe.

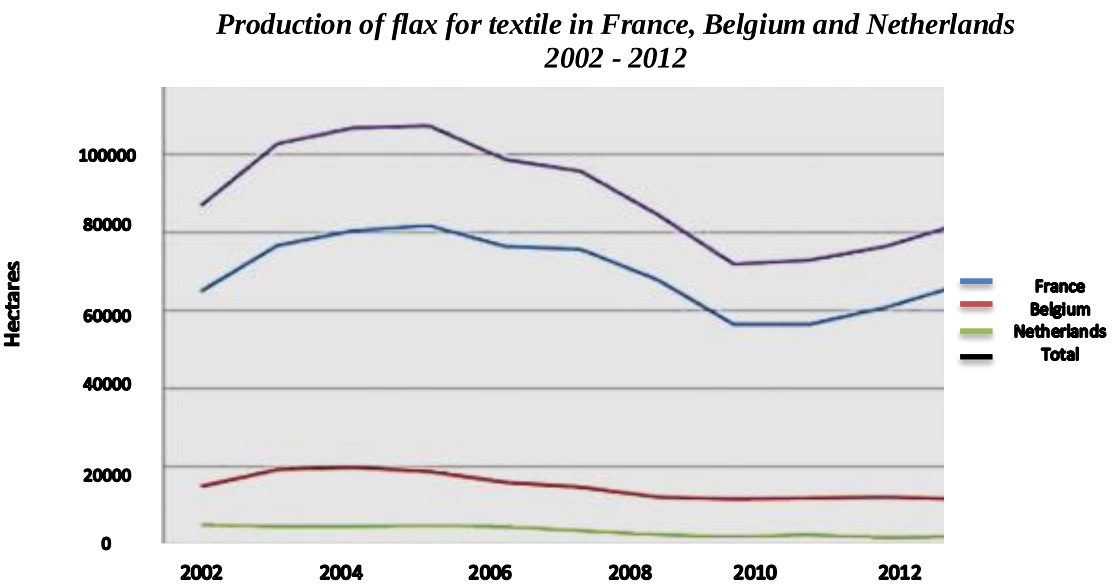

Figure 39. Flax primary cultivation in hectares by leading EU flax producing countries [Source : FAO].

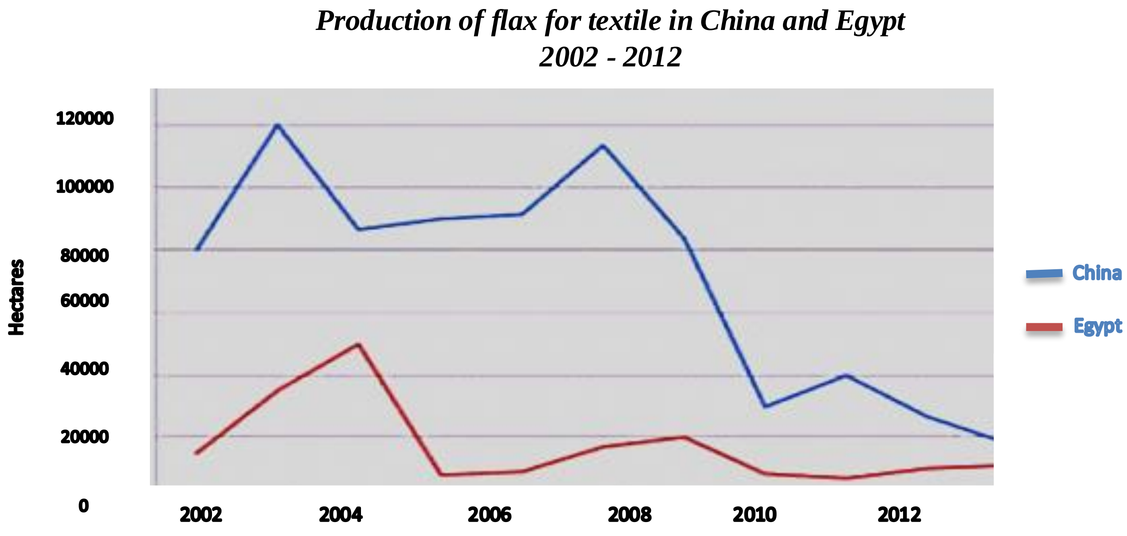

Figure 40. Flax primary cultivation in hectares for China (blue) and Egypt (red) 2002-2012 [Source: FAO].

The leading producers of flax fibre in Europe are France, Belgium and the Netherlands. Other significant producers are China, Belarus and the Russian Federation. The total area dedicated to flax cultivation for fibre is estimated at around 80 000 ha in Europe (Figure 39), and less than 200 000 ha worldwide (Figures 38). France accounts for more than 50% of the total area used for flax fibre cultivation in Europe, whilst China's production of flax fibre is estimated to cover 30 000 ha (Figure 40) [108].

In terms of flax seed production, Canada is the world's leader in the production and export of flax seed - a position it has held since 1994, followed by Argentina, Chile, USA and India. Canada is also the world's largest exporter of linseed for crushing. Saskatchewan is the single largest producer of flaxseed in Canada and, on average, accounts for 72 per cent of Canada's flaxseed crop production according to Statistics Canada's 10 year average production depicted in Figure 41 [126].

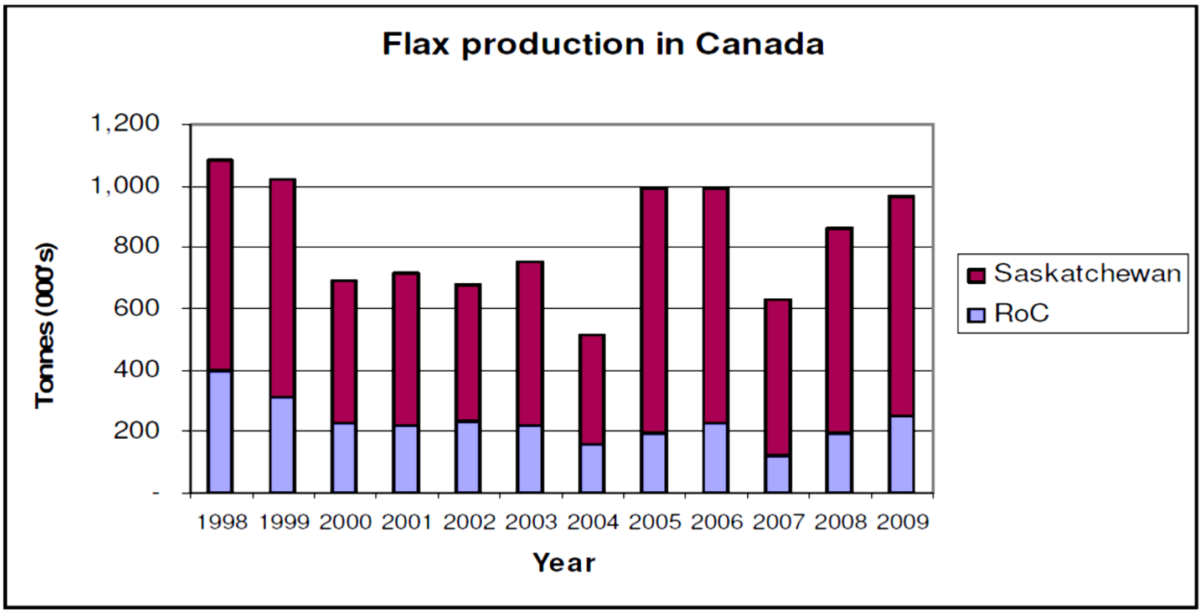

Figure 41. Flaxseed production in Canada (RoC = Rest of Canada) [126]

Table 7 illustrates the flax long fibre and tow production data ranked according to the production of the leading flax fibre producing countries in the world, published in the U.N. Food and Agriculture Organization's FAOSTAT database downloaded from FAOSTAT on 03/30/2012 [108].

Table 7. Flax long fibre and tow production data by country ranking for 2012 [108].

Rank	Country	Flax fibre and tow	Flax fibre raw	Flax tow waste	Flag
		Production (tonnes)	*Export Value (1000 US$)*	*Export Value (1000 $)*	
1	France	373,043	18,446	29,764	F
2	China	116,940	n/a	3,107	*
3	Belarus	45,782	n/a	807	
4	Russian Federation	35,220	n/a	183	
5	United Kingdom	14,300	22	n/a	Im
6	Belgium	11,520	464	22,210	
7	Netherlands	10,519	258	4,232	
8	Egypt	8,300	2,345	240	Im
9	Chile	2,800	n/a	9	Im
10	Argentina	1,800	n/a	n/a	Im
11	Italy	490	93	608	Im
12	Ukraine	400	n/a	n/a	
13	Czech Republic	370	n/a	152	Im
14	Poland	358	n/a	2,242	
15	Estonia	130	n/a	n/a	Im
16	Bulgaria	90	3	159	Im
17	Romania	80	n/a	n/a	Im
18	Latvia	42	133	71	
19	Lithuania	40	n/a	2,179	Im
20	Turkey	3	n/a	44	

Flags: *[ ] = Official data; * = Unofficial figure; Im= FAO data based on imputation methodology;F= FAO estimate.*

In terms of fibre yield, France, China, Belarus, Russia, UK, Belgium and the Netherlands are world leaders in flax fibre and tow production volumes. Fibres that are at least 50 cm long after scutching when arranged in parallel strands are classified as long fibres. Short flax is material less than 50 cm and, like hemp fibres, are obtained by at least partial separation of the fibres and the woody parts of the stem [127]. There are still some discrepancies in the capturing of flax production data, as indicated by the flag column, particularly for countries in Eastern Europe, South America and Asia. This suggests that these countries allow some of the fibre flax to mature to produce seeds which are harvested for cultivation in the following year, with the resultant straw being used to produce fibres [127]. The low quality extracted fibres are then used in non-textile application (e.g., paper) and may or may not be included in official statistics. Flax tow may also be sold with varying levels of shive (i.e., non-fibre) and hence one lot of tow from one country or area may not be the same as another lot of tow from a different country or area, in terms of its true fibre content. There are also external circumstances (e.g., local taxes) causing sellers or producers of such fibre to conceal the true quantities known so as to avoid paying taxes [127]. Straw and fibre may also be stored for more than one year before being sold or consumed – this coupled with a wide spectrum of accounting skills and motivations to record production, inventory, use and sales levels, directly impact on the statistical data capturing for flax fibre production in various flax producing countries [127]. Flax fibre production, processing and consumption statistics from Western Europe are much more dependable than those from China, Russia and Belarus [127].

Most of the global scutching mills are located in Europe, mainly in Belgium, the Netherlands and France, as well as in the Russian Federation, Ukraine, Belarus and Poland. The largest spinning mills in Europe are located in Italy, Belarus and Russia. China grows and processes fibre flax on a large scale using manual harvesting techniques, with processing being done by big scutching mills. Pure and blended linen fabrics are produced in many countries in the world, such as Italy, Ireland, China, Russia, but also in Lithuania and Poland [127].

2.3.2.2 Flax Markets

Flax has been used throughout the world for a variety of purposes, with its early use being in textiles, because of the tough and durable nature of flax fibres. The high quality, top grade long flax fibres are used for spinning into yarn for weaving of linen fabrics, such as damasks, lace and sheeting, whilst poorer (rougher) grades of fibres are used for the manufacture of twine and rope. The use of flax fibres in industrial applications is approximately as follows:

54% in apparel, 20% in household goods, 17% in technical applications and 9% in furniture coverings [128].

Flax fibre is also a raw material for the high-quality paper industry for the use of printed banknotes and for rolling paper for cigarettes. Novel applications for the shorter flax fibres in non-textile markets now exist, including in packaging materials, reinforcements for plastics and concrete, asbestos replacement, panel boards, lining materials for the automotive industry, alternatives for fibreglass and insulation. There is already a high penetration of flax fibre based nonwovens in the automotive sector, driven by the EU regulations on the disposal of used cars [129]. The largest potential market for fine flax fibre is in blends with other textile fibres, especially polyester, for ultimate conversion into apparel and industrial textiles [130]. Global trends toward sustainable development have brought to light natural, renewable, biodegradable raw materials, including flax fibres. Science and technology continue in extending flax use in textile and other industries. The recent increase in consumer environmental awareness, along with an increased commercial desire to use natural materials, has led to a number of new innovations and applications for flax fibre. Composites derived from synthetics are currently occupying many market sectors, of which a number are suitable for the introduction of natural fibre composites as an alternative. Currently, the largest areas in which natural fibre composites are being used, include the automotive and construction industries. The two most important factors, now driving the use of natural fibres by the automotive industry are cost and weight, but ease of vehicle component recycling is also an ever increasing consideration to meet the requirements of the end of life vehicle directive. An estimated 19 000 tonnes of flax fibre are currently used in the manufacture of auto-components in Germany [131]. The construction industry constitutes the second largest sector to employ natural materials, in which flax fibre can be used in a range of products, such as light structural walls, insulation material, floor and wall coverings and geotextiles.

Flaxseed has been used for many years as a food source, and recently there has been an interest in exploring the potential medicinal and neutraceutical value of flax. Flax seed is an important source of omega-3 fatty acids that are useful to humans. Products which have been produced from the seeds, include flaxseed oil and flax meal which, due to its high protein content, is used as a livestock feed. Other areas of opportunity exist in the neutraceutical, food (dietary fibre), industrial (anti-spalling treatment for concrete to prevent breakup, drying agents for paints and varnishes) and livestock feed industries [132].

Enhanced technical know-how on all aspects relating to flax fibre value addition, starting from breeding to high niche application areas, by researchers worldwide is driven by heightened consumer environmental and health awareness. These represent the key driving force fuelling world interest and uptake of flax seed and fibre for use in various industrial systems (textiles, technical textiles and foods) that will continue to lead to more and more flax based products entering the marketplace in the future.

Flax crop has a value chain tree demonstrating its industrial usage similar to Roulac's hemp value chain tree illustrated in Figure 29 in Section 2.2.

Global trends driving interest in the use of flax fibre.

There is a resurgence of interest in flax, as a versatile low-input crop, which, in addition to fibre, produces products from virtually every part of the plant useful for various industrial applications. Several developments are changing flax straw from being seen as a "problem" into a new "opportunity." It is even feasible that some growers will in future grow fibre flax (i.e. linen flax) instead of oilseed flax and receive the majority of their income from the straw and not from the seed. However, management and technical requirements, and planting and processing costs will also increase if a higher net income from flax straw is to be realized and if rural communities want more value-added processing of the flax straw. The potential use of the flax crop includes, but is not limited to, the following differentiated product lines [133]:

- *Flax fibre composites:* Flax fibre is being used as a reinforcement and filler to produce flax fibre composites, with synthetic polymer acting as a binder. The automotive industry is the driving force behind the use of flax fibre in the production of environmentally friendly automotive components.
- *Flax fibre bio-based construction:* The use of flax fibre and other bio-fibre materials, i.e. fibres originating from natural resources, in the manufacture of home and commercial construction products is gaining momentum worldwide owing to environmentally sound and innovative building practices and products or materials that are cost effective with superior features.
- *Biofuel production:* Flax straw has the potential to be a valuable biofuel, even without being processed into ethanol or bio-oil, burned as-is, it has a heating value similar to soft coal, with two great advantages: it's cheaper, and it's carbon-neutral, because the carbon released by burning flax straw is taken up during the growing season by the next year's crop.
- *Technical textiles:* Currently, most geotextile and insulation products for use for slope stabilisation during road construction and in building construction are made from synthetic fibres. The use of alternative natural fibres, such as flax, in the manufacture of geotextile and insulation products, is on the increase because they can degrade and decompose easily during their disposal in landfills.
- *Linen fabric production:* The use of long and biotechnologically treated flax fibre for linen production will continue to constitute a major use of flax, since cotton production will not satisfy the demands of the growing population for comfortable apparel fashion products. Success in technological developments, to produce cotton-like flax fibre that is

easily spun in reasonable blends with other fibres on short staple systems, will provide stiff competition to cotton and capture some of its global market share.

- *Pulp and paper:* The value of bast fibres, as a component in paper pulp, is widely acknowledged. Small pulp mills for processing flax and other specialty fibres have been established in Britain, Spain, Eastern Europe and Asia for the production of speciality paper. Specialty paper markets include currency, cigarette papers, filter papers, and tea bags. The use of these fibres for pulp and paper production is driven by the global pressure to address deforestation as well as rising wood prices and regulatory practices. With the tightening of the domestic wood chip supply, there is a strong upward price pressure, and the pulp and papermaking companies are constantly looking for alternatives to replace wood chips [134].

According to Lucintel [77], the increasing use of natural fibre composites in automotive applications is driving the market and is expected to remain the largest market until at least 2016. The automotive industry's adoption of natural fibre composites is led by price, weight reduction and marketing incentives, rather than by technical demands. The range of products is no longer restricted to interior and non-structural components, such as door panels or rear shelves. In terms of value shipment, Europe is expected to continue its dominance, accounting for more than 50% of the worldwide market. North America is expected to be the second-largest region and the rest of the world will be at third in terms of value shipment by 2016. It is forecast that the natural fibre market will experience an 11% CAGR during this period [77]. In the future, Lucintel expects higher market fragmentation due to emerging economies that will be highly competitive, and in which companies with innovative capabilities will thrive and gain market share [135]. In many cases, this innovation is, and will be, primarily driven in part by a greater understanding and exploitation of natural fibres, such as flax, at the macromolecular level for process optimisation for niche value added products.

2.4 South African flax & hemp fibre sector overview

The attainment of democracy in 1994 brought about the possibility for South Africa to address poverty and inequality and to restore the dignity of its citizens and ensure that South Africa belongs to all who live in it. In line with the democratic dispensation and in pursuit of constitutional imperatives guaranteeing a rights-based environment and the rule of law, new policies were put in place to improve people's quality of life. Table 8 provides some brief country data about South Africa [9].

Table 8. South Africa at a glance [9].

Indicator	Values	
Real GDP (2012)	R2 880 billion	USD408.24 billion
Real GDP per capita (2011)		USD3131.59
Adult Literacy Rate	Male – 87.2	Female – 86.9
Population Total (2011)	Total	50 586 757
	Male	24 515 036
	Female	26 071 721
Land surface area		1 220 813km²
Key economic sectors	Mining services, transport, energy, manufacturing, tourism, agriculture.	

As a member state of the United Nations, South Africa is a signatory to the Millennium Development Goals (MDGs) and targets that come from the Millennium Declaration, signed in September 2000 by 189 countries, including 147 Heads of State and Government, and a further agreement by member states at the 2005 World Summit (Resolution adopted by the General Assembly). The eight MDGs are [136]:

- To eradicate extreme poverty and hunger
- To achieve universal primary education

- To promote gender equality and empower women
- To reduce child mortality
- To improve maternal health
- To combat HIV/AIDS, malaria and other diseases
- To ensure environmental sustainability
- To develop a global partnership for development

The goals and targets are interrelated and should be seen as a whole. They enjoin both the developed and the developing countries to work together, through a partnership, for the development of its people and the elimination of poverty.

In the South African context, poverty and unemployment remain structurally inter-linked. The employment to population ratio in South Africa since 2001 is low, averaging 51% for males and approximately 37% for females, the national average being approximately 43%. This ratio suggests a high level of unemployment in South Africa which, although declined from a high of 29% in 2000 to a low of 25.5 % in 2009, still remains high by any standard [9]. Figure 42 illustrates the result of the South African labour force survey conducted between 2000 and 2008.

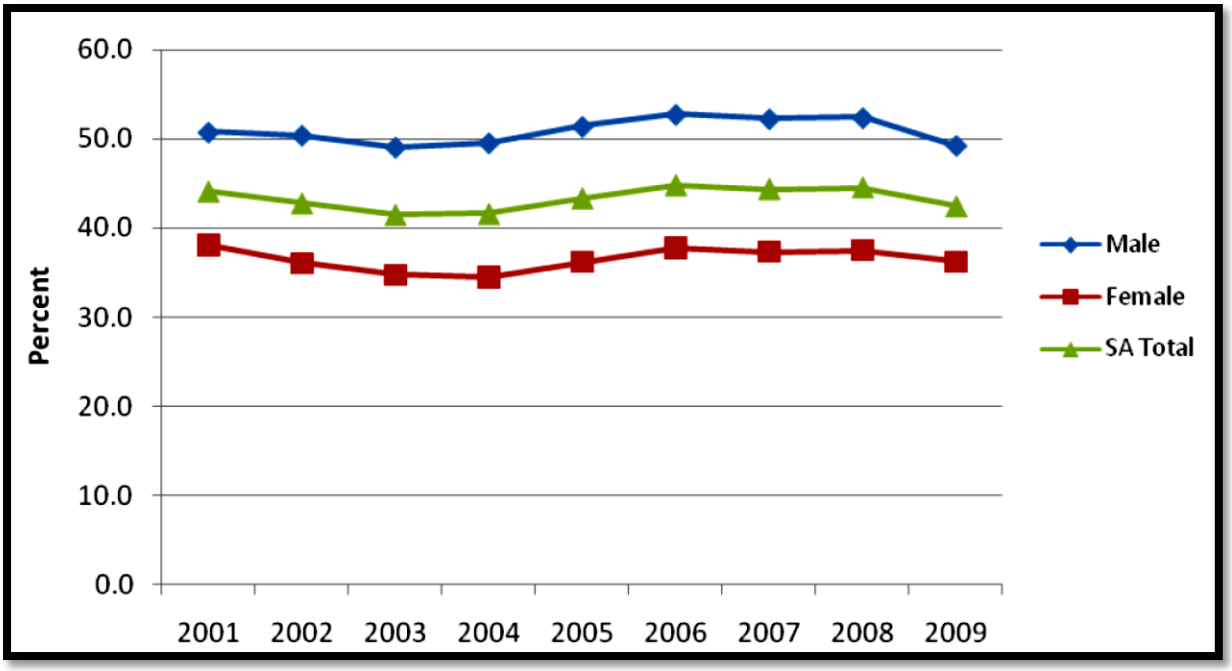

*Figure 42. Employment to population ratio (*Source: Labour Force Survey 2000-2008, Quarterly Labour Force Survey 2009).

The development of the flax and hemp fibre industry in South Africa should be seen within the context of addressing some of the socio-economic challenges confronting the country today and its attempts to bring about real development in the rural areas through the cultivation and complete beneficiation of these fibre crops. This would have a direct impact on the alleviation of unemployment, poverty and underdevelopment, and also boost the manufacturing sector in the country. All relevant local stakeholders, namely government, research councils, tertiary education institutions, farmers and communities, are involved in efforts to investigate the commercial cultivation, processing and manufacturing of flax and hemp fibre crops in South Africa.

2.4.1 Agricultural feasibility

A study of the agricultural potential for flax and hemp in South Africa was carried out by the Agriculture Research Council – Institute for Soil, Climate and Water (ARC-ISCW) and was based on the data bank of local climatic conditions covering the whole country and are represented in Figures 43 and 44 [137]. The maps indicate those areas rated suitable for the growing of these two fibre crops under rainfed conditions, if acceptable cultivation, fertilisation and best farming management practices are applied. The green colour indicating the areas with the highest prospects, and the brown colour indicating areas with moderate prospects, and purple colour indicating areas with marginal prospects for flax and hemp cultivation in the country.

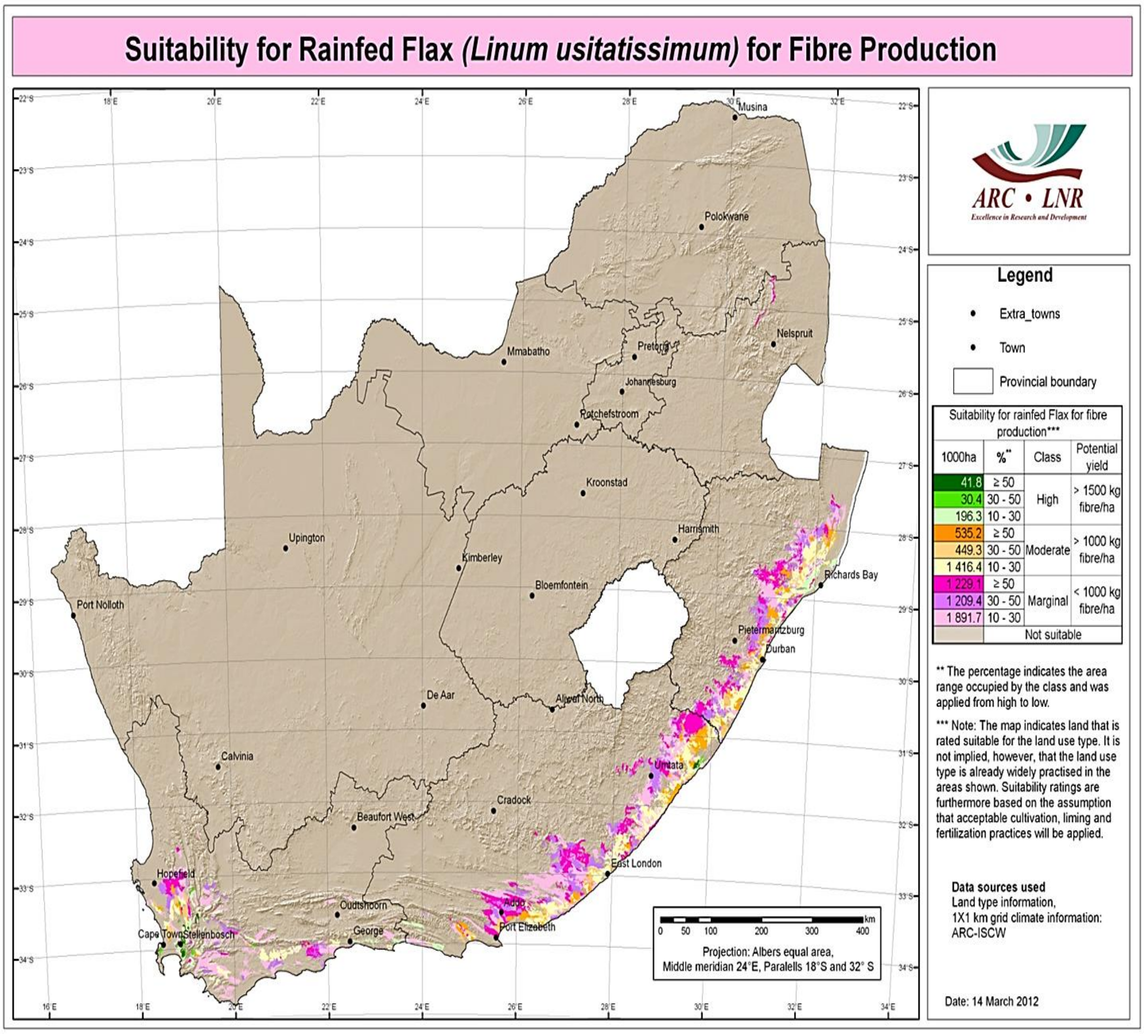

Figure 43. Suitable areas for flax cultivation in South Africa [137]

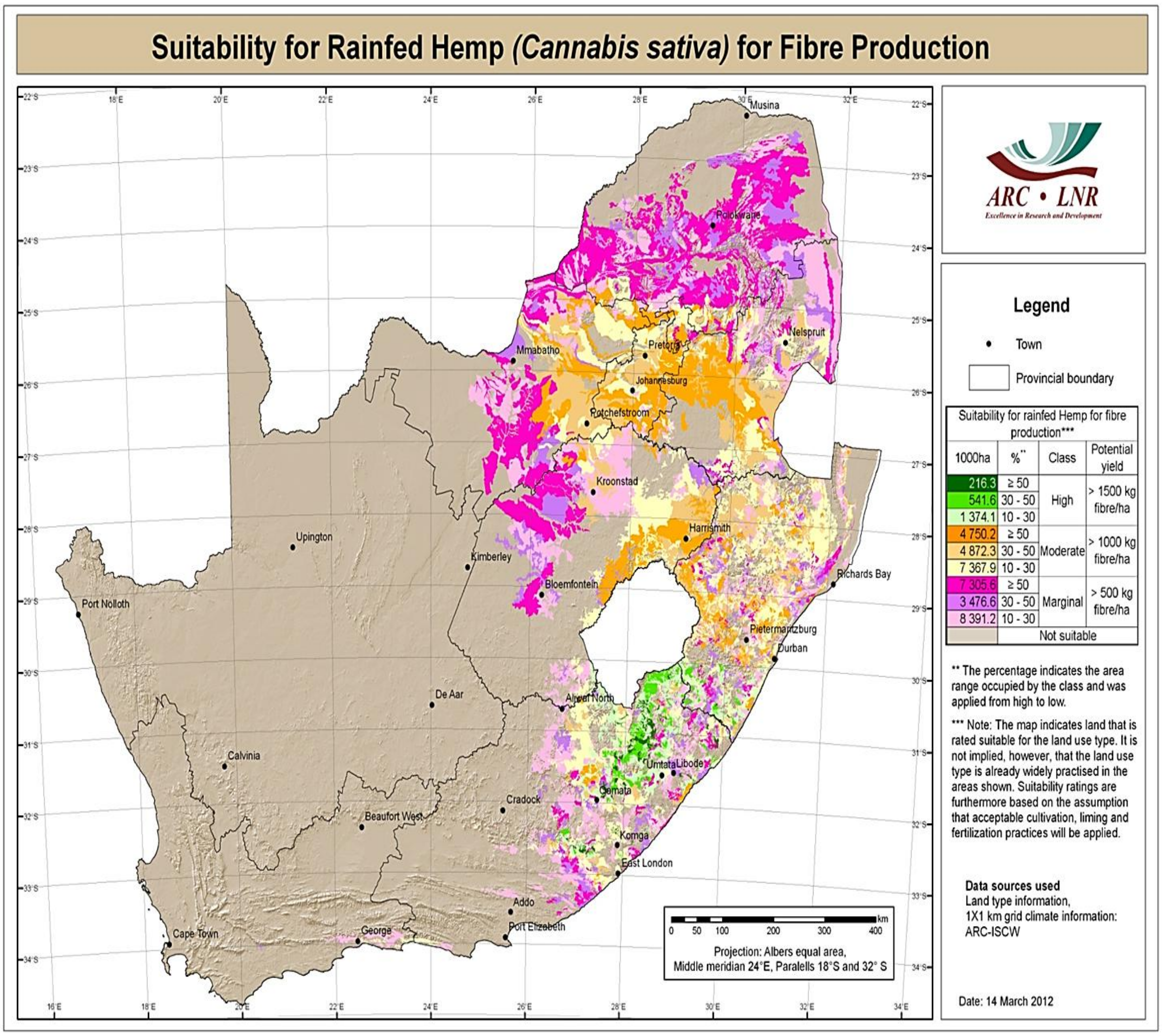

Figure 44. Suitable areas for hemp cultivation in South Africa [137]

It should be noted that the analysis of the suitable climatic conditions for the cultivation and field retting of flax and hemp was carried out on the basis of natural (i.e. rainfed) climatic conditions, and that the opportunity exists that these crops could be grown in numerous other regions under irrigation. Thus, there is a very strong possibility that flax and hemp cultivation areas could even be larger than the ones shown in the two maps.

2.4.2 Production potential

There is currently no primary production and processing of flax or hemp fibre crops in South Africa, except for the agronomic research trials that were undertaken to investigate the adaptability of the two fibre crops to local climatic conditions. The research trials proved that both flax and hemp fibre crops could be grown successfully in South Africa as detailed in Chapter 2.1. The only successful commercial trial on flax cultivation, done under irrigation, was conducted by the Industrial Development Corporation (IDC) at Brits in the North West Province in the 1990s, producing tonnes of long flax fibres, having similar fibre properties to those of the leading flax producing countries. No commercial hemp cultivation trials have ever been undertaken in South Africa as it is still illegal to commercially cultivate hemp in the country. This is due to the fact that the current legislation on *Drug Trafficking and Related Substances Act* does not make a distinction between hemp and its narcotic *Cannabis sativa* variety. The plant is currently grown only for experimental or research purposes, under a licence from the Department of Health (DoH), which issues permits for growing hemp for these specific purposes only [138].

There are several research projects underway in South Africa to investigate the viability of flax and hemp fibre crop cultivation and processing, as well as their subsequent use in high niche applications. The Western Cape Province leads efforts in investigating the commercial potential of flax cultivation, whilst the Eastern Cape Province is leading in hemp research trials and subsequent commercial cultivation opportunities. The Agriculture Research Council-Institute for Industrial Crops (ARC-IIC) leads the agronomic research and is ably assisted by provincial departments of agriculture, whilst the Council for Scientific and Industrial Research (CSIR) is the lead organisation on all post-farm gate activities, including fibre extraction, processing and product development.

Notwithstanding the absence of the commercial primary production of flax and hemp fibre crops in South Africa, the national government recognises the potential socio-economic benefits that could be derived from these crops for the country and included their commercial beneficiation potential in its Industrial Policy Action Plan (IPAP) – 2009/13 documents.

IPAP articulates the country's key manufacturing sectors that government has identified as important in reviving the economy of the country so as to address unemployment, poverty and underdevelopment [139,140]. The primary target markets, other than textiles, is in the biocomposite industry development, such as automotive, construction, aerospace and packaging.

2.4.3 Trade analysis

South Africa has been, and still is, a net importer of flax and hemp fibres, yarns and final products. Although hemp is not legally produced in the country, demand for hemp products is expanding, thus resulting in South African manufacturers importing them from other countries. It would appear that South Africa imports raw hemp fibre for processing purposes and then exports the processed products.

Tables 9 and 10 illustrate the trends in South Africa's flax and hemp imports and exports over the period 2006 -2010 [141].

Table 9. South African flax imports and exports (Source: Statistic South Africa)

PERIOD	IMPORTS		EXPORTS	
	***Trade Value* (U$D)**	***Net Mass* (kg)**	***Trade Value* (U$D)**	***Net Mass* (kg)**
2006	1 489 586	511 054	4 414	1 438
2007	607 442	194 850	848	316
2008	1 723 371	373 864	20 858	1 316
2009	916 454	235 484	5 332	302
2010	1 584 390	445 010	3 388	106

Table 10. South African hemp imports and exports (Source: Statistic South Africa)

PERIOD	IMPORTS		EXPORTS	
	***Trade Value* (U$D)**	***Net Mass* (kg)**	***Trade Value* (U$D)**	***Net Mass* (kg)**
2006	355	50	3 678	468
2007	7 478	1 262	1 191	1 370
2008	61 266	1 760	16 113	3 260
2009	3 072	196	11 509	1 428
2010	4 968	406	17 506	8 814

South African manufacturers import more flax than hemp, both in raw and fabric form, for the production of different products. South Africa has one flax yarn spinning operation, known as Herdmans, located in the Western Cape Province that imports flax sliver and converts it into 100% pure flax (linen) yarns for primarily the domestic and international markets. The significant volumes of flax imported into South Africa are due, in part, to the existence of this flax processing mill. The other local textile mills import flax yarns for the production of fabrics to satisfy the local market demand, and hence the low volumes of exported flax products.

The low traded volumes of hemp materials in South Africa could be explained in two possible ways, namely;

- that the global hemp fibre and tow production has been in decline, falling from over 109 500 tons in 2006 to just under 66 700 tons in 2008. Hemp producing countries, of which China accounts for close on 84% of hemp primary production, are producing hemp largely for their own consumption, as less than 7% of hemp is globally traded.
- legislation making hemp growing illegal in South Africa has resulted in uncertainty on the legal status of products derived from hemp, causing the local manufacturers

and entrepreneurs to act on the side of caution regarding the import and export of hemp products.

The discrepancies in the traded volumes of hemp imports and exports in South Africa can be attributed to the following:

- there is no legal and formal hemp producing sector in South Africa, and therefore there is no local data on its production, and
- the large export volumes of hemp are mainly destined for the SADC region, there being no duties paid in exporting hemp to the region.

According to the FAO fibre crops import/export data, the leading exporters of flax to South Africa are Belgium, Ireland and Belgium, whilst for hemp it is mainly Germany and the Netherlands, with small amounts coming from other European countries [108].

2.4.4 Industry challenges

Research aimed at investigating the adaptation trials of European flax and hemp cultivars to local South African climatic and agronomic conditions indicated that these cash crops could be grown in South Africa without negatively impacting on agricultural land and food security. Nevertheless, the lack of industry structures in South Africa, similar to those that exist in flax and hemp producing countries, for the commercial exploitation of fibres derived from flax and hemp across the value chain, as represented in Figure 45, demonstrates the weak industrial linkages which impact negatively on the development of globally competitive local flax and hemp industrial sectors [110].

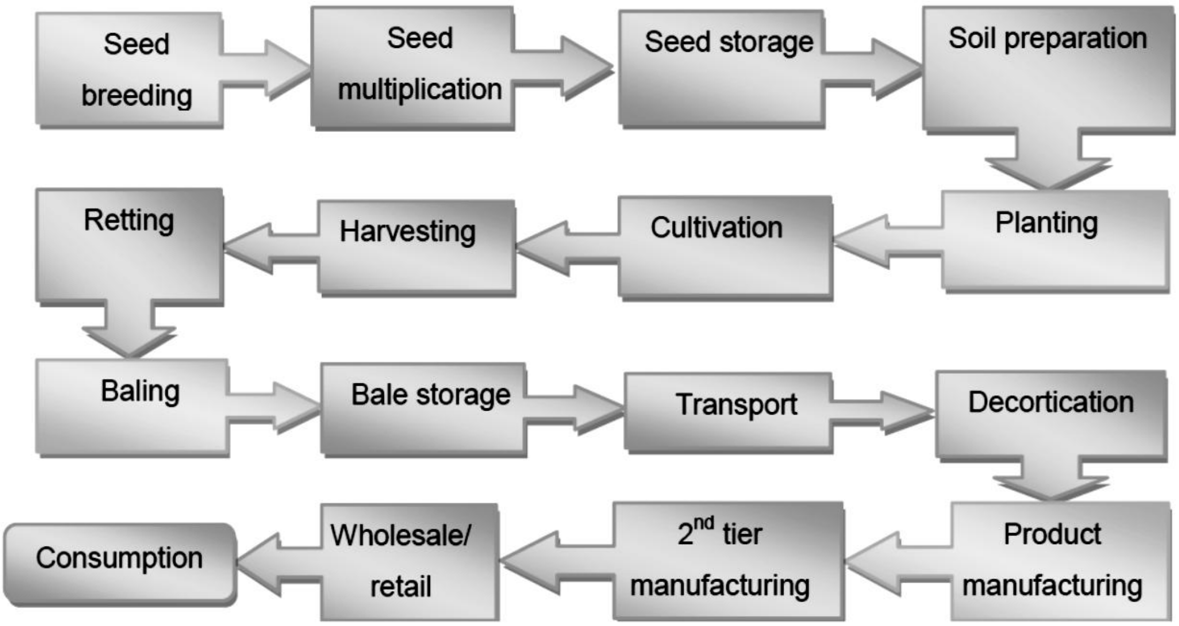

Figure 45. Flax and hemp market value chain [Source: Department of Agriculture, Forestry and Fisheries (DAFF, SA)]

Notwithstanding the fact that a number of local stakeholders, such as government; research institutions; parastatals; private sector and subsistence farmers, are involved in research and development activities aimed at establishing a flax and hemp industry in South Africa, a lack of strong coordination of individual stakeholder research work further weakens any industrial linkage opportunities for the establishment of such an industry. The low numbers of people with the requisite strong technical expertise in the breeding, cultivation, processing and production of flax and hemp fibre crops, as well as underdeveloped production technologies, negatively impact on the industrial potential to mass produce fibres with specific properties for utilisation by the different local fibre market segments.

To be successful, flax and hemp fibres will be required to match or surpass the performance characteristics of currently used feedstock or materials by manufacturers and other potential customers, without interrupting the production line. In addition to performance characteristics, processing implications and raw material price, the commercial entities using these fibres place a heavy emphasis on the reliability of raw material supply over the duration of their yearly production schedule. The risk to the company - in terms of financial, market share and reputation - of not delivering a product as per market demand, even if the environmental benefits are promising, is simply too great for it to become actively involved in this market segment.

The current legislative and regulatory constraints and challenges in South Africa do not permit the large scale commercial cultivation of hemp, thus hampering its viability, growth and development potential [138]. The legislation that needs to be amended to allow for full scale hemp commercialisation includes:

- The Medicines and Related Substances Act, 1965 (Act No 101 of 1965), which requires that a permit should be obtained from the Department of Health (DoH) in accordance with Section 22A (9) (a)(i) of this Act, and
- The Drugs and Drug Trafficking Act, 1992 (Act No 140 of 1992), which describes hemp as dagga. The Act prohibits the possession, processing, transportation and commercialization of hemp materials.

To unlock the country's potential for hemp market, it is proposed that this sector should be regulated through a permit system for all those stakeholders, from breeders to manufacturers, with a commercial interest to partake in the hemp industry.

In summary, the key challenges faced by flax and hemp industry development in South Africa relate to the strict government legislation (for hemp), the availability of more arable land for non-food crops, poor infrastructural rail services to transport unprocessed biomass (which is usually bulky), availability of the technical expertise (in breeding, agronomic and processing) as well as cultivation, harvesting, extraction and processing technologies.

2.4.5 Markets

The development and commercialisation of advanced materials based on natural resources (Advanced Biocomposites), that include flax, hemp and kenaf, has been identified as a key industry development cluster in the Industrial Policy Action Plan (IPAP2) of the Department of Trade and Industry. The Biocomposites strategy aims to concurrently develop a number of selected product technology platforms for downstream value addition, as well as to strengthen and develop the upstream production of high quality natural fibres and other required raw materials. The establishment of a successful South African Biocomposites Industry will contribute significantly to economic growth and the increased competitiveness of the South African economy. An opportunity analysis for South Africa showed that, for a fully developed local biocomposites industry, there will be a potential market for natural fibres of between 10 000 to 15 000 tons per annum. The associated employment is estimated at 11 000 to 15 000 jobs in upstream plant cultivation and fibre extraction/processing, and an additional 2 500 to 3 000 jobs in the downstream manufacturing industries [7]. Figure 46 illustrates the fact that the SA agricultural sector has not reached its full potential in being one of the major employment creators in South Africa, and has shed thousands of jobs over the years. The successful development of a flax and hemp industry will play a significant role in alleviating this downward trend in agricultural employment numbers.

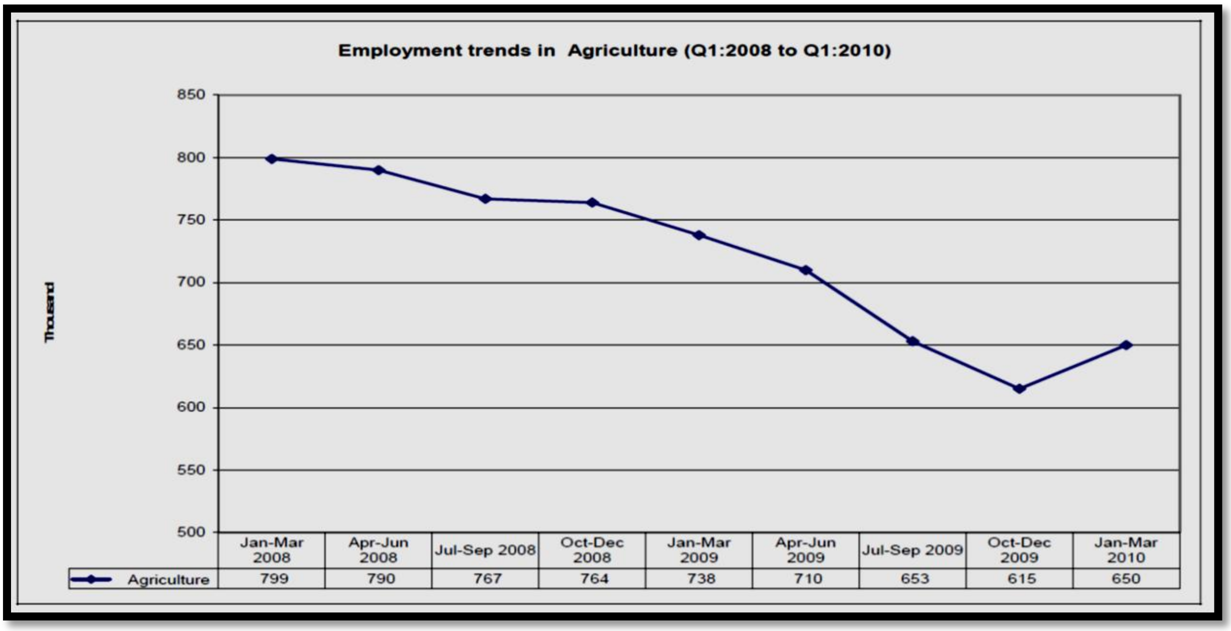

Figure 46. Employment trends in Agriculture in South Africa [Source: QUARTERLY LABOUR FORCE SURVEY: Quarter 1 (January to March Q1:2008 to Q1:2010), 2010]

Other than the applications in the textile and apparel sectors, the South African biocomposite strategy has identified key industrial sectors, such as the automotive, aerospace, building and construction, packaging and generally moulded biocomposite application areas, in which flax and hemp fibres could be used and thus form an integral component of the overall thrust to establish a SA bast fibre (flax, hemp and kenaf) industry.

Figure 47, originating from the recent South Africa Statistics report of 2012, show South Africa's manufacturing sales values over the 12 year period demonstrating the vibrancy of the local sector. As can be seen from Figure 46, the South African manufacturing sector has grown by 400% in the last 12 years.

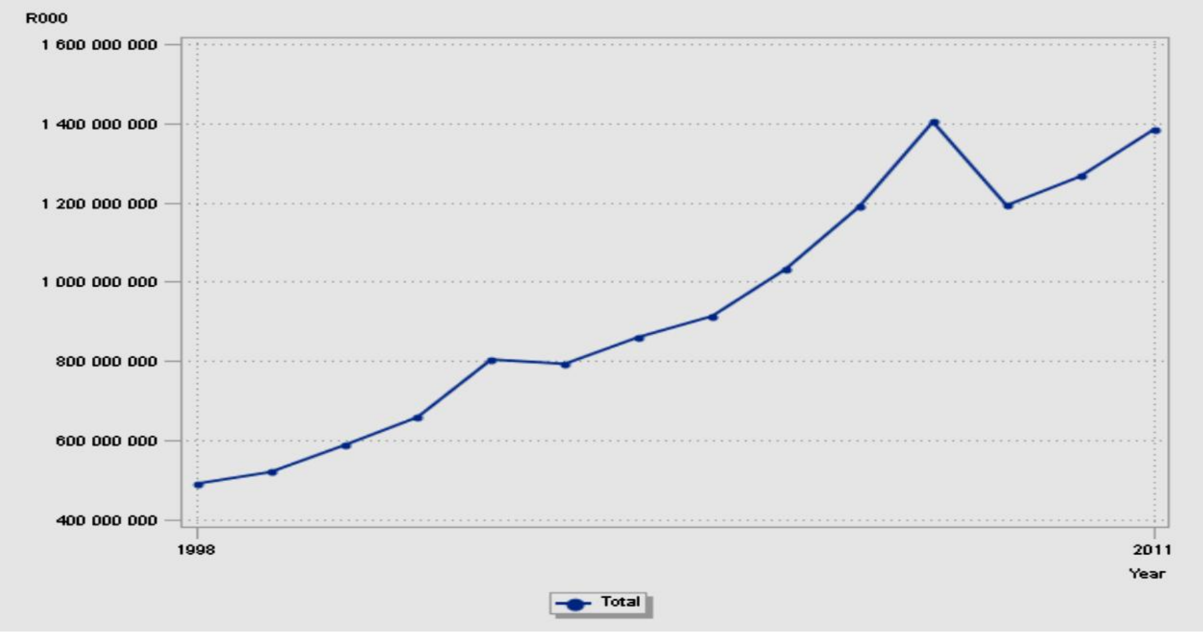

Figure 47. South Africa Manufacturing Sales Values between 1998-2011 [Source: Stats SA, Manufacturing: Production and sales (Statistical release P3041.2)]

Table 11 illustrates market opportunities in selected manufacturing subsectors for the use of natural fibres derived from flax and hemp could be used as a substitute material for the manufacture of environmentally friendly products in key sectors of the economy as is already the case in leading developed countries in the world, specifically in terms of the production of natural fibre reinforced biocomposite products which can form the basis for the local bast fibre industry development.

Table 11. SA sales values [in R000] of manufacturing sub-sectors in which natural fibres (including flax and hemp) can possibly have significant market share.

Year	Spinning, weaving and finishing of textiles	Textiles products other than weaving & spinning	Plastics	Paper & paper products	Car parts, accessories and engines	Furniture
1998	5 162 955	8 292 602	11 894 940	19 719 368	17 859 133	5 447 119
1999	5 003 690	8 816 582	12 123 588	21 926 523	20 210 538	5 919 371
2000	5 111 644	9 473 346	13 544 172	25 046 169	27 696 447	5 823 648
2001	5 527 912	10 320 927	15 293 901	27 047 292	32 566 763	5 799 844
2002	6 868 474	12 138 425	18 886 880	32 027 240	40 561 624	6 759 477
2003	6 487 230	11 353 789	19 890 881	32 115 310	40 040 728	7 189 920
2004	6 170 187	12 474 523	21 460 161	31 910 935	41 995 265	8 276 506
2005	5 144 998	13 617 204	22 613 951	31 358 435	46 437 497	9 305 924
2006	5 140 468	14 420 942	26 388 420	35 776 116	55 986 610	10 392 202
2007	5 443 983	14 961 471	32 219 535	38 310 051	68 773 358	10 930 879
2008	5 455 297	14 868 824	36 740 820	45 959 873	73 066 550	11 234 103
2009	4 843 882	11 911 517	38 478 018	42 844 378	48 904 780	9 958 003
2010	4 434 749	11 285 992	42 178 372	47 056 025	56 427 275	10 639 747
2011	4 426 801	11 406 902	44 817 181	48 571 169	62 802 464	11 613 033

Source: Source: Stats SA, Manufacturing: Production and sales (Statistical release P3041.2)

Recent successes in the biotechnological modification of flax and hemp fibres for the production of tailor-made fibres, e.g. "cotton-like", for application in the textile and pulp & paper commodity markets, as well as advances in science and technology research and development, will significantly make bast fibres more economically appealing to the local manufacturing sector and industry as a whole.

According to the House of Hemp (HoH), the local demand for flax and hemp fibres for the automotive, construction and paper industries is estimated at 28 400 tonnes per annum [142]. South Africa's annual vehicle production is estimated at 570 000. Assuming a current average global usage of 3 kg fibrous components per vehicle this implies that there is a latent growth potential of some 1 710 tons per annum for fibre in the local automotive industry. This can be grown on about 1000 hectares of land, creating 3000 seasonal jobs (assuming that 3 jobs are created per hectare).

The availability of huge tracts of land in rural areas that presently under-utilised and associated low production costs on growing flax and hemp, due to advancement in breeding of local cultivars and agronomics, demonstrate the ability to grow flax and hemp, field ret, decorticate, scutch and mechanically modify the fibres in South Africa to develop innovative textile and biocomposite products, and access to large potential domestic and SADCC / Africa markets, will provide important competitive advantages for the flax and hemp industrial sector in South Africa. Currently there exists in the country an industrial scale size Temafa Lin line bast fibre separation equipment with a capacity to process 4 tonnes per hour of retted bast fibre straw.

In terms of Economic Value-add, it is estimated that the potential size of the local industry, primary agriculture fibre production and biocomposite product manufacturing, when fully developed would be [7]:

- Fibre production (rural): R300 – 350 million p.a.
- Final products: R 2 – 2.5 billion p.a.

CHAPTER 3. EXPERIMENTAL, RESULTS AND DISCUSSION

Chapter 3 is broadly divided into three main parts, namely Part I dealing with hemp, Part II dealing with flax and Part III dealing with the cottonisation of hemp and flax.

PART I: THE PERFORMANCE OF EUROPEAN HEMP CULTIVARS UNDER SOUTH AFRICAN AGRONOMIC CONDITIONS

3.1 Effect of Agronomic Parameters on Hemp Biomass and Fibre Yield

3.1.1 Introduction

Industrial hemp (plant species *Cannabis sativa*) has been grown for hundreds of years in many countries as a raw material source of fibre and oilseed for the production of a variety of industrial and consumer products [12]. It is estimated that more than 30 countries are presently involved in hemp production as an agricultural commodity used in a variety of industrial applications [143]. Studies indicate that hemp grows well under a variety of climatic conditions and soil types, particularly in regions with temperate climate and a daylight length of preferably 14 hours or more. There is no history or local experience of the primary production and processing of hemp in South Africa, since the commercial cultivation of hemp in the country has been, and still is, prohibited by law. To effect any relaxation of the current legislative prohibition on the commercial cultivation of hemp, and elicit interest from both commercial and subsistence farmers to grow it as a cash fibre crop, compelling evidence, based on scientifically planned actual agricultural trials was necessary to demonstrate the commercial potential and viability of hemp cultivation in South Africa.

In the years between 1999/2000, the ARC-IIC and CSIR, supported by the relevant government departments, obtained permits from the National Department of Health to conduct trials aimed at establishing the optimal agricultural parameters required to produce hemp fibre yields similar to those achieved in other hemp producing countries. In all, a total of four European (EU) hemp cultivars, namely Novosadska (Yugoslavia), Futura-77 (France), Felina-34 (France) and Kompolti (Hungary) and four planting sites in the Eastern Cape Province, namely the Addo Research Station (referred to as Addo), Dohne, Libode and Qamata, were used in these trials [144]. The use of EU hemp cultivars in agronomic trials in South Africa was motivated by the fact that all hemp cultivars bred in the EU are certified to contain less than 0.2 % of tetrahydracannabinol (THC), which is the principal psychoactive constituent of the cannabis plant, which distinguishes it as industrial hemp for fibres. The selection of cultivars was done by the ARC-IIC and was based on seed availability. Table 12 summarises the various agronomic trials.

Table 12. Summary of agronomic trials.

Experiment 1: Effect of Row Spacing and Seeding Density
Objective: To determine optimum row spacing , seeding rate, and population density ***Cultivar :*** Novosadska, a cultivar originating from Yugoslavia **Straw samples tested:** 5 subsamples, of 2kg each, were evaluated for each cultivar sample **Spacing (Factor 1):** 12.5cm (S1) ; 25.0cm (S2) and 50.0cm (S3) **Density (Factor 2) seeding/hectare :** 50kg (D1) ; 80kg (D2) and 110kg (D3) **Combination used: (**S1D1); (S1D2); (S1D3); (S2D1); (S2D2); (S2D3); (S3D1); (S3D2); and (S3D3) **Planting site :** Addo
Experiment 2: Effect of Weed Control Treatment
Objective: To identify and select a suitable herbicide and weed control method **Cultivar:** Novosadska; Felina-34 and Futura-77, the latter two cultivars originating from France **Straw sample tested :** 5 subsamples, of 2kg each, were evaluated for each sample **Herbicide used:** Accotab, Frontier Afalon and Dual S, at the recommended dosage **Control:** Weed removal by hand **Planting Site :** Addo

Experiment 3. Effect of Planting Date

Objective: To evaluate the effect of planting date on fibre yield
Cultivars: Novosadska; Felina-34, Futura-77 and Kompolti, the latter from Hungary.
Planting dates: October and November
Straw sample tested : 5 subsamples, of 2kg each, were evaluated for each sample
Planting method : Cultivars were all planted at a seed density of 50kg.ha^{-1} and a row spacing of 25 cm
Planting sites : Addo, Dohne, Libode and Qamata

Experiment 4. Effect of Fertiliser Treatment

Objective: To evaluate the effect of different fertiliser treatment
Cultivar: Novosadska
Straw sample tested : 5 subsamples, of 2kg each, were evaluated for each sample
Fertilizers used : Nitrogen (N) and Potassium (K)
Fertilizer level (kg): Nitrogen = 0 (N1); 50 (N2); 100 (N3); 150 (N4)
Potassium = 0 (K1); 120 (K2)
Treatment combinations used: (0kg N and 0kg K); (0kg N and 120kg K); (50kg N and 0kg K); (50kg N and 120kg K); (100kg N and 0kg K); (100kg N and 120kg K); (150kg N and 0kg K); and (150kg N and 120kg K).
Planting site : Addo

The ARC-IIC was responsible for the experimental design and implementation of the agronomic trials, including sourcing of suitable hemp cultivars, seed viability tests, identification and preparation of the pilot sites, cultivation and harvesting of straws. The role of the CSIR was related to all the post farm-gate activities, including retting, fibre extraction, and estimation of fibre yield and evaluation of fibre properties and processing.

The following agronomic parameters, relating to hemp fibre production and fibre yield, and considered to be important for establishing a viable hemp fibre industry in South Africa, were covered in this study:

A. Row spacing and seeding density,
B. Different weed control treatments,
C. Planting date, and
D. Fertilisation.

One of the most important economic fundamentals in establishing a hemp fibre industry is to achieve the maximum yield of high quality fibres from the harvested crop, which is a function of the fibre yield per hectare and determines the potential profitability of hemp cultivation business. Therefore, the purpose of this work was to obtain an objective estimate of the fibre yield and quality of fibres extracted from hemp grown under different agronomic conditions at the different sites in the Eastern Cape, which were identified as the most suitable areas for hemp cultivation in South Africa. In accordance with the objectives of the project plan, selected hemp straw samples, obtained from the various pilot sites, were analysed to determine the effect of the different agronomic conditions on fibre yield. Full details of the agricultural experimental design and parameters are presented in the Progress Reports on Hemp Research prepared by the Agriculture Research Council-Institute for Industrial Crops, the ARC-IIC [144].

A summary of the relevant agronomic studies undertaken by the ARC-IIC is given here for each agronomic trial, since it provides a background and context to the research on hemp fibre production and physical properties of the fibre bundles reported and discussed in detail in this thesis.

3.1.2 Experimental

3.1.2.1 Effect of Row Spacing and Seeding Density

Low seeding densities and wide inter-row spacings are known to produce plants with highly bulky stems. The cultivation of hemp for fibre primarily focuses on the production of plants with slender stems and minimal branching, so as to produce long fibres with minimal variability along the length of the fibre. Such long and uniform fibres are suitable for processing and developing various industrial applications. Low plant densities also reduce the potential for suppressing weed growth, thus requiring high input costs in crop management.

Three inter-row spacing, namely 12.5 (S1), 25 (S2) and 50 cm (S3), each with a length of 4m, and three seeding densities of 50 (D1), 80 (D2) and 110 (D3) ($kg.ha^{-1}$), respectively, were investigated to establish the optimum combination for producing a high fibre yield hemp crop. Plots consisted of crops in four, eight and sixteen row spacings, each between seed plantings of 4 metres in length. A one metre-wide path divided the plots, facilitating access to the plants and data collection. The experiments were replicated three times. The Novosadska cultivar grown at Addo, was used in this experiment and experimental row spacing and seed density combinations were S1D1; S1D2; S1D3; S2D1; S2D2; S2D3; S3D1; S3D2; and S3D3.

The plant lengths generally varied between 1.5m and 1.69m, decreasing with an increase in row spacing. A mean dry biomass (hemp straw) yield of 6740 $kg.ha^{-1}$ was obtained for the different row spacing and seed density trials. This corresponds favourably with hemp production figures achieved by other hemp growing countries, reported averages being 5 to 7 tons of hemp straw per hectare [145].

3.1.2.2 Effect of Weed Control Treatment

Weeds, if not properly controlled, can influence plant population density and nutrient deficiencies which lead to lower crop yields, thereby negatively affecting the profitability and viability of the primary agricultural sector. The objective of this part of the study was to determine the best weed control programme to support the local production strategy aimed at producing both better yields and good quality fibres. Three hemp cultivars, namely Novosadska, Futura-77 and Felina-34, and four herbicides, were used in the trials conducted at Addo. Crop scientists from the ARC-IIC reported these four herbicides produced no visible phytotoxic effect on the three hemp cultivars. They, however, strongly recommend that herbicides should be tested under varying climatic conditions and cultivation practices before they can be recommended for hemp.

3.1.2.3 Effect of Planting Date

Hemp, particularly the European cultivars used in these trials in South Africa, was originally bred to be suitable for the European long day light periods in summer, which positively affects the plant's stem growth. The summer day-light periods in South Africa are not as long as those in Europe, therefore it is important to evaluate how the European hemp cultivars adapt to this difference. Table 13 shows the daylight duration during the months of September to January at the localities in which the various trials were carried out [146]. Two planting dates, October and November, were selected by the ARC-IIC crop scientists as most suitable for planting the cultivars.

Table 13. Duration of daylight [146].

Locality	Altitude* (m)	Latitude	Longitude	Daylight (hours)				
				30 Sept	31 Oct	30 Nov	31 Dec	31 Jan
Addo	852	31° 59'S	27° 28'E	13.35	13.35	14.08	14.22	13.71
Dohne	899	32° 31'S	27° 28'E	12.39	13.38	14.12	14.26	13.68
Libode	225	31° 30'S	28° 28'E	12.38	13.32	14.04	14.18	13.62
Qamata	150	33° 30'S	25° 40'E	12.40	13.43	14.20	14.34	13.74

*Sea level

Four hemp cultivars, namely Novosadska, Felina-34, Futura-77 and Kompolti, were evaluated at the planting sites by ARC-IIC crop scientists. The planting sites used were Addo, Dohne, Libode and Qamata. They observed that for the first planting date (October), Novosadska and Kompolti outperformed Felina-34 and Futura-77 in terms of stem length and biomass, at all the localities. It was concluded that the first planting date provided ideal agronomic climatic conditions for the planting of hemp in the Province of the Eastern Cape resulting in high biomass and stem yields as recorded by the ARC-IIC.

3.1.2.4 Effect of Fertilization

The objectives of these specific trials were to determine the effect of different levels of fertilizer on hemp biomass and fibre yield for the Novosadska cultivar planted at Addo. Different combinations of Nitrogen [N], namely 0, 50,100 and 150kg, and Potassium [K], namely 0 and 120 kg, were tested, namely (0kg N and 0kg K); (0kg N and 120kg K); (50kg N and 0kg K); (50kg N and 120kg K); (100kg N and 0kg K); (100kg N and 120kg K); (150kg N and 0kg K); and (150kg N and 120kg K). A randomised block experimental design, all with a row spacing of 0.25m, plant spacing of 0.05m and row length of 4m, was used. At harvest time, 10 plants of each plot were weighed for yield determination. An overall mean biomass yield of 28 108kg.ha^{-1} was recorded. An application of N of 100kg.ha^{-1} on its own resulted in good plant growth compared to that involving K. After the straw was retted, they were sent to CSIR for evaluating the various fibre properties.

3.1.2.5 Retting and Decortication

The following two processes were required in order to separate the fibres from the plant parts (woody core) so as to evaluate the effect of the various agronomic parameters on hemp fibre production and properties:

- **Retting,** a natural, but controlled / monitored, “rotting” process by which micro-organisms break down the layers of pectin that bind the fibres to the bast tissue. In dew (field) retting, hemp straws are cut near to the root region and are thinly evenly spread on the field touching the ground to allow indigenous aerobic fungi to degrade the straw, which was the favoured approach adopted in South Africa. Local agronomists and field researchers, however, lacked the necessary knowledge, information, training and experience to effectively apply the correct retting methodology, which, most of the time, resulted in the delivery of improperly (under) retted straw to the CSIR for decortication and testing. The hemp pilots took place in summer during which time the Eastern Cape Province climatic conditions are characterised by plentiful rainfall and increase in humidity which are good conditions for crop growth and field retting.

- **Decortication,** a mechanical process for breaking the retted stems for subsequent scutching to remove the broken woody parts.

3.1.3 Mechanical Fibre Extraction (Decortication) and Determination of Fibre Yield

3.1.3.1 Decortication

After the retted hemp straw was received from the ARC-IIC, representing all the agronomic conditions under investigation, giving a total of 42 samples, the fibres were extracted using a CMT-200M flax breaker-scutching machine of Russian origin, as shown in Figure 48. It is a small-scale machine about one metre wide, consisting of a leather feed table and a pair of rapidly rotating blades. The two rollers rotate in opposite directions and their turbines intersect each other, which results in the separation of the fibre from the woody core. It is a simple, easy to operate and inexpensive machine, ideally suited for undertaking small-scale experiments of this nature.

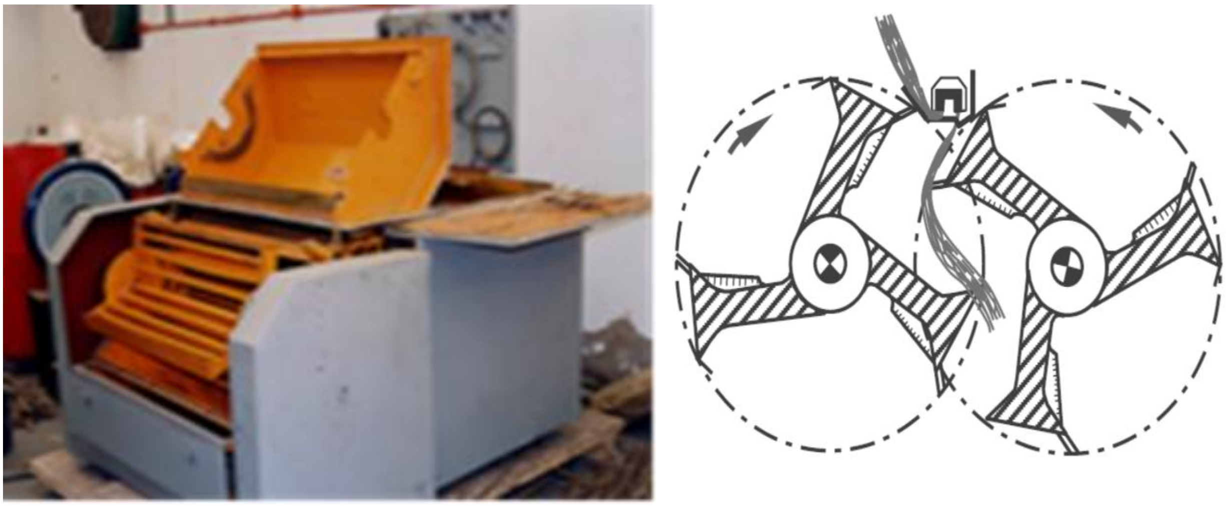

Figure 48. The CMT-200M flax breaker-scutch machine [Source: Own photo picture] and diagram illustrations on mechanism of fibre separation [43].

The hemp retted straws, 2kg per subsample (5 subsamples giving 10kg in total weight), was placed on the feed table and fed into the machine by two driven rubber rollers, the straws being gripped in the nip of the two rollers, thereby preventing the fibres from being lost during the decortication process. The retted straws firstly pass through two fluted rollers in which the woody core is crushed and fibre bundles are loosened from the woody part. Immediately after the retted straw crushing process, the now pliable retted straw with loose fibre bundles are exposed to two scutching turbines rotating in opposite directions to remove the woody parts (shivs) and tow fibres. After scutching for a period of a minute, the feed rollers reverse their rotation and withdraw the long fibre bundles from the machine. The timing device on the machine controls the duration of the forward and backward movements of the leather feed table [147].

3.1.3.2 Fibre Yield Determination

The extracted (decorticated) line fibres (from the decorticator feed table) and short fibre waste (woody core removed) were collected and weighed on Avery floor weighing scale, manufactured in United Kingdom by Avery Weigh Tronix company. The hemp fibre yield (B), in percentage, was calculated using the following formula [147]:

$$B(\%) = \frac{Total\,mass\,of\,long\,and\,short\,fibres\,(mf)}{Mass\,of\,retted\,straw\,(mrs)} \times 100;$$

For each cultivar, five subsamples were taken during the fibre extraction process for the determination of the percentage fibre content, referred to as fibre yield (%).

3.1.3 Results and Discussion

3.1.3.1 Results

The results illustrating the effects of the various agro-parameters on the fibre content of the hemp crops grown at the different pilot sites in the Province of the Eastern Cape, are summarized in Appendix 1 Table 1-4. The under-retted hemp straw received by the CSIR made the process of fibre extraction an extremely laborious one. Traditional organoleptic method was used to measure the degree of retting on hemp straws which included retted straw weight loss, colour difference and visual ranking of how loose as well as how easy the fibres would break when extracted by hand. The extracted fibres were mostly still in a coarse bundle (bonded) form but had to be used for analysing the effect of the various agro-parameters on the hemp fibre production and yield. For each sample, fibre content (yield) was measured taking into consideration both the long and short fibre bundles. The mean fibre percentage yield of the five subsamples tested was used for the statistical data analysis. From the limited amount of data gathered (due to the limited number of good samples available for testing) an attempt was made to extract as much useful information as possible in terms of South Africa's potential to establish a hemp fibre industry. The lack of technical skills in agronomy, retting, appropriate laboratory size fibre extraction and processing technologies, such as the hackling unit, and universally accepted principles on fibre testing techniques, were some of the major challenges faced in carrying out this research.

3.1.3.1.1 Effect of Row Spacing and Seeding Density

The fibre yield results of the row spacing and seeding density trials carried out at Addo with the Novosadska cultivar are shown in Figure 49, the detailed data being given in Appendix 2 Table 1.

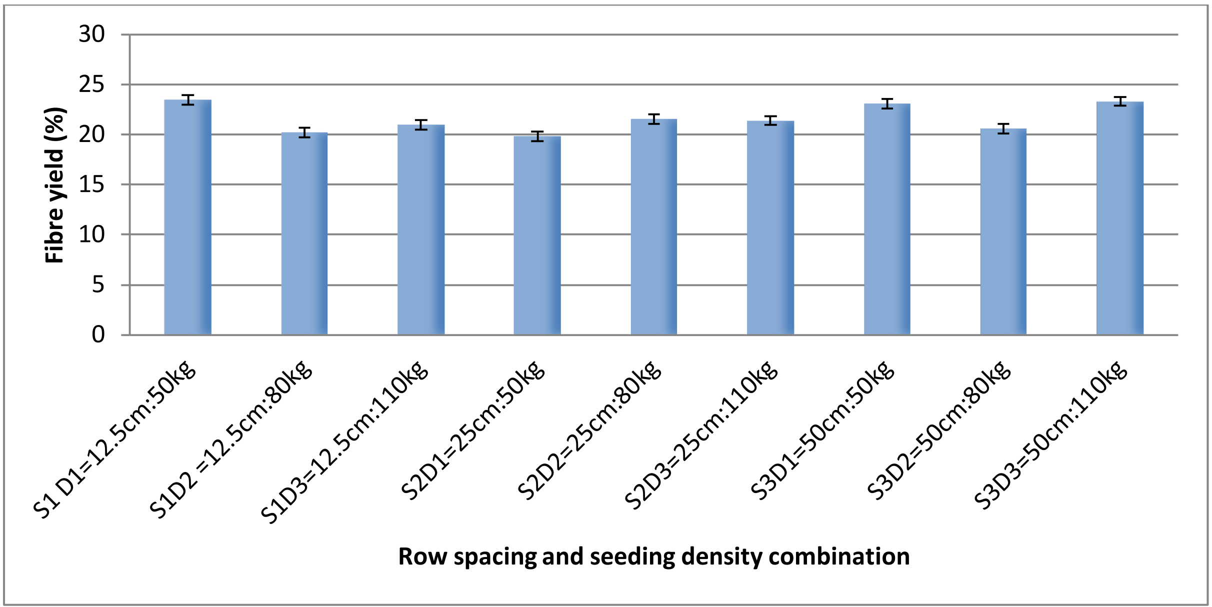

Figure 49. Effect of row spacing and seeding density on fibre yield.

The results obtained for the total biomass (dry straw) and fibre yield per hectare ($kg.ha^{-1}$) for the different row spacing and seeding density for the Novosadska cultivar are shown in Figure 49. The average fibre yield is derived from the mass (weight) of extracted fibre from each subsample of 2kg. The values for the total biomass yield were obtained from the agronomic experimental research report of the ARC-IIC from which the total fibre yield per hectare was calculated, using the fibre yield (%) values.

According to the above results as in Figure 49, the fibre yield was the highest (23.4%) for the S1D1 (12.5 cm row spacing and 50kg seeding rate) combination followed by the S3D3

(23.3%) and S3D1 (23.1%) combinations, the fibre yield values being indicated in brackets. The fibre yield should not be the only determining factor used in evaluating the agronomic performance of the cultivars under specified field conditions, but must always be considered in combination with the biomass yield to establish the overall fibre yield per hectare of land. A wrong conclusion can quite easily be drawn if only the fibre yield is considered.

In these trials, the combinations of row spacing and seeding density that provided more than 2 tonnes of fibre per hectare, as a result of high biomass yields (kg.ha^{-1}), were S1D2, S2D2 and S3D1, respectively. As shown in Figure 50, in general, the average biomass yield increased with an increase in seeding density from 50 to 80 kg.ha^{-1}, the exception being S3D2, whereafter, it decreased with further increases in seeding density, a relatively low biomass yield being recorded at the highest seeding density of 110 kg.ha^{-1}. This may be attributed to excessive seeds that did not fully germinate due to plant germination over-crowding. This trend is also visible in the case of average percentage fibre yield, the exception once again being S3D2.

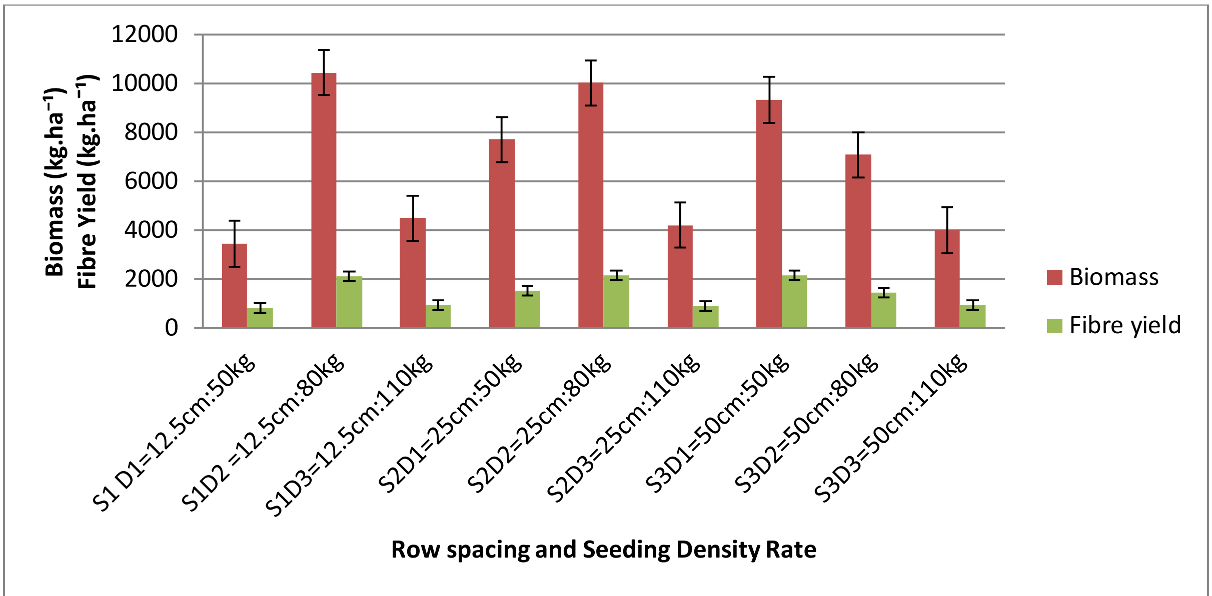

Figure 50. Effect of row spacing and seeding density on total dry biomass (straw) and fibre yields per hectare (kg.ha^{-1}).

The relative low values for the mechanical extracted fibre content are directly correlated to the technical agronomic skills deficiencies on hemp primary production and retting which takes place at the field level in which the ARC-IIC is the responsible institute.

Statistical analysis

Unless otherwise specified, statistical significance was always assessed at the 95% confidence level. The *p*-factor is an indication of the statistical significance of the different variables interactions, when $p<0.05$, it indicates a statistically significant interaction at the 95% confidence level between the relevant parameters.

Figure 50 and Tables 14 & 15 illustrate the results obtained from the analysis of variance (ANOVA) on the interactive effects of row spacing and seeding density on the fibre yield, the *p*-factor value indicating the statistical significance of the interactions between the independent variables, i.e., row spacing and seeding density, and the response (dependent) variable, i.e., fibre yield, respectively. Table 14 provides a summary of the results of the ANOVA involving row spacing and seeding density interactions, whilst Table 15 gives the individual p-factor values for the various interactions between specific row spacing and seeding density combination that influence the overall p-factor value. Figure 51 provides for the **qualitative interpretation** of interactions between the combinations factors, in terms of the overlap and non-overlap of the respective error bars, the interaction not being deemed significant when they cross each other's centres (i.e., average values). For example, for the spacing & density combination 5 & 6 in Figure 50, the error bars cross each other's centres, and therefore the interactions are considered not significant ($p>0.05$). The *p*-values in Table 15, provide for the **quantitative interpretation** of the specific individual interactions of the independent variables in determining their statistical significance and thus their overall contribution to the *p*-value as in Table 14. The higher the proportion of $p<0.05$ to $p>0.05$, the higher the chances that the overall $p<0.05$, and therefore significant and vice-versa.

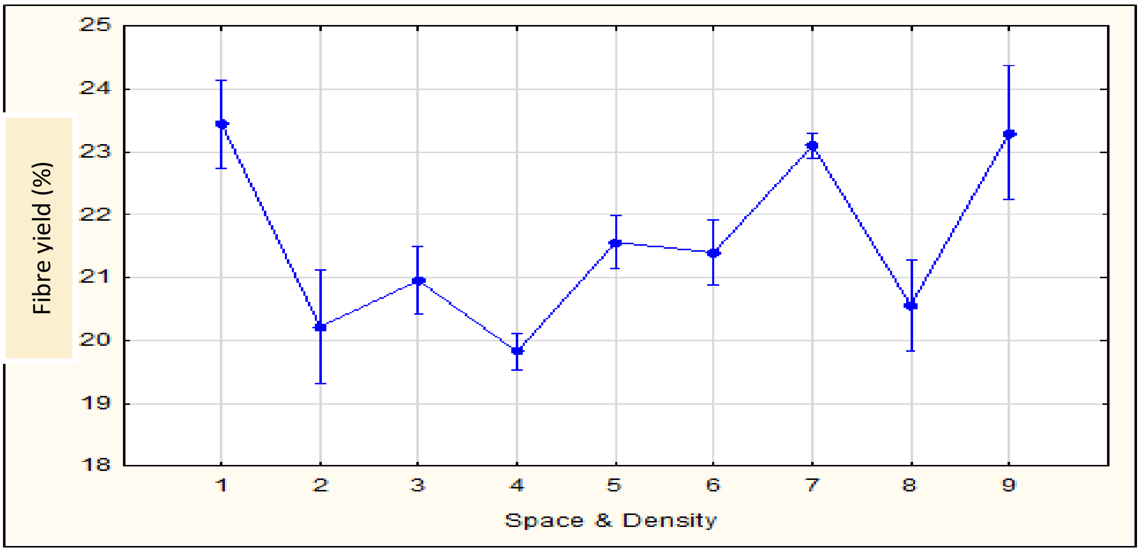

Figure 51. Means graph with 95% error bars illustrating the effect of row spacing and seeding density on fibre yield [1=S1D1, 2=S1D2, 3=S1D3, 4=S2D1, 5=S2D2, 6=S2D3, 7=S3D1, 8=S3D2, 9=S3D3].

As can be seen from Table 14, the high F value (=34.3) and very small p-value (<0.05) indicate that there are significantly strong interactions between the row spacing and seeding rate combinations on fibre yields at the 95% confidence level for the particular cultivar under study.

Table 14. ANOVA results on the interactions between row spacing and seeding density

Factors	dF	Sum Square (SS)	Mean Square (MS)	F	p-Value	Significance (Yes or No)
Row spacing & seeding density	8	75.7	9.5	34.3	0.000	Yes
Error	36	9.9	0.3			
Total	44	85.6				
S = 0.5251 R-Sq = 88.41% R-Sq(adj) = 85.83%						

Table 15. p-Factor values on the interactions between row spacing and seeding density

	{Density 1}**	{Density 2}**	{Density 3}**	{Density 1}	{Density 2}	{Density 3}	{Density 1}	{Density 2}	{Density 3}
Row S1* {1}		0.000140	0.000140	0.000140	0.000191	0.000149	0.980930	0.000140	0.999966
Row S1* {2}	0.000140		0.424766	0.950346	0.007502	0.026680	0.000140	0.980930	0.000140
Row S1* {3}	0.000140	0.424766		0.038268	0.662521	0.909081	0.000143	0.955670	0.000140
Row S2 {1}	0.000140	0.950346	0.038268		0.000346	0.001053	0.000140	0.410371	0.000140
Row S2 {2}	0.000191	0.007502	0.662521	0.000346		0.999907	0.001458	0.096533	0.000346
Row S2 {3}	0.000149	0.026680	0.909081	0.001053	0.999907		0.000440	0.252408	0.000181
Row S3 {1}	0.980930	0.000140	0.000143	0.000140	0.001458	0.000440		0.000140	0.999510
Row S3 {2}	0.000140	0.980930	0.955670	0.410371	0.096533	0.252408	0.000140		0.000140
Row S3 {3}	0.999966	0.000140	0.000140	0.000140	0.000346	0.000181	0.999510	0.000140	

**Row1/2/3 denotes row spacings of 12.5cm, 25.0cm and 50.0cm, respectively;*
***Density 1/2/3 denotes seeding rates of 50kg, 80kg and 110kg, respectively.*

Note: *the p-values in red signify those interactions that are statistically significant (i.e., with p<0.05), while those in black that are not significant (p>0.05).*

Discussion of statistical analysis involving individual variable interactions:

More detailed analysis of the 1-way ANOVA results (Table 15), show the respective combinations of row spacing and seeding density that contribute to the overall p-value obtained in Table 14, highlighting interactions at individual combination level. The following conclusions relating to the individual variable interactions can be drawn:

- *p*-**value qualitative interpretation:** a significant interaction exists with the S1D1 (12.5cm, 50kg) treatment combination which influences average fibre yield when compared with all the other treatment combinations in which p<0.05, except for S3D1 (50cm, 50kg) and S3D3 (50cm, 110kg) in which p>0.05, as indicated by overlap in error bars for the two combinations, i.e, the *p*-value calculations is based on the interactions between the true averages, as represented by the error bar, of the fibre yield of subsamples obtained for different combinations.
- *p*-**value quantitative interpretation:** other treatment combinations with p>0.05 included the following {S1D2 (15.2cm, 80kg) and S1D3 (12.5cm, 110kg)}; {S1D2

(12.5cm, 80kg) and S2D1 (25sm, 50kg)}; {S1D3 (12.5cm, 110kg) and S2D2 (50cm, 80kg)}; {S1D3 (12.5cm, 110kg) and S2D3 (25cm, 110kg)}; {S2D2 (25cm, 80kg) and S2D3 (25cm, 110kg)} and {S3D1 (50cm, 50kg) and S3D3 (50cm, 110kg)}.

- It can be shown that the *p*-value data table (Table 15) provides additional detailed information on those individual interactions that influence the overall *p*-value, such information not being available if only the p-value in Table 14 was used.
- The variation in *p*-value for some non-significant interactions can be attributed to inherent variation in the material and other factors, such as the degree of retting, planting site and crop management, as the hemp straw delivered to CSIR for analysis were harvested after seed had formed and matured.
- The statistical analysis results of the interaction between individual variables provide information relating to identifying the significant ($p<0.05$) and non-significant ($p>0.05$) interactions having a direct effect on the overall *p*-value.

Main conclusions

The main conclusions are;

- the row spacing and seeding density combinations that produced fibre and biomass yields that were close to those achieved in hemp producing countries, namely, 5 to 7 tonnes per hectare of dry straw biomass yield, 23 to 35% fibre yields and 0.85 to 3.7 tonnes total fibre yield per hectare [37, 38], were S2D2 (25cm, 80kg) and S3D1 (50cm, 50kg), with dry straw biomass yields of 10021 and 9319 $kg.ha^{-1}$, fibre yields of 22% and 23%, and total fibre yield ($kg.ha^{-1}$) of 2160.5 and 2152.7, respectively.
- the other row spacing and seeding rate combinations that produced dry straw biomass yields of more than 7 tonnes per hectare and total fibre yields of more than 0.85 tonnes per hectare were S1D2 (12.5cm and 80kg) at 10432 and 2109.4 $kg.ha^{-1}$, S2D1

(25.0cm and 50kg) at 7706 and 1527.3 kg.ha^{-1}; and S3D2 (50.0cm and 80kg) at 7074 and 1454.4 kg.ha^{-1}, respectively, with fibre yield ranging from 19.8% to 20.6%, which was lower than the minimum of 23%.

- that row spacing and seeding rate have direct effect on hemp yield (biomass and fibre content) as it affects stem size uniformity, plant growth and the ability to produce high yields (biomass and fibre content) by the hemp crop, as well as suppression of the weeds.

3.1.3.1.2 Effect of Weed Control Treatment

The results of the weed control trials, involving three cultivars planted at Addo (Novosadska, Felina-34 and Futura-77) and four herbicides, are captured in Figures 52 & 53, with the detailed data being given in Appendix 2 Table 2.

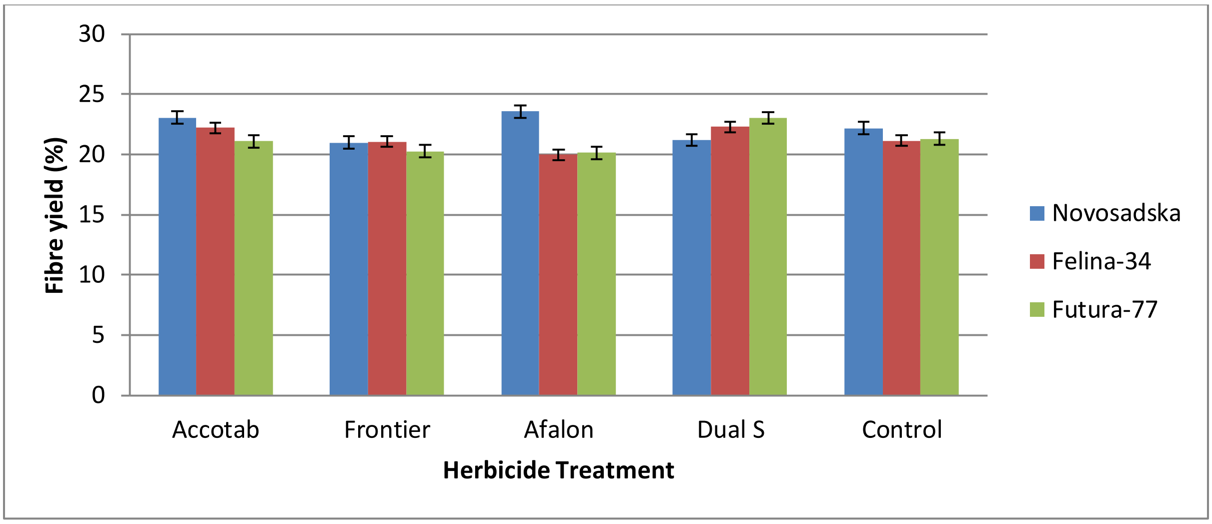

Figure 52. Effect of herbicide treatment on the fibre yield

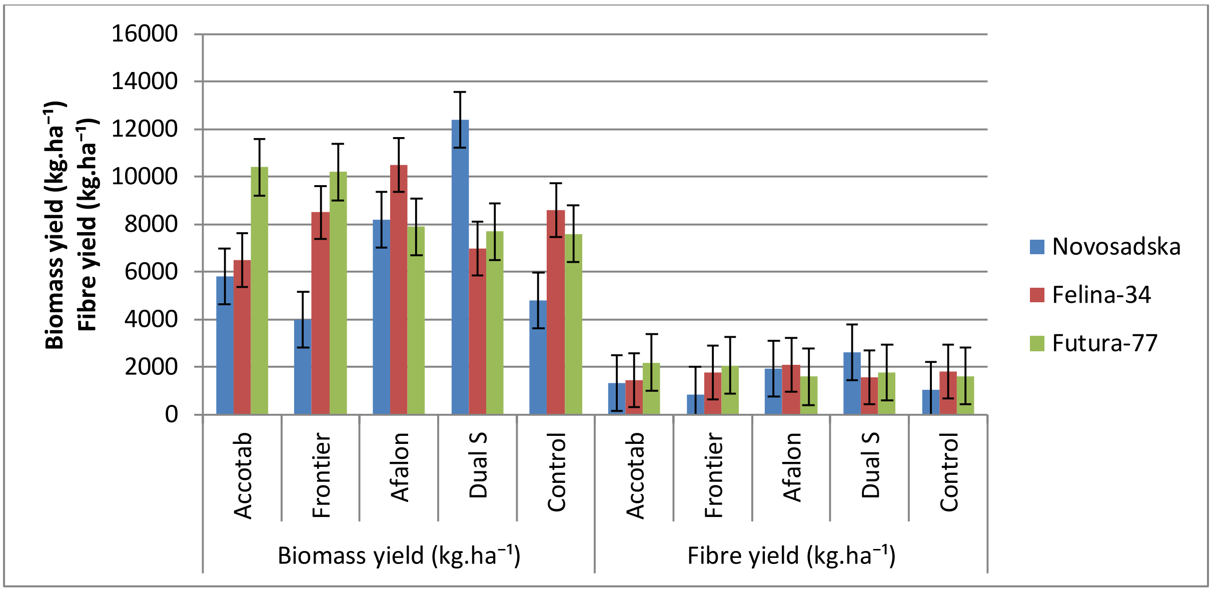

Figure 53. Effect of herbicide treatment on biomass and fibre yields per hectare

Discussion

As can be seen from Figure 52, the application of the various herbicides used in the trials did not have a major effect on the fibre yield (%) of the three hemp cultivars grown at Addo, with fibre yield ranging from 20% to 23.6%, none of the herbicide treated cultivars produced yields much higher than that of control, which ranged from 21% to 22%. According to Figure 53, Novosadska cultivar treated with Dual S herbicide produced the highest biomass and total fibre yields of 12400 and 2628.8 kg.ha^{-1}, respectively, but when treated with Frontier it produced the lowest biomass and total fibre yields (4000 and 839 kg.ha^{-1}) of all the cultivars. Whilst it appeared that the Dual S applied to Novosadska had a beneficial effect in terms of biomass and total fibre yields per hectare, there was no concomitant improvement in the fibre yield (Figure 53).

Generally, the suppression of weeds by herbicides is expected to improve the vegetative growth of a crop and thereby result in significantly better yields, which was not the case in these trials, this being in line with the generally accepted fact that hemp is itself effective in suppressing weed growth.

Statistical analysis

Figure 54 and Tables 16 & 17, show the ANOVA results on the effect of herbicide treatment on fibre yield, the *p*-factor value providing an indication of the level of the statistical significance of the interactions between the two variables.

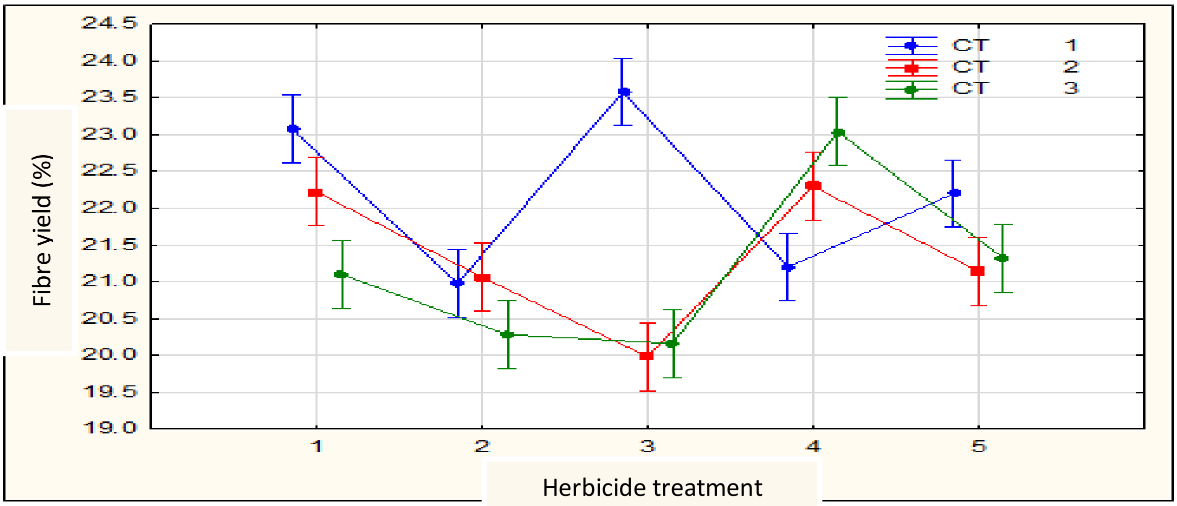

Figure 54. Mean and 95% error bars indicating the effect of the various herbicide treatments [1 = Accotab; 2= Frontier; 3= Afalon; 4= Dual S and 5 = Control] on fibre yield for three hemp cultivars grown at Addo, [CT 1= Novosadska; CT 2= Felina-34 and CT 3= Futura-77]

Qualitative interpretation of the various interactions between herbicide treatment and cultivar performance, as shown in Figure 53, indicated a mixed response, some significant and others non-significant.

Table 16 gives the 2-way ANOVA results on the interactions between two factors, namely, herbicide treatment and cultivar. The detailed ANOVA results, giving the p-factor values for each interaction between herbicide treatment and cultivar, are tabulated in Table 17.

Table 16. ANOVA results showing the effect on fibre yield of herbicide and cultivar, and their interaction

Factors	dF	Sum Square (SS)	Mean Square (MS)	F	p-Value	Significant (Yes or No)
Herbicide treatment	4	21.5	5.4	20.2	0.000	Yes
Cultivar	2	15.3	7.6	28.8	0.000	Yes
Herbicide*cultivar	8	49.3	6.2	23.2	0.000	Yes
Error	60	15.9	0.27			
Total	74	102	82.7			
S = 0.5155 R-Sq = 84.38% R-Sq(adj) = 80.74%						

As can be seen from Table 16, all three factors showed significant interactions (p<0.05) which can be explained as follows:

- The low (significant) p-value implies that the average fibre yield of at least two cultivars differ significantly.
- The effect of the herbicide treatment on the average fibre yield is mainly influenced by the cultivar.
- The ANOVA results given in Table 16 do not provide information on which specific cultivar and herbicide treatment contributed to the significant p-value, Table 17 providing the more detailed individual p-values.

Table 17. p-Values relating to herbicide treatment and cultivar

		Herbicide Treatment		Cultivar Type		{CT 1}**	{CT 2}	{CT 3}	{CT 1}	{CT 2}	{CT 3}	{ CT 1}	{CT 2}	{CT 3}	{CT 1}	{CT 2}	{CT 3}	{CT 1}	{CT 2}	{CT 3}
1	HT*	Accotab	1	Novo	1		0.367179	0.000152	0.000147	0.000149	0.000146	0.965798	0.000146	0.000146	0.000167	0.529883	1.000000	0.330567	0.000156	0.000246
2	HT		1	Felina	2	0.367179		0.065391	0.023764	0.047228	0.000156	0.007851	0.000146	0.000148	0.138357	1.000000	0.446005	1.000000	0.089222	0.296095
3	HT		1	Futura	3	0.000152	0.065391		1.000000	1.000000	0.446005	0.000146	0.065391	0.233983	1.000000	0.033689	0.000156	0.076515	1.000000	0.999995
4	HT	Frontier	2	Novo	1	0.000147	0.023764	1.000000		1.000000	0.699025	0.000146	0.158807	0.446005	0.999995	0.011466	0.000148	0.028333	1.000000	0.999187
5	HT		2	Felina	2	0.000149	0.047228	1.000000	1.000000		0.529883	0.000146	0.089222	0.296095	1.000000	0.023764	0.000152	0.055691	1.000000	0.999963
6	HT		2	Futura	3	0.000146	0.000156	0.446005	0.699025	0.529883		0.000146	0.999800	1.000000	0.263909	0.000149	0.000146	0.000159	0.367179	0.119971
7	HT	Afalon	3	Novo	1	0.965798	0.007851	0.000146	0.000146	0.000146	0.000146		0.000146	0.000146	0.000146	0.016586	0.937852	0.006484	0.000146	0.000146
8	HT		3	Felina	2	0.000146	0.000146	0.065391	0.158807	0.089222	0.999800	0.000146		1.000000	0.028333	0.000146	0.000146	0.000146	0.047228	0.009508
9	HT		3	Futura	3	0.000146	0.000148	0.233983	0.446005	0.296095	1.000000	0.000146	1.000000		0.119971	0.000146	0.000146	0.000148	0.181506	0.047228
10	HT	Dual S	4	Novo	1	0.000167	0.138357	1.000000	0.999995	1.000000	0.263909	0.000146	0.028333	0.119971		0.076515	0.000181	0.158807	1.000000	1.000000
11	HT		4	Felina	2	0.529883	1.000000	0.033689	0.011466	0.023764	0.000149	0.016586	0.000146	0.000146	0.076515		0.615583	1.000000	0.047228	0.181506
12	HT		4	Futura	3	1.000000	0.446005	0.000156	0.000148	0.000152	0.000146	0.937852	0.000146	0.000146	0.000181	0.615583		0.405724	0.000162	0.000304
13	HT	Control	5	Novo	1	0.330567	1.000000	0.076515	0.028333	0.055691	0.000159	0.006484	0.000146	0.000148	0.158807	1.000000	0.405724		0.103663	0.330567
14	HT		5	Felina	2	0.000156	0.089222	1.000000	1.000000	1.000000	0.367179	0.000146	0.047228	0.181506	1.000000	0.047228	0.000162	0.103663		1.000000
15	HT		5	Futura	3	0.000246	0.296095	0.999995	0.999187	0.999963	0.119971	0.000146	0.009508	0.047228	1.000000	0.181506	0.000304	0.330567	1.000000	

**HT denotes herbicide treatment, and*
*** CT denotes cultivar*

Discussion of results of statistical analysis on individual variable interactions

The following represents a summary of the significant interactions between the two factors (Figure 54 and Table 17), namely herbicide treatment and cultivar type, highlighting those factors which contributed to the significant p-value ($p<0.05$):

- Significant interactions ($p<0.05$) for the treatment combination of CT1 (Novosadska) and 1 (Accotab) were observed against [CT2 (Felina-34) and 1 (Accotab)]; [CT3 (Futura-77) and 1 (Accotab)]; [CT1 (Novosadska) and 2 (Frontier)]; [CT2 (Felna-34) and 2 (Frontier)]; [CT3 (Futura-77) and 2 (Frontier)]; [CT2 (Felna-34) and 3 (Afalon)]; [CT3 (Futura-77) and 3 (Afalon)]; [CT1 (Novosadska) and 4 (Dual S)]; [CT2 (Felina-34) and 4 (Dual S)]; [CT1 (Novosadska) and 5 (Control)]; [CT2 (Felina-34) and 5 (Control)] and [CT3 (Futura-77) and 5 (Control)], with all other interactions not listed having $p>0.05$ (i.e. insignificant).
- Significant interactions ($p<0.05$) for the treatment combination of CT 2 (Felina-34) and 1 (Accotab) were observed against [CT3 (Futura-77) and 1 (Accotab)]; [CT1 (Novosadska) and 2 (Frontier)]; [CT2 (Felina-34) and 2 (Frontier)]; [CT3 (Futura-77) and 2 (Frontier)]; [CT1 (Novosadska) and 3 (Afalon)]; [CT2 (Felina-34) and 3 (Afalon)]; [CT3 (Futura-77) and 3 (Afalon)]; [CT1 (Novosadska) and 4 (Dual S)]; [CT2 (Felina-34) and 5 (Control)] and [CT3 (Futura-77) and 5 (Control)], with all other interactions not listed having $p>0.05$ (i.e. insignificant).
- Significant interactions ($p<0.05$) for the treatment combination of CT 3 (Futura-77) and 1 (Accotab) were observed against [CT2 (Felina-34) and 2 (Frontier)]; [CT1 (Novosadska) and 3 (Afalon)]; [CT2 (Felina-34) and 3 (Afalon)]; [CT3 (Futura-77) and 3 (Afalon)]; [CT2 (Felina-34) and 4 (Dual S)]; [CT3 (Futura-77) and 4 (Dual S)] and [CT1 (Nocosadska) and 5 (Control)], with all other interactions not listed having $p>0.05$(i.e. insignificant).

Main conclusions

The following main conclusions can be drawn from the foregoing discussion:

- The fibre yield, as determined by the dry biomass straw yield and fibre content (%), for cultivars grown without the application of herbicide treatment was mostly comparable to that when the cultivars were treated with the various herbicides. These results confirmed the inherent weed suppressing function of hemp as reported in the literature [70], and therefore the environmental benefits of hemp and its potential use as a rotational crop when compared to cotton, which uses a variety of chemicals during its growth. Fibre yields of all the cultivars ranged from 20 to 23%, which is at the lower end of the ranges reported in the literature [62].
- All the cultivars produced dry biomass yields ($kg.ha^{-1}$) of more than 5 tonnes, comparable to the values reported for hemp producing countries [64], the only exception being the Novosadska cultivar, both untreated (i.e. control) and treated with the Frontier herbicide.

3.1.3.1.3 Effect of Planting Date

The results representing the effect of planting date (October or November) on the fibre yield at the four planting sites, namely; Addo, Dohne, Libode and Qamata are, shown in Figure 55, the detailed data being given in Appendix 2 Tables 3 and 4.

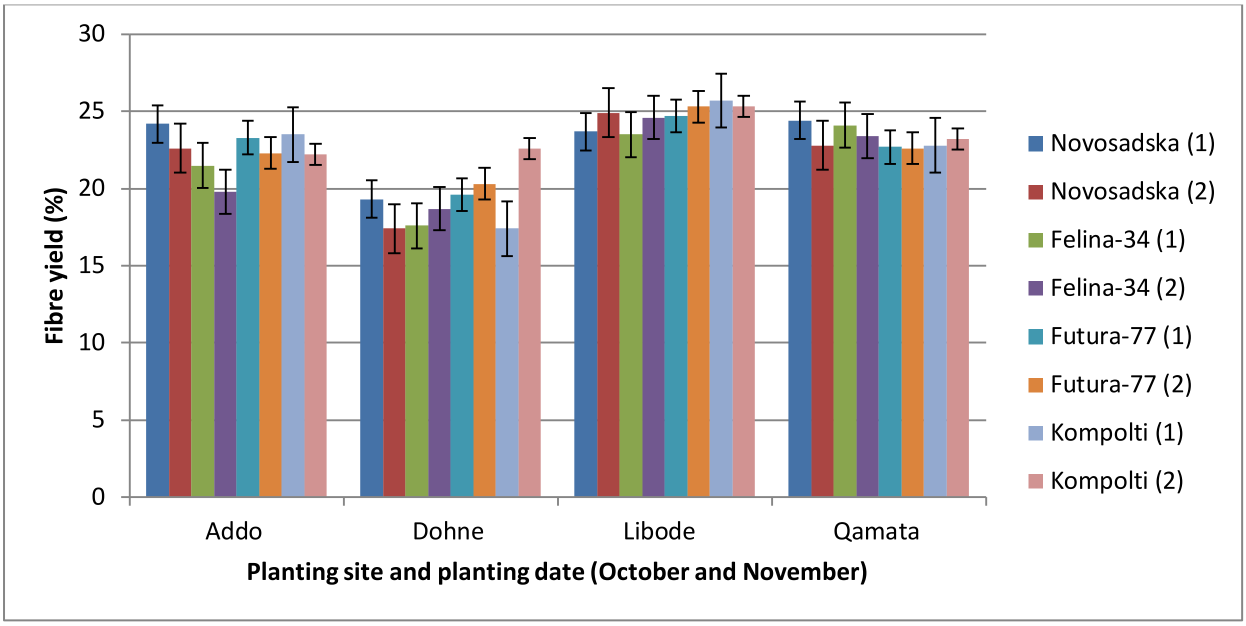

Figure 55. Effect of planting date on the fibre yield of four cultivars grown at four different sites (the figure in brackets of the cultivar indicates the planting date, i.e, 1=October and 2 = November).

The results representing the calculated average total fibre yield per hectare ($kg.ha^{-1}$) for the hemp cultivars grown at the four different sites are plotted in Figure 56, while the detailed results are given in Appendix 2 Table 5.

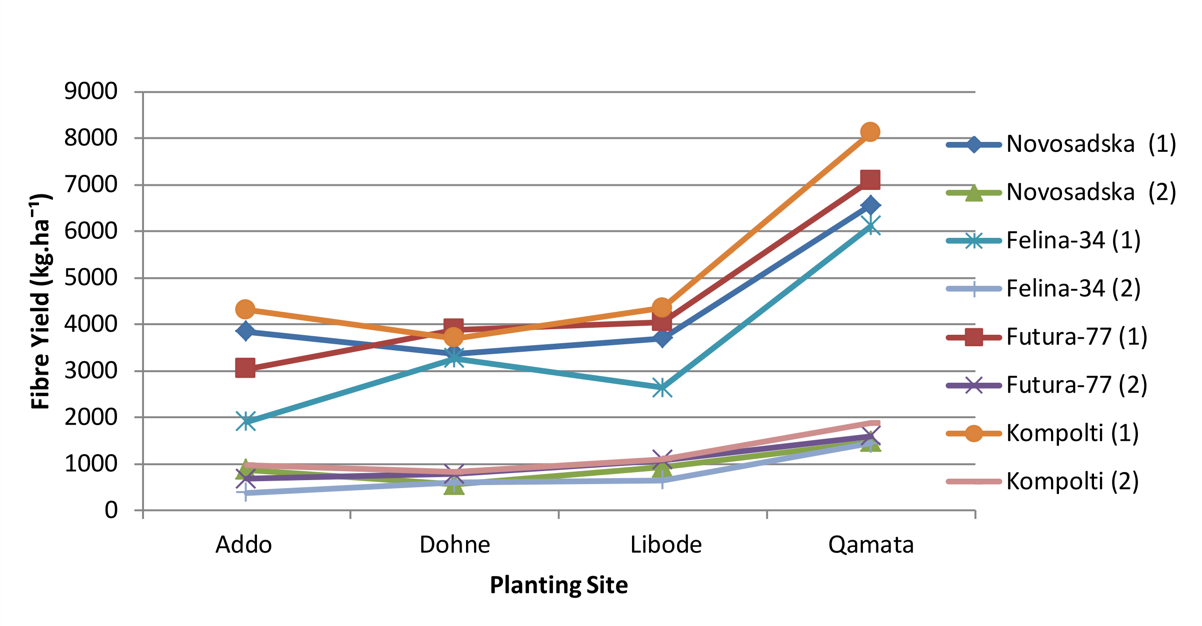

Figure 56. Total fibre yield (kg.ha^{-1}) of four hemp cultivars for two planting dates and four different sites. (1) First planting date (October), (2) Second planting date (November).

According to Figure 55, there were no significant or major differences between the two planting dates, with the exception of the Kompolti cultivar at Dohne which gave a better fibre yield of 22.6% for the second planting date than for the first planting date (17.3%). Nevertheless, the first planting date (October) generally produced slightly higher fibre yields, generally around 23% or more (the exception being Felina-34 at Addo), than the second planting date (around 22% or more), with Felina-34 planted at Addo again being the exception. Compared to Addo and Qamata, the Libode site produced consistently higher fibre yields, of between 23% and 26% for both planting dates, meeting the minimum fibre yields quoted in the literature [62]. It can also be seen that the fibre yields obtained at Dohne were generally lower than 21%, the exception being the Kompolti cultivar planted in November (Figure 55).

The 1st (i.e. October) planting date gave better fibre yields per hectare (Figure 55), as determined by both the dry biomass yield and fibre content, when compared to the November planting date. Except for the Dohne site, the dry biomass and fibre yields achieved for all the cultivars for the October planting date, were generally comparable to the minimum values of 5 tonnes for dry biomass, and 23% for fibre yield, quoted in the literature [62].

The poor performance of the cultivars at the Dohne site, compared to the other sites, could possibly be attributed to the lack of technical expertise in hemp production there.

Statistical analysis

The mean values and error bars, derived from the ANOVA, of the interactions between the cultivar type and planting date for the different sites on fibre yield, are plotted in Figure 57, with the ANOVA results on the overall significance of interactions (p-factor values) shown in Table 18.

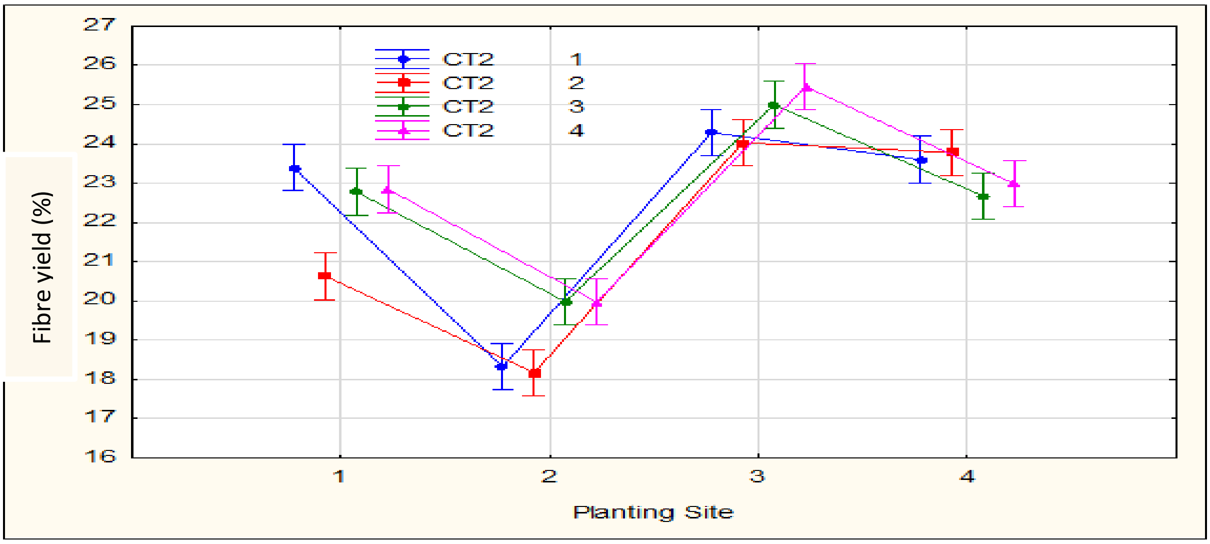

Figure 57. Mean values and 95% error bars for fibre yield plotted for different cultivars and sites [1 = Addo; 2=Dohne; 3=Libode and 4=Qamata].
[CT2 1 = Novosadska; CT2 2=Felina-34; CT2 3=Futura-77; CT2 4=Kompolti]
NOTE: Means and error bars represent the pooled results for the two planting dates.

Table 18. ANOVA of the effect on fibre yield of planting site, cultivar and planting date and their interactions

Factors	*dF*	*Sum Square (SS)*	*Mean Square (MS)*	*F*	*p-Value*	*Significance (Yes or No)*
Planting site	3	672.9	224.3	2513.2	0.000	Yes
Cultivar	3	30.8	10.3	115.1	0.000	Yes
Planting date	1	0.01	0.01	0.1	0.7	No
Planting site*cultivar	9	64.8	7.2	80.7	0.000	Yes
Planting site*planting date	3	43.3	14.4	161.7	0.000	Yes
Cultivar *planting date	3	19.7	6.6	73.5	0.000	Yes
Planting site * cultivar * planting date	9	55.5	6.2	69.0	0.000	Yes
Error	128	11.4	0.1			
Total	159	898.4				

As can be seen from Table 18, with the exception of planting date, all three factors and their interactions had a significant effect ($p<0.05$) on fibre yield, from which the following conclusions may be drawn:

- The effect of planting date on its own was not significant ($p>0.05$), i.e. not considering its interactions with the cultivar and site.
- The average fibre yield of at least two cultivars differed significantly.
- The effect of a particular variable on the average fibre yield was influenced by its interactions with the other two variables.
- The ANOVA results given in Table 18 do not provide information on which of the variables contributed most to the p-value in Table 18.

Table 19 shows the detailed p-values for the interaction between the planting site and cultivar type.

Table 19. p-Values reflecting the significance of the effects of planting site and cultivar and their interactions on fibre yield

	Planting Site	Cultivar	{CT}** 1	{CT} 2	{CT} 3	{CT} 4	{CT} 1	{CT} 2	{CT} 3	{CT} 4	{CT} 1	{CT} 2	{CT} 3	{CT} 4	{CT} 1	{CT} 2	{CT} 3	{CT} 3
PS*	1	1		0.000029	0.988709	0.996835	0.000029	0.000029	0.000029	0.000029	0.753053	0.981998	0.014220	0.000147	1.000000	0.999934	0.948527	0.999877
PS	1	2	0.000029		0.000073	0.000047	0.000035	0.000030	0.979166	0.975996	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000198	0.000032
PS	1	3	0.988709	0.000073		1.000000	0.000029	0.000029	0.000029	0.000029	0.032718	0.193859	0.000047	0.000029	0.861978	0.582330	1.000000	1.000000
PS	1	4	0.996835	0.000047	1.000000		0.000029	0.000029	0.000029	0.000029	0.055933	0.281399	0.000073	0.000029	0.928379	0.704687	1.000000	1.000000
PS	2	1	0.000029	0.000035	0.000029	0.000029		1.000000	0.009119	0.009980	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029
PS	2	2	0.000029	0.000030	0.000029	0.000029	1.000000		0.002164	0.002392	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029
PS	2	3	0.000029	0.979166	0.000029	0.000029	0.009119	0.002164		1.000000	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029
PS	2	4	0.000029	0.975996	0.000029	0.000029	0.009980	0.002392	1.000000		0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029
PS	3	1	0.753053	0.000029	0.032718	0.055933	0.000029	0.000029	0.000029	0.000029		1.000000	0.954226	0.295603	0.964212	0.998323	0.013029	0.135636
PS	3	2	0.981998	0.000029	0.193859	0.281399	0.000029	0.000029	0.000029	0.000029	1.000000		0.635886	0.060189	0.999777	1.000000	0.098193	0.492379
PS	3	3	0.014220	0.000029	0.000047	0.000073	0.000029	0.000029	0.000029	0.000029	0.954226	0.635886		0.999495	0.074620	0.228779	0.000033	0.000243
PS	3	4	0.000147	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.295603	0.060189	0.999495		0.001299	0.007598	0.000029	0.000030
PS	4	1	1.000000	0.000029	0.861978	0.928379	0.000029	0.000029	0.000029	0.000029	0.964212	0.999777	0.074620	0.001299		1.000000	0.704687	0.986746
PS	4	2	0.999934	0.000029	0.582330	0.704687	0.000029	0.000029	0.000029	0.000029	0.998323	1.000000	0.228779	0.007598	1.000000		0.388754	0.883809
PS	4	3	0.948527	0.000198	1.000000	1.000000	0.000029	0.000029	0.000029	0.000029	0.013029	0.098193	0.000033	0.000029	0.704687	0.388754		0.999997
PS	4	4	0.999877	0.000032	1.000000	1.000000	0.000029	0.000029	0.000029	0.000029	0.135636	0.492379	0.000243	0.000030	0.986746	0.883809	0.999997	

**PS denotes planting site*
*** CT denotes cultivar*

Discussion of the results of the statistical analysis on the individual variable interactions

The following is a summary of the significant factors (Figure 57 and Table 19), namely planting site, cultivar and planting date and their interactions in determining fibre yield:

- Significant interactions ($p<0.05$) for the treatment combination of CT2-1 (Novosadska) and 1 (Addo site) were observed against [CT2-2 (Felina-34) and 1(Addo site)]; [CT2-2 (Felina-34) and 2 (Dohne)]; [CT2-3 (Futura-77) and 2 (Dohne)]; [CT2-4 (Kompolti) and 2 (Dohne)]; [CT2-3 (Futura-77) and 3 (Libode)]; [CT2-4 (Futura-77) and 4 (Qamata)], with all other interactions not listed having $p>0.05$ (i.e. insignificant).
- Significant interactions ($p<0.05$) for the treatment combination of CT2-2 (Felina-34)and 1 (Addo) were observed against [CT2-1 (Novosadska) and 1 (Addo)]; [CT2-3 (Futura-77) and 1(Addo)]; [CT2-4 (Kompolti) and 1 (Addo)]; [CT2-1 (Novosadska) and 2 (Dohne)]; [CT2-2 (Felina-34) and 2 (Dohne)]; [CT2-1 (Novosadska) and 3 (Libode)]; [CT2-2 (Felin-34) and 3 (Libode)]; [CT2-3 (Futura-77) and 3 (Libode)]; [CT2-4 (Kompolti) and 3 (Libode)]; [CT2-1 (Novosadska) and 4 (Qamata)]; [CT2-2 (Felina-34)and 4 (Qamata)]; [CT2-3 (Futura-77) and 4 (Qamata)] and [CT2-4 (Kompolti)and 4 (Qamata)] with all other interactions not listed having $p>0.05$ (i.e. insignificant).
- Significant interactions ($p<0.05$) for the treatment combination of CT2-3 (Futura-77) and 1 (Addo) were observed against [CT2-2 (Felina-34) and 1 (Addo)]; [CT2-1 (Novosadska) and 2 (Dohne)]; [CT2-2 (Felina-24) and 2 (Dohne)]; [CT2-3 (Futura-77) and 2 (Dohne)]; [CT2-4 (Kompolti)and 2 (Dohne)]; [CT2-1 (Novosadska) and 3 (Libode)]; [CT2-2 (Felina-34) and 3 (Libode)]; [CT2-3

(Futura-77)and 3 (Libode)] and [CT2-4 (Kompolti) and 3 (Libode)] with all other interactions not listed having *p*>0.05 (i.e. insignificant).

- Significant interactions (*p*<0.05) for the treatment combination of CT2-4 (Kompolti) and 1 (Addo) were observed against [CT2-2 (Felina-34) and 1 (Addo)];]; [CT2-1 (Novosadska) and 2 (Dohne)]; [CT2-2 (Felina-34) and 2 (Dohne)]; [CT2-3 (Futura-77) and 2 (Dohne)]; [CT2-4 (Kompolti) and 2 (Dohne)]; [CT2-1 (Novosadska) and 3 (Libode)]; [CT2-3 (Felina-34) and 3 (Dohne)] and [CT2-4 (Kompolti) and 3 (Libode)] with all other interactions not listed having *p*>0.05 (i.e. insignificant).

Main conclusions

The main conclusions are as follows:

- On examining the overall planting date results, using both the total biomass and fibre yield per hectare as determining factors, it emerged that the 1st planting date (October) generally produced better yields than the second planting date. It therefore appears that October planting may be preferable to November, for growing hemp in South Africa, for these particular European cultivars, although this was not always the case.
- The results obtained here in terms of planting date are very tentative and need to be confirmed by more elaborate commercial trials over a number of years.

3.1.3.1.4 Effect of fertiliser treatment

The effects of the different fertiliser treatments on fibre yield of Novosadska planted at Addo are illustrated in Figure 58, with the detailed data being given in Appendix 2 Table 4.

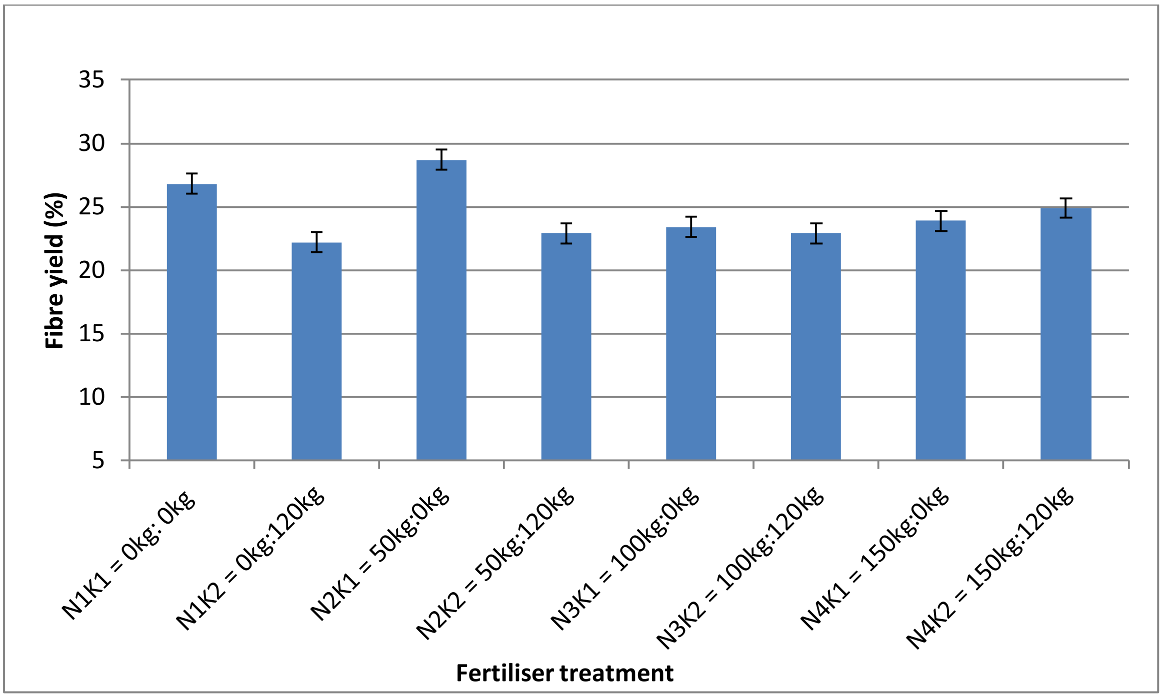

Figure 58: Effect of fertiliser treatment on fibre yield (Novosadska cultivar).

According to the results of the fertilizer trials (Figure 58 and Table 24), an addition of 50kg of nitrogen (without potassium) improved the fibre yield slightly when compared to the control (no fertiliser applied), whereas none of the other applications of fertiliser appeared to beneficially affect the fibre yield. Nevertheless, in order to put this in perspective, one also needs to consider the total dry biomass yield per hectare in order to assess the cultivar performance in terms of the total fibre yield per hectare.

Figure 59 illustrates error bar chart on the effect of the different combinations of nitrogen and potassium fertiliser treatment on dry biomass and total fibre yields ($kg.ha^{-1}$).

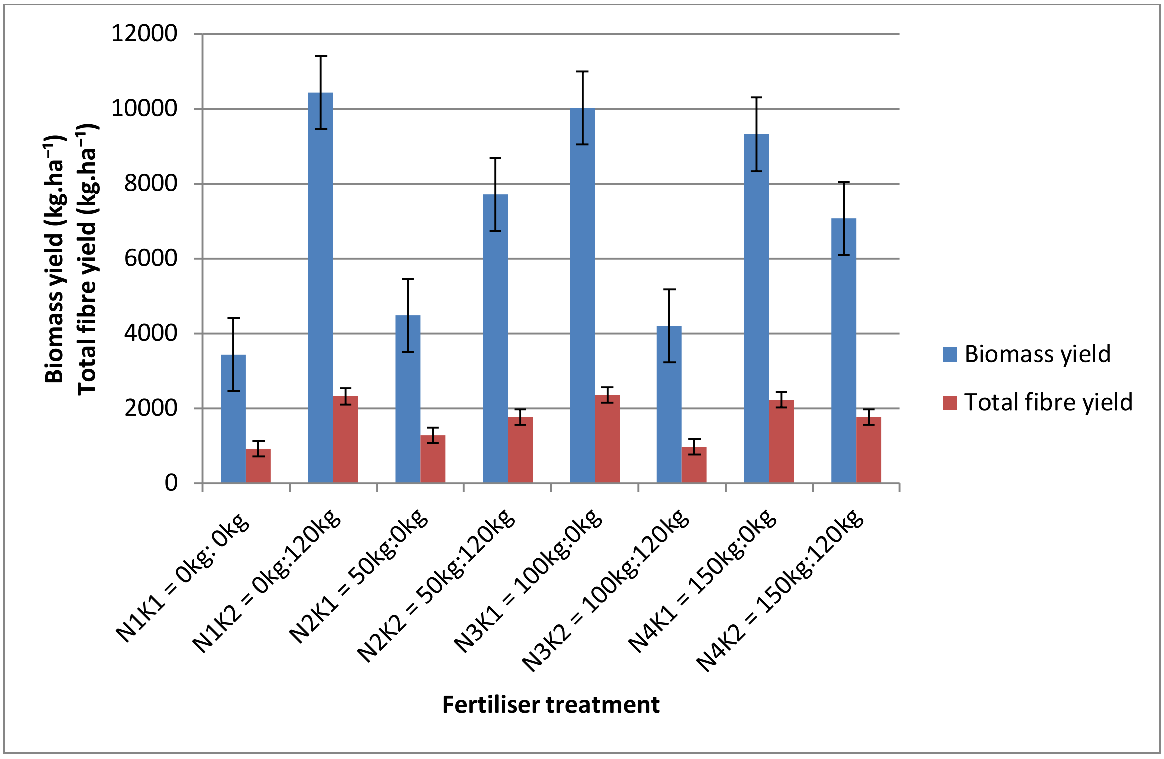

Figure 59: Effect of fertiliser treatment on dry biomass and total fibre yields (kg.ha^{-1}) of Novosadska cultivar, planted at Addo

In terms of the overall effect of fertiliser on the total biomass and fibre yields per hectare (Figure 59), it emerged that the fertiliser treatment combinations of N1K2 (0kg: 120kg); N3K1 (100kg: 0kg) and N4K1 (150kg: 0kg) produced better yields of 10432, 10021 and 9319 kg.ha^{-1} of dry straw biomass, and 2316, 2345 and 2227 kg.ha^{-1} of fibre, respectively.

Statistical analysis

Figure 60 shows the means and error bars for fibre yield, as derived from the ANOVA, for the qualitative interpretation of interactions between fertiliser treatment and fibre yield.

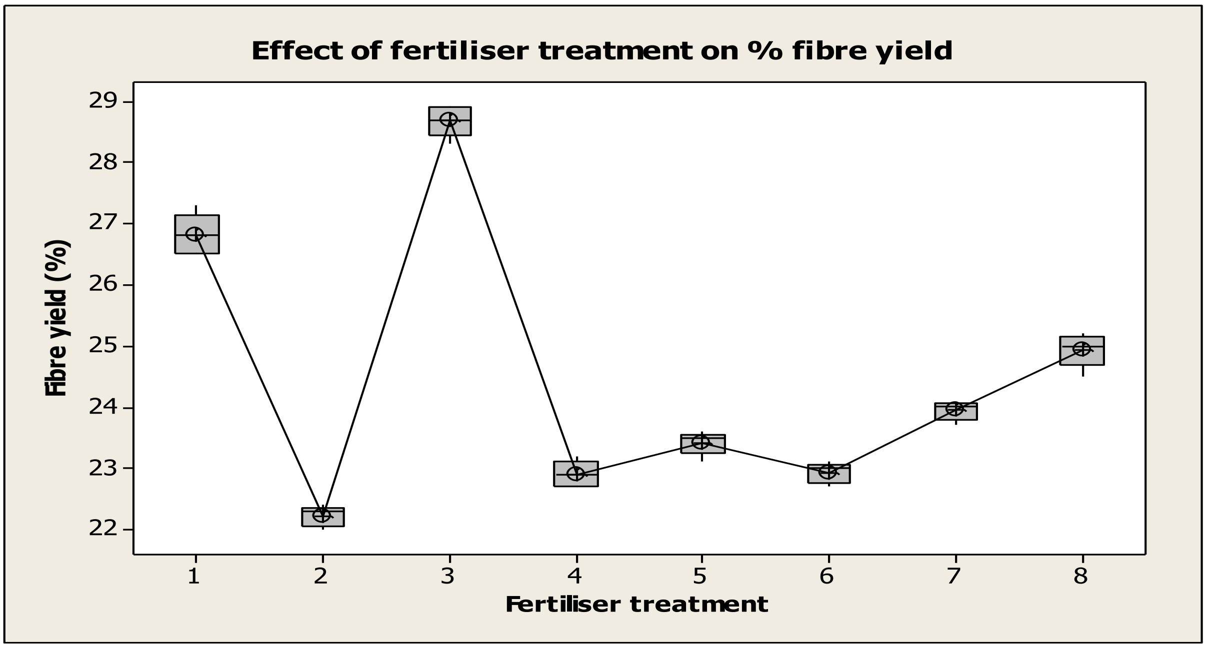

Figure 60. Effect of fertilizer treatment on fibre yield.
Treatment [1=(N1K1=0kg:0kg); 2 =(N1K2=0kg:120kg); 3=(N2K1=50kg:0kg); 4=(N2K2=50kg:120kg); 5=(N3K1=100kg:0kg); 6=(N3K2=100kg:120kg); 7=(N4K1=150kg:0kg) and 8=(N4K2=150kg:120kg).

Table 20 gives the ANOVA results in terms of the statistical significance of the effect of the fertilizer treatment (p-factor) on the average fibre yield.

Table 20. ANOVA results for the effect of fertiliser treatment on fibre yield.

Factors	dF	Sum Square (SS)	Mean Square (MS)	F	p-Value	Significance (Yes or No)
Fertiliser treatment	7	173.9	24.8	405	0.000	Yes
Error	32	1.6	0.05			
Total	39	175.5				
S = 0.2267 R-Sq = 99.06% R-Sq(adj) = 98.86%						

According to Table 20, the application of fertiliser had a significant influence on fibre yield as shown by p<0.05, and can be explained as follows:

- The highly significant p-value for this test implies that the average fibre yield differed significantly for at least two of the fertiliser treatments.

- Qualitative interpretation of the interactions between fertiliser treatment and cultivar performance, as shown in Figure 60, indicated that strong interactions between all the combinations of fertiliser treatment occurred, with the exception of the N2K2 (50kg:120kg) and N3K2 (100kg:120kg) interactions which produced non-significant results ($p>0.05$) for the individual interactions.

Main conclusions

The following general observations can be made on the basis of the fertiliser treatment trials:

- Moderate increases were observed in the biomass and fibre yields with an increase in nitrogen fertiliser application, from 50kg to 100kg, the application of 150kg nitrogen having a negative effect on both biomass and fibre yields.
- The application of 120kg potassium fertiliser greatly increased the biomass yield but not the fibre yield.
- The application of both nitrogen and potassium fertiliser did not seem to have a beneficial effect on either the biomass or fibre yield.
- It is recommended that the soil nutrients should be analysed prior to application of fertiliser to determine the correct type and quantity of fertiliser required, since both excessive and inadequate levels of fertiliser can affect hemp fibre yield.

3.2 Effect of Daylight and Artificial light, Retting Duration and certain other Agronomic Parameters on Hemp Fibre Yield and Properties

3.2.1 Introduction

Natural fibres, hemp included, by their nature, are very variable, both within and between fibres, and this variability is translated directly into the fibre properties and performance. Hemp fibre properties are controlled by the molecular fine structure of the fibres, as affected by genetics and growing and processing conditions. Hemp plant growth is proportional to the duration and intensity of light, and young hemp plants respond favourably to longer daylight periods of up to 16 hours. Short daylight periods inhibit stem growth, while daylight periods of 16 hours or more will result in hemp growing continuously in the vegetative phase. The daylight period, however, must be shortened to less than 10 hours to induce flowering and complete the growth cycle [147]. In South Africa, the longest daylight periods, reported in Section 3.1 (Table 12), vary between about 12 and 15 hours at the selected experimental planting sites.

In its natural state, hemp fibres can be regarded as nature's composite material that consists of a hierarchy of different fibre formations or hierarchical structures, i.e., bast fibre bundle-to-microfibril, glued together by such materials as the hemicellulose and lignin. In Figure 61, a schematic representation of the bast fibre hierarchy is presented [148].

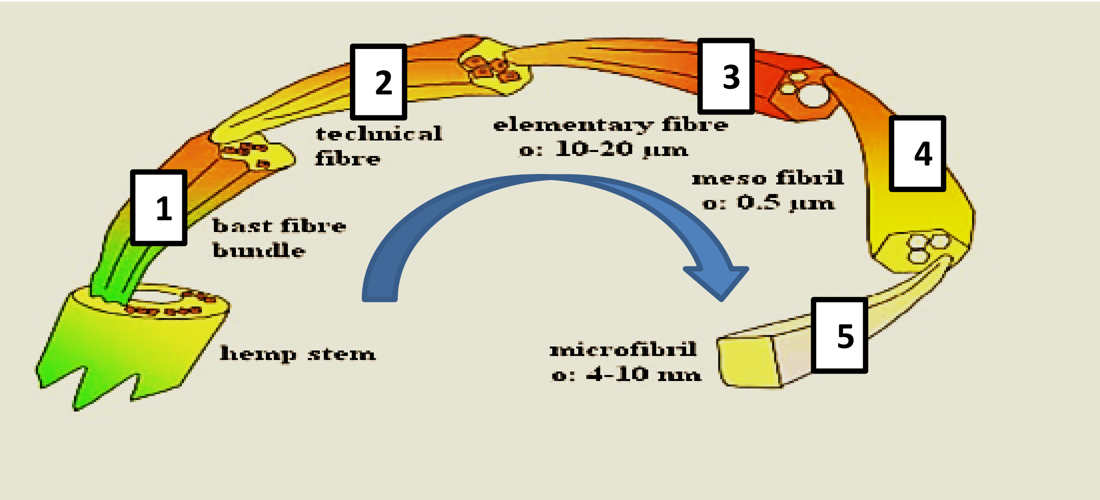

Figure 61. Schematic representation of the fibre hierarchy in bast fibres, such as hemp [148].

The microfibrils, with a diameter range of 4 to 10nm (marked 5), are the basic units bonded together by the hemicellulose to form mesofibrils, the diameter of which ranges between 0 to 0.5 µm (marked 4), from which elementary fibres, with a diameter range of 10 to 20 µm (marked 3), are formed [149 - 151]. The technical fibres, having a diameter range of 50 to 100 µm (marked 2), are formed by packed elementary fibres, glued together by pectin and lignin. It is from the combination of these strands of fibres that bundled fibres (marked 1) are formed [152]. The current global research agenda is focused on efforts to continuously investigate the various types of fibre treatments, namely mechanical, chemical and biotechnological, that could best separate bast fibres into their constituent ultimate/single fibre form for the development of high value added niche products.

Bundles of primary and secondary fibres are found in the cortex part of the hemp stem, as shown in Figure 62 [153]. The primary fibres, nearest to the stem surface, are coarse and formed at the early growth stage during the phase of rapid stem elongation, and contribute 92 to 95% of the bast fibres located in the cortex. The secondary fibres near the cambium layer, are finer and only present in the thick part of the stem [154].

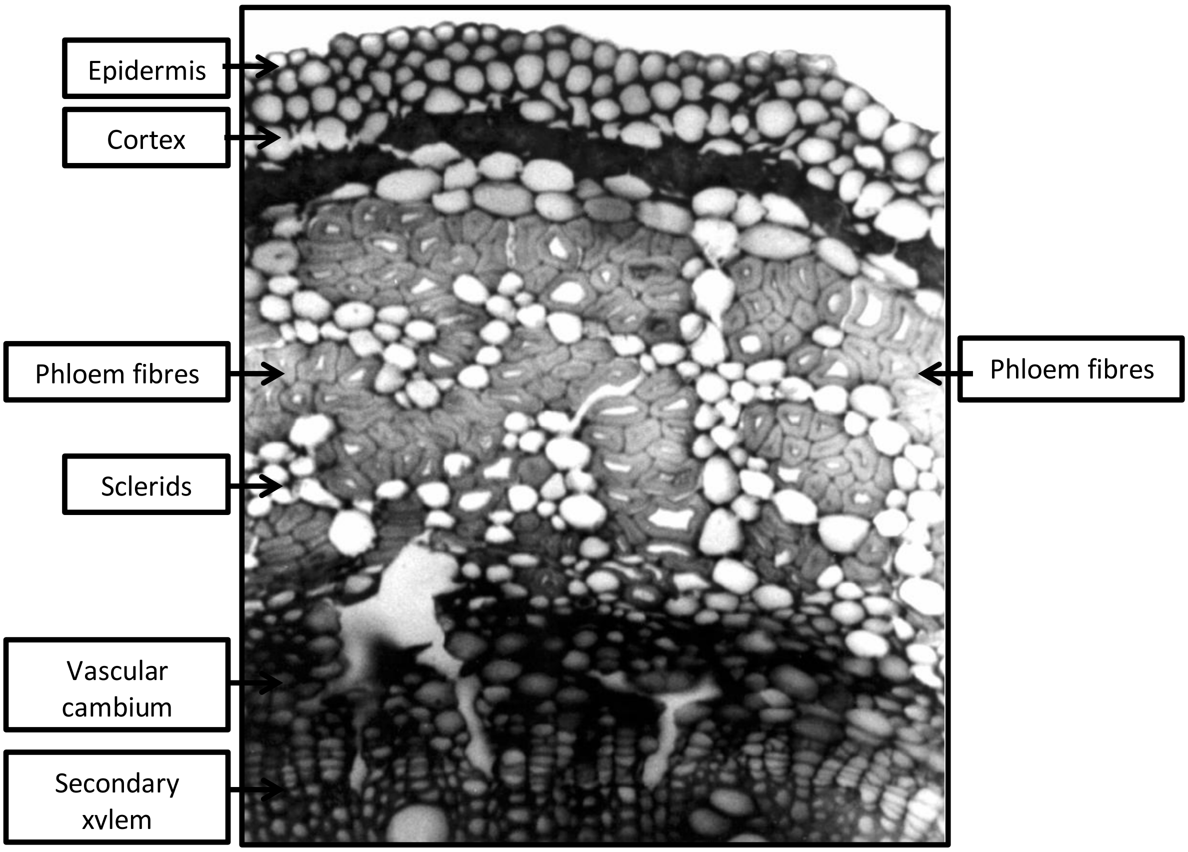

Figure 62. Magnified cross-section of a fibre hemp stem excised at the midpoint (photo: H. Sankari [153]).

The hemp stem is made up of the pith, xylem, cambium, phloem, cortex and the epidermis, and it is the phloem that contains the actual fibres, together with sieve tubes, parenchyma cells and sclerids. Bast fibre bundles form a ring around the outer part of the stem (dark ring in Figure 62), with the fibres joined together by a middle lamella, and mainly composed of pectin [155 - 157].

Table 21, compiled from various sources [158, 159], compares the physical properties of certain fibres to provide a background to the assessment of the hemp fibres produced in the present trials.

Table 21. Comparative physical, mechanical and chemical properties of various fibres [158, 159]**.

Properties	Flax	Hemp	Jute	Kenaf	E-Glass Fibre
Single fibre length (mm) Range	10-70	7-55		1.4-5	-
Average	32	25	2-5	2.6	-
Bundle fibre length (mm)	250-1200	1000-4000	1500-3600	1500-4000	-
Mean diameter (µm)	19	25	20	21	-
Density (g/cm^3)	1.4	1.48	1.46	1.2	2.55
Moisture absorption (%)	7	8	12	12	
Tensile strength (N/m^2)	800-1500	550-900	400-800	275-450	2400
Young's modulus, E (Gpa)	60-80	70	10-30	*	73
Specific E/density	26-46	47	7-21	*	29
Elongation at break (%)	1.2-1.6	1.6	1.8	*	3
Cellulose (%)	78.5	68.1	58-63	60.8	-
Hemi-cellulose (%)	9.2	15.1	21-24	20.3	-
Lignin (%)	8.5	10.6	12-14	11	-
Pectin (%)	2.3	3.6	#	3.2	-
Ash (%)	1.5	2.5	0.5	4.7	-

* No authoritative value available

****Note:** *Properties of natural fibres vary greatly, depending upon fibre preparation, testing method, fibre origin, agricultural parameters, etc.*

Inherent variability along the length of the fibre, differences between plants, molecular chain orientation, weak spots or deficiencies along the fibre length and chemical composition have all a direct bearing on the mechanical properties of hemp fibres [159]. Therefore, large variations in fibre mechanical properties generally occur, with differences between fibres from different parts of a plant as well as different plants.

In Section 3.2.1, it was reported that only coarse fibre bundles, indicated by number **1** in Figure 61, could be extracted from the retted hemp straw samples grown during these trials owing to the lack of local expertise on retting. The coarse fibre bundles were all that were available for testing and evaluating the fibre physical properties. Light combing with a metal fine toothed comb having 12 teeth/cm with each tooth about 0.25 mm in diameter and 25 mm long, was used to refine the bundle fibres, but because of their under retted state, the bundle fibres were still rather coarse after combing. All tests therefore had to be carried out on bundle fibres in a rather "coarse" and variable state, despite attempts to homogenize them by a simple blending procedure. The tests carried out included:

- Colour (subjective assessment),
- Fineness (tex),
- Specific strength (cN/tex), and
- Coefficient of variation (%) of specific strength

Each set of results has been presented individually in a separate table in the Appendix 2 and despite some limitations, it was still possible to examine the effects of the various agro-variables on each measured property, and to extract information that can assist in decision-making on the potential to establish a primary hemp fibre production industry in South Africa.

3.2.2 Experimental

3.2.2.1 Cultivar cultivation experimental trials

a) Natural lighting (normal day-length) conditions

Six cultivars, namely Novosadska, Ferimon-12, Fedora-19, Felina-34, Fedrina-74 and Futura-77 were planted at four sites (Addo, Libode, Mtiza and Qamata) in plots of sixteen rows, each being at 4m long and 25cm apart. A one metre-wide path divided the plots, facilitating access to the plants and sample collection. A seed density of 80kg.ha^{-1} was used at all the sites. Table 22 shows which cultivar was planted at each site, the experiments being replicated three times.

Table 22. Cultivar planted at each site

Planting site	Cultivar
Addo	Novosadska, Ferimon-12, Fedora-19 and Futura-77
Libode	Novosadska, Ferimon-12, Fedora-19, Felina-34, Fedrina-74 and Futura-77
Mtiza	Fedora-19, Felina-34, Fedrina-74 and Futura-77
Qamata	Felina-34

b) Artificial lighting conditions

This experiment was undertaken only at the Addo site, using the same planting method as that described for a) above except that only three cultivars, namely Novosadska, Ferimon-12 and Fedora-19 were planted and the cultivars received an extra four hours of artificial using electrical bulbs of 60 Watts as light source at a height of 1.3 meter from the ground (Figure 63).

Figure 63. Hemp plants receiving an extra four hours per day of artificial light

c) Harvesting, retting and fibre extraction

No other treatments, such as fertiliser or herbicide, were used during the plant growth stage, any weeds being removed by hand. The matured plants were harvested and left on the field to dry, after which the dry biomass of straw was weighed. The mean dry biomass obtained at each site is shown in the Results section in Table 29. The straw was subjected to field retting (Figure 64) for periods ranging from two to four weeks at the respective sites, after which the retted straw was sent to the CSIR for testing and evaluation.

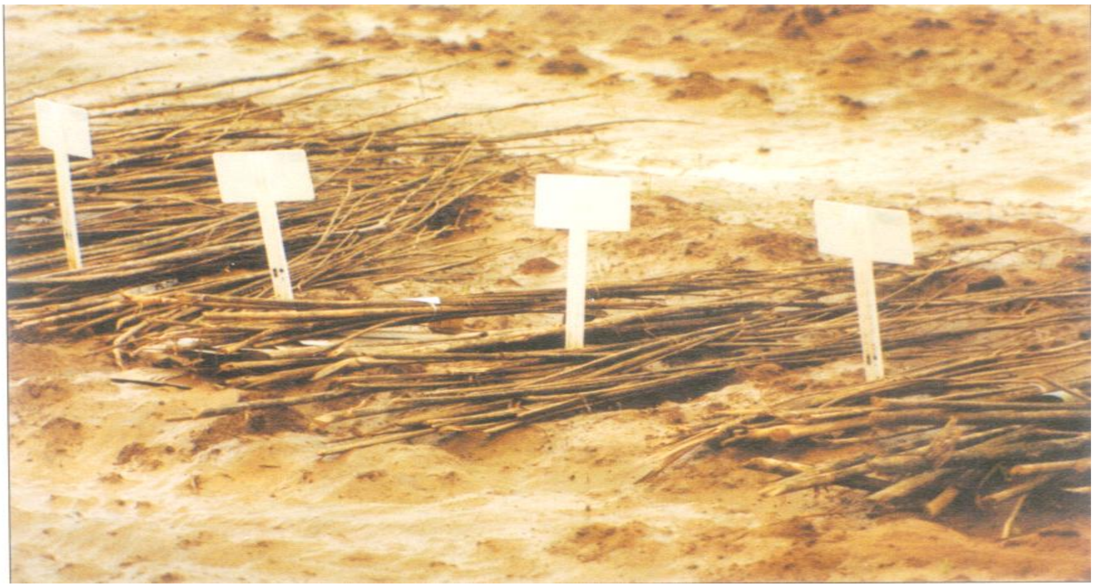

Figure 64. Field retting of hemp straw at Addo

Fibre extraction from the retted hemp straw was carried out in a similar manner to that described in Section 3.1.3, after which the extracted fibres were tested for various properties.

3.2.2.2 Fibre physical properties

3.2.2.2.1 Sample preparation

Fibres, from the various cultivars and trials sites (Addo, Libode, Mtiza and Qamata), were analysed to determine the effect of planting site, cultivar type, retting and lighting conditions on the fibre physical properties. Subjective assessment of the degree of retting of the extracted fibres, using straw colour as a criteria and a rating scale of 1 to 5, was also undertaken. Not all six cultivars were planted at all the sites due to limitations in the quantity of seed available (see Table 23). Small quantities of fibre bundles were randomly selected from each blended sample and carefully combed to reduce coarseness.

For each sample, a collective test of bast fibres bundles was undertaken to ascertain the quality of the fibres in terms of three objectively measured properties, namely bundle tensile tenacity (specific strength), its co-efficient of variation (CV%) and fibre fineness / linear density, as well as in terms of the subjectively assessed fibre colour. Table 23 gives an overview of the experimental design and provides the background and context to the evaluation and discussion of the physical properties.

Table 23. Experimental design for determining the effect of different agronomic parameters on the physical properties of fibres from different hemp cultivars

Experimental design Code = $a_1n_1n_2n_3a_2$				
Site a_1	Cultivar n_1	Planting n_2	Retting (weeks) n_3	Light Exposure a_2
A (irrigation)	1	2	2	N
	1	2	3	N
	1	3	2	N
	1	3	3	N
	1	2	2	I
A (irrigation)	2	2	2	N
	2	2	2	I
	2	2	3	I
	2	2	4	I
	2	3	3	I
A (irrigation)	3	2	2	I
	3	2	3	N
A (irrigation)	6	2	3	N
	6	2	4	N
L (dry land)	1	2	3	N
	2	2	3	N
	3	2	3	N
	4	2	3	N
	5	2	3	N
	6	2	3	N
M (dry land)	1	2	3	N
	-	-	-	-
	3	2	3	N
	4	2	3	N
	5	2	3	N
	6	2	3	N
Q (irrigation)	4	2	3	N
Key to Sites A=Addo L=Libode M=Mtiza Q=Qamata	**Key to cultivars** 1=Novosadska 2=Ferimon-12 3=Fedora-19 4=Felina-34 5=Fedrina-74 6=Futura-77	**Key to plantings** 2=2nd planting (November) 3 = Repeat Planting in November	**Key to retting** 1=1 week 2=2 weeks 3=3 weeks 4=4 weeks	**Key to Light Exposure** N=Natural I=Increased (artificial)

3.2.2.2.2 Fibre tests

Five specimens per sample were tested, the individual results being used for the statistical analysis, while only the mean (average) values were presented in the Results and Discussion section.

a) Bundle tensile strength

Fibre bundle tensile testing was carried out on an Instron Tensile Tester (Model 4411) at zero gauge, using Pressley clamps lined with the recommended standard black leather. The method used was essentially that of IWTO Test Method 32 and similar to that developed for Sisal [160]. Clamping distance of 25 mm was used. Light combing of the fibre bundles, with a metal toothed comb (12 teeth/cm, each about 0.25mm in diameter and 25 mm in length) was used to produce the fine fibre bundles required for tensile testing.

The breaking tenacity (or specific strength in cN/tex) of the fibres was obtained by dividing the maximum force, applied to the test specimen when extended until it ruptured, by the bundle linear density (Heyland et al. 1995, ISO 5079 1995) [161]:

$$Breaking\ Tenacity\ \left({}^{cN}/_{tex}\right) = {}^{F_{max}}/_{m_f} \times l_f \times 10^{-4}\ ,\ where \qquad (2)$$

Fmax = the maximum breaking force applied to the fibre bundle [N],
m_f = mass of the fibre bundle tested [g],
lf = length of the fibre bundle tested [mm], and
1 tex = g/1000m.

Ten fibre bundles were tested per sample, each bundle being carefully assembled from single parallelised fibres that were continuous between the outside edges of the Pressley clamps. The choice of a ten fibre bundles for bundle strength test for each sample was a result of few retted hemp straws delivered to CSIR by ARC-IIC for evaluation.

b) Linear density

Because of its simplicity, the gravimetric method of fibre fineness measurement was used to determine the fibre linear density. The method involved the use of a metal plate into which a groove (100x10x10 mm) had been cut and into which a metal "key" fitted perfectly. A collective bundle of fibres, of total mass ≈ 0.50g, was pressed firmly into the groove and any protruding fibre ends were sheared off at both ends of the groove. The average linear density of the fibres was derived from the collective bundle mass, the total number of fibres in the collective bundle and the collective bundle length of 100mm.

The average fibre linear density (T) was calculated using the following formula [162]:

$$T = {}^{m}/_{n.l} \times 10^3 \text{, where}$$

T – linear density (Tex); m –mass of sample (mg); n- number of fibres, l- sample length (mm) = 100mm.

c) Other aspects of fibre quality

Factors, such as the appearance, colour and handle of the fibre, levels of impurities, also contribute towards fibre quality and need to be considered when assessing the quality. The retting process is normally based on subjective judgement and is highly dependent on many years of field experience by hemp growers to know the right time to retrieve the perfectly retted hemp straws before the onset of the irreversible rotting process. In commercial dealings, buyers and traders use subjective fibre evaluation techniques for determining hemp fibre quality and value. Subjective assessments of the degree of retting of straw and fibre colour are some of the subjective measurement criteria used.

As part of building local expertise at the CSIR for assessing bast fibre quality, including subjective assessment, hemp fibres, varying in their degrees of retting, were subjectively analysed by tracking the changes in fibre colour resulting from exposure to fungal activity and climatic conditions during retting. The photographs in Figure 65 depict the scale used to assess the colour of the retted hemp fibre, ranging from pale yellowish-brown (1) to greyish (5).

Figure 65. Hemp fibre colour chart used to conduct subjective assessment of retting degree [Source : Own development] .

d) Microscopy

Longitudinal and cross-sectional scans of fibres from the hemp cultivars grown at the various sites were taken using a scanning electron microscope (SEM), Model: JEOL- JSM 7500F Scanning Electron Microscope, located at the CSIR-campus in Pretoria. All sample preparation for SEM analysis was done in Pretoria. The JSM-7500F offers the highest resolution at the lowest kV of any SEM available, achieving a resolution of 1.4 nm at 1 kV. It provides in-lens performance (0.6 nm at 30 kV) but can handle samples up to 200 mm in diameter x 10 mm length.

3.2.2.3 Fibre chemical properties and composition

3.2.2.3.1 Chemical analysis.

The chemical composition, including the cellulose, lignin, moisture and ash content, of the raw hemp fibres was determined for the cultivars grown at the different sites. The Kurschner-

Hoffer method was used for determining the cellulose content, while the standard method TAPPI (1998) acid insoluble lignin in wood and pulp-T22 om-98, 169) was used for the determination of lignin content [163]. The hemicellulose content was determined using the neutral detergent fibre method of Goering and Van Soest (1975) [164].

The moisture, ash and extractives (ashing) contents were determined by the relevant ASTM standard methods, ASTM D2866. Ash content (%) was estimated as the residue after "ashing" at 600-800°C. Ash samples were sent to the CSIR National Metrology Laboratory, Pretoria, for microprobe analysis of their elemental composition, in order to determine the quantity of specific elements in the fibre.

3.2.4 Results and discussion

The experimental results reported and the subsequent discussions in this section are based upon the agronomic experimental design for the cultivar planted at each site. An incomplete experimental design was employed, with no specific cultivar planting being replicated at all four sites, thus affecting the statistical analysis and limiting the scope of the analysis. Despite these limitations, the available results were analysed and interpreted in order to make recommendations concerning future experimental designs aimed at further investigating and establishing the optimal agro-parameters for hemp cultivation in South Africa.

3.2.4.1 Results

3.2.4.1.1 Fibre physical properties

Fibres were extracted from the retted straw of the five subsamples available for each cultivar, weighed and the mean fibre yield (%) calculated, see Appendix 3 Table 1 for the raw data. The results, illustrating the effect of the various agronomic parameters on the physical properties of the different cultivars grown at the different planting sites, are given under the following sub-sections.

Possible effects for CV values above 20% are as a result of fibre non-uniformity and quality of fibre (degree of retting, length, thickness, impurities).

3.2.4.1.1.1 Fibre Yield, Linear Density, Bundle Tensile Tenacity and CV

The **overall** mean results for fibre yield (%),fibre yield (kg.ha^{-1}), linear density (tex), bundle strength (cN/tex) and its standard deviation (std. dev), are shown in Table 24.

Table 24. Fibre properties of hemp cultivars grown under different agronomic conditions

Site	Cultivar	Planting Date	Retting Weeks	Day-light	Sample* Code	Mean fibre yield (%)	Standard deviation (std. dev)	Mean fibre yield (kg.ha^{-1})**	Fibre density (tex)	Zero gauge bundle tenacity	
										Mean (cN/tex)	CV (%)
ADDO	*Novosadska*	*November*	2	N	A122N	22.8	0.2	3302	45.0	46.9	11.3
	Ferimon-12	*November*	2	N	A222N	20.9	0.3	559	32.1	32.1	6.6
	Fedora-19	*November*	2	N	A322N	16.6	0.3	295	25.7	53.1	9.9
	Ferimon-12	*November*	2	I	A222I	22.6	0.4	1397	30.8	37.1	20.2
	Fedora-19	*November*	2	I	A322I	14.6	0.4	673	17.4	53.7	15.2
	Novosadska	*November*	2	I	A122I	17.9	0.2	737	37.6	39.9	38.2
	Novosadska	*November*	3	N	A132N	22.3	0.4	2510	68.0	42.5	18.5
	Futura-77	*November*	3	N	A623N	19.8	0.6	106	12.2	40.9	21.8
LIBODE	*Novosadska*	*November*	3	N	L123N	19.9	0.5	549	14.8	50.4	15.2
	Ferimon-12	*November*	3	N	L223N	22.7	0.6	818	29.4	51.7	12.3
	Fedora-19	*November*	3	N	L323N	20.0	0.6	578	42.2	55.5	10.9
	Felina-34	*November*	3	N	L423N	19.1	0.2	359	26.7	66.8	10.0
	Fedrina-74	*November*	3	N	L523N	23.0	0.2	788	30.9	57.7	21.5
	Futura-77	*November*	3	N	L623N	21.5	0.5	663	38.9	49.3	14.9

Site	Cultivar	Planting Date	Retting Weeks	Day-light	Sample* Code	Mean fibre yield (%)	Standard deviation (std. dev)	Mean fibre yield (kg.ha^{-1})	Fibre density (tex)	Zero gauge bundle tenacity	
										Mean (cN/tex)	CV (%)
MTIZA	*Novosadska*	*November*	3	N	M123N	18.8	0.2	705	12.6	50.9	11.1
	Fedora-19	*November*	3	N	M323N	18.3	0.3	245	46.4	52.1	14
	Felina-34	*November*	3	N	M423N	21.2	0.5	474	51.8	47.2	16.3
	Fedrina-74	*November*	3	N	M523N	21.7	0.3	578	28.8	43.5	17.9
	Futura-77	*November*	3	N	M623N	19.7	0.6	538	53.3	52.7	7.2
QAMATA	*Felina-34*	*November*	3	N	Q423N	14.8	0.4	223	45.5	54.7	18
ADDO	*Ferimon-12*	*November*	3	I	A223I	21.8	0.3	1314	41.1	44.3	16
	Futura-77	*November*	4	N	A624N	16.9	0.2	80	26.6	20.1	43.9
	Ferimon-12	*November*	4	I	A224I	18.8	0.3	983	37.3	44.5	9.8
Mean of Cultivars						19.8	0.4	803	34.6	47.3	16.6

*__Sample code__ is based on **Site** (represented by __first letter__ of planting site); __Cultivar__ (**1** = Novosadska; **2** = Ferimon-12; **3** = Fedora-19; **4** = Felina-34; **5** = Fedrina-74 and **6** = Futura-77]; __Planting Date__ (**1** = October; **2** = November and **3** = late November); __Retting Period__ (**2** = 2 weeks; **3** = 3 weeks and **4** = 4 weeks] and __Light Exposure__ (**N** = natural day length period and **I** = natural day length period + artificial (bulb) lighting).

** The wide range in Mean fibre yield (kg.ha^{-1}) yields obtained at Addo site were as a result of small sample size from which fibre yields were determined.

A) Effect of planting site, cultivar, retting period and lighting on fibre yield, linear density, bundle strength and CV

A.1 Cultivars grown at four sites under natural light and retted for two and three weeks, respectively

A.1.1 Two weeks retting

Figure 66 shows the effect of cultivar on fibre properties for the three hemp cultivars grown at Addo under **natural light** and which had been **retted for two weeks** (see Table 24). Five specimens per sample from each cultivar were tested and the testing protocol as described under section 3.2.2.2.2 (a-b) was followed. No climatic data on conditions of dew retting such as temperature and humidity was recorded by the ARC-IIC.

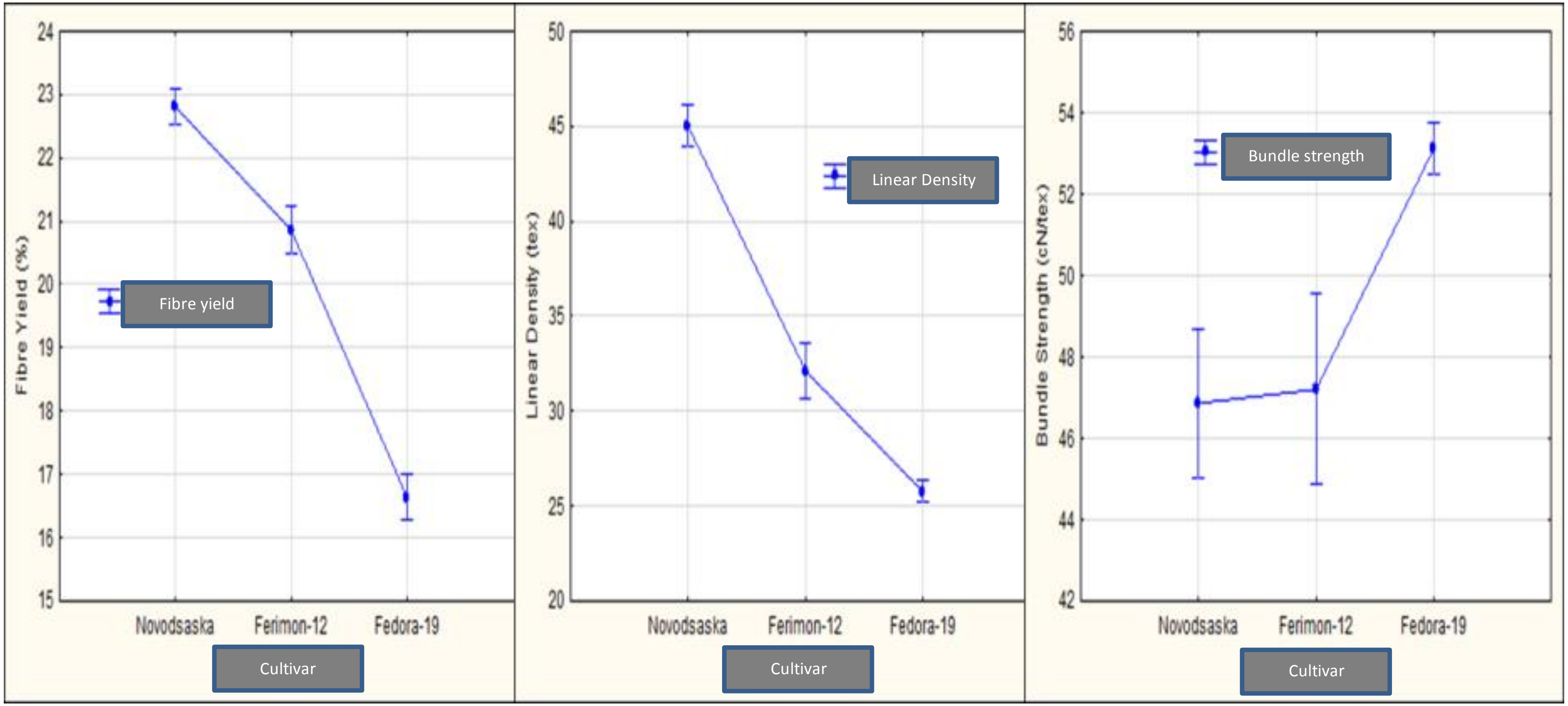

Figure 66. Fibre yield, linear density and bundle strength for cultivars grown at Addo under natural light and retted for two weeks.

According to the results given in Figure 66, it appears that:

- The average fibre yield of the three cultivars differed significantly, Novosadska, with a fibre yield of 23%, performing the best of the three cultivars. According to the published literature, hemp fibre yield can vary between 23 and 35% [62, 165], the levels achieved here are therefore rather on the low side.
- The average fibre linear density of the three cultivars differed significantly, with Fedora-19 having the lowest linear density, i.e. being the finest.
- Only the bundle strength Fedora-19 differed significantly from the other two.

A.1.2 Three weeks retting

Figure 67 shows the fibre yield (%), linear density (tex), bundle strength (cN/tex) and its CV (%) of the different cultivars grown at **different sites** under **natural light** and **retted for 3 weeks**.

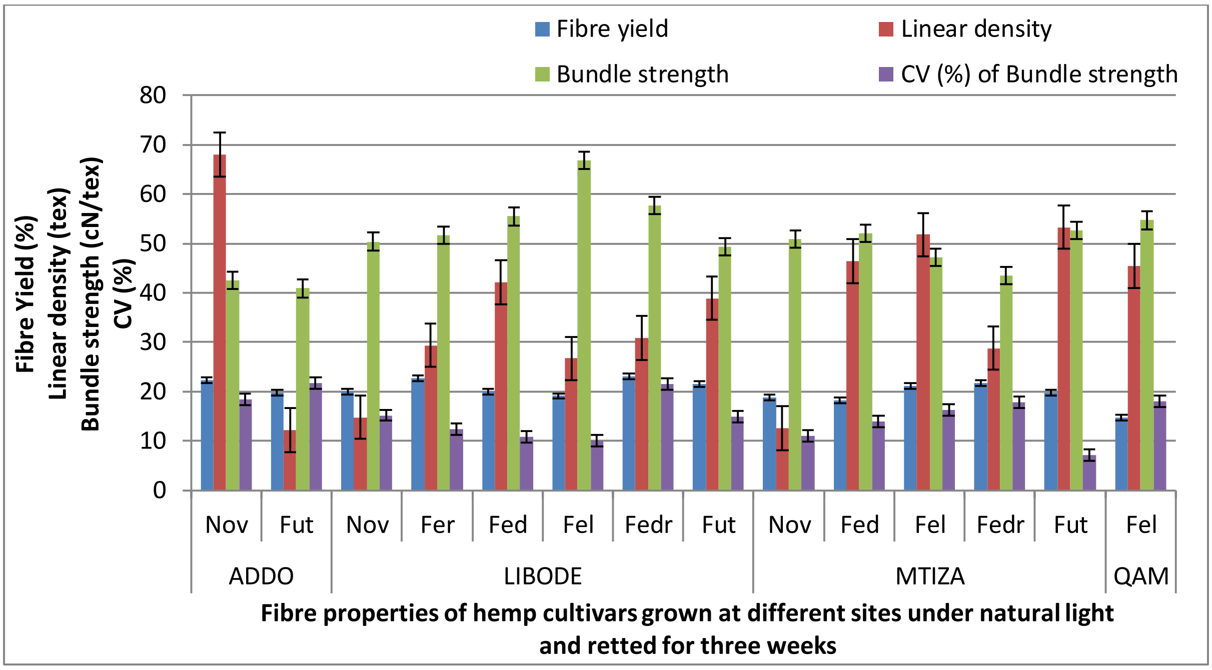

Figure 67. Fibre properties of hemp cultivars grown at different sites under natural light and retted for 3 weeks. [Nov=Novosadska; Fut=Futura-77; Fer=Ferimon-12; Fed=Fedora-19; Fedr=Fedrina-74; Fel=Felina-34; QAM=Qamata]

Figure 68 shows the effect of cultivar and planting site on the various fibre properties. The results of the ANOVA are given in Appendix 2 Table 3, where the incomplete experimental design is clearly evident, meaning that no meaningful statistical results were possible.

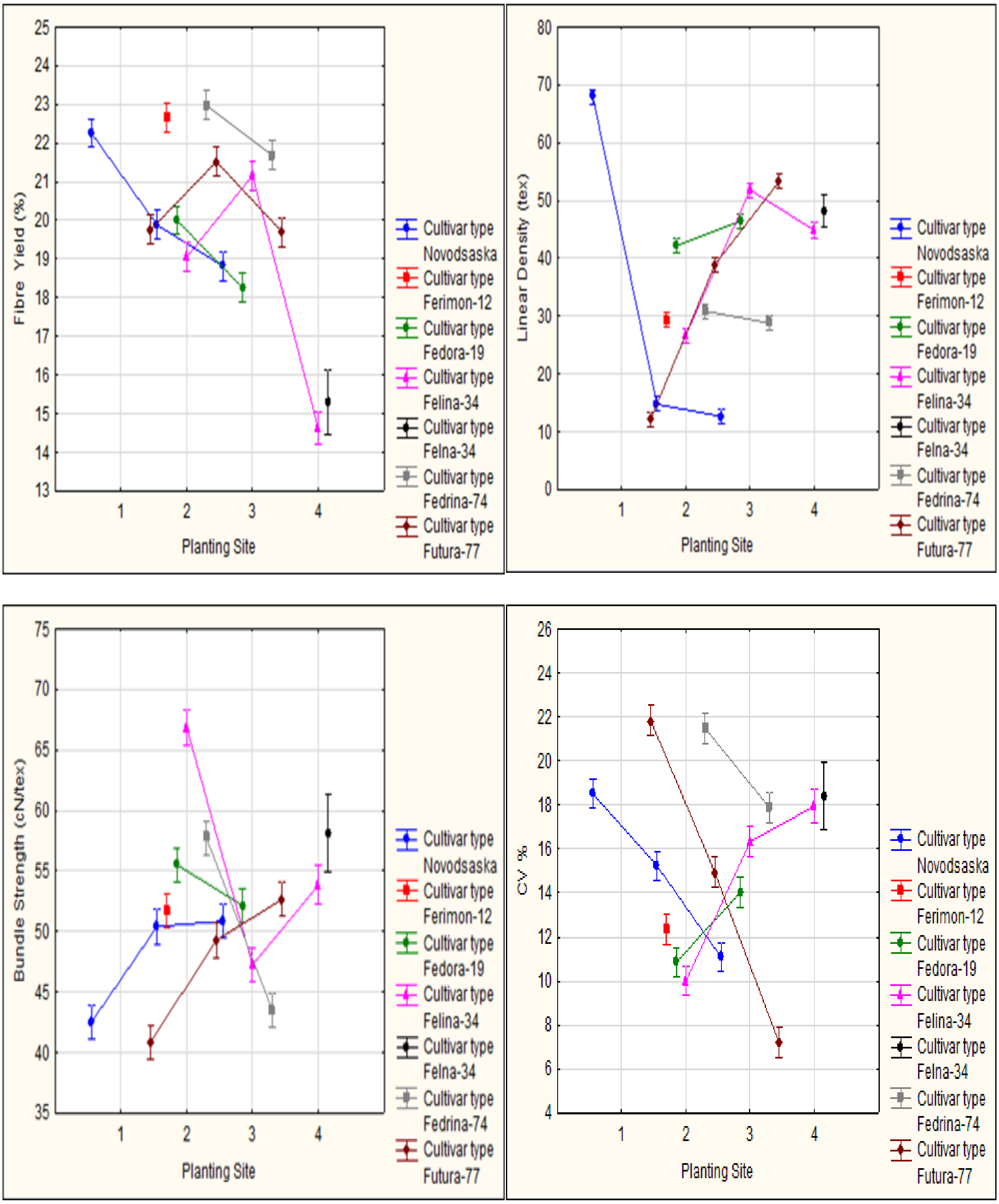

Figure 68. Effect of cultivar and planting site on fibre yield, linear density, bundle strength and CV of bundle strength (3weeks retting)

Main conclusions:

The main conclusions which can be drawn from the results plotted in Figure 67 are the following:

- Qamata produced the lowest fibre yield, with the highest yield being obtained with Fedrina-74 planted at Libode. The fibre yield levels achieved here are lower than the minimum of 23% reported in the literature [62, 165], all the cultivars therefore failing to meet the internationally accepted minimum standards in terms of fibre yield. Since the main trading item in hemp fibre crop production is the fibre, the low levels of fibre yield achieved here will negatively affect the economic viability of the primary fibre production industry, unless it is to some extent compensated for by high biomass yields per hectare.
- Significant inconsistencies were present in the linear density for Novosadska, being, for example 68 tex when grown at Addo compared to 12.6 tex when grown at Mtiza and 14.8 tex when grown at Libode. These discrepancies are probably due to the different times of harvesting and the degree of retting, both of which are known to affect fibre linear density. The cultivar that produced the finest fibres, i.e. lowest linear density, the Futura-77 grown at Addo.
- Felina-34 grown at Libode produced the strongest fibres, with a bundle strength of 66.8 cN/tex, the weakest being Futura-77 grown at Addo, with a strength of 20.1 cN/tex. The variations in strength values are due to sampling processes (such as variation in degree of retting, defects on tested fibres and number of single fibres contained in test specimen).
- The CV of the collective strength of bast fibre bundles tended to show the opposite trend to bundle strength, a higher bundle strength tending to be associated with a

lower CV, which is not unexpected. Felina-34 and Fedora-19 exhibited the lowest CV values when grown at Libode, while Novosadska and Futura-77 exhibited the lowest CV values when grown at Mtiza and the highest values when grown at Addo.

- The cultivar that came closest to meeting the minimum requirements for the fibre properties investigated here, namely fibre yield (high value), linear density (low value), bundle strength (high value) and CV of bundle strength (low value), was Novosadska grown at Libode.
- The significant differences in fibre properties of the same cultivar grown in different sites of the same region having similar soil types and climatic conditions can probably be attributed to two factors, namely low seed germinating viability arising from planting old seeds, and the lack of technical agronomic expertise in hemp cultivation and the retting process that affect sample processing to obtain more uniform elementary fibres for testing of physical properties.

A.2 Effect of retting period and lighting (natural and artificial) on fibre properties.

A.2.1 Ferimon-12 cultivar

The effects of the retting period and lighting conditions (natural or artificial) on the fibre properties of the Ferimon-12 cultivar grown at Addo (2-4 weeks retting) and Libode (3 weeks retting) are shown in Figures 69 and 70.

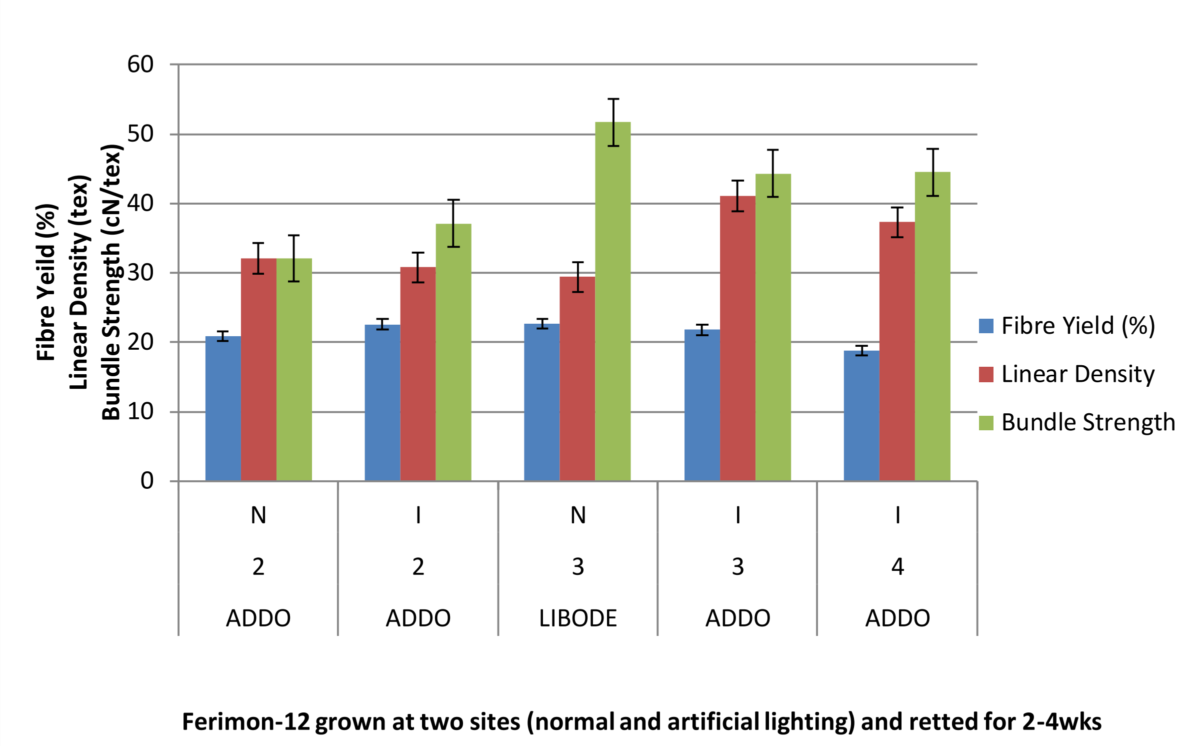

Figure 69. Effect of retting period and light on fibre physical properties of Ferimon-12 [N=natural day light; I = artificial lighting + natural day light; 2, 3, 4 = retting period in weeks].

According to Figures 69 and 70, it appears that a retting period of around 2 to 3 weeks was optimum, although the differences were not necessarily all that large or always consistent. It also appears that the results for the two different lighting conditions did not differ in a consistent manner in terms of the three fibre quality parameters covered, which is contrary to the expectations that the extra artificial light exposure would stimulate plant growth, thereby resulting in higher fibre yields.

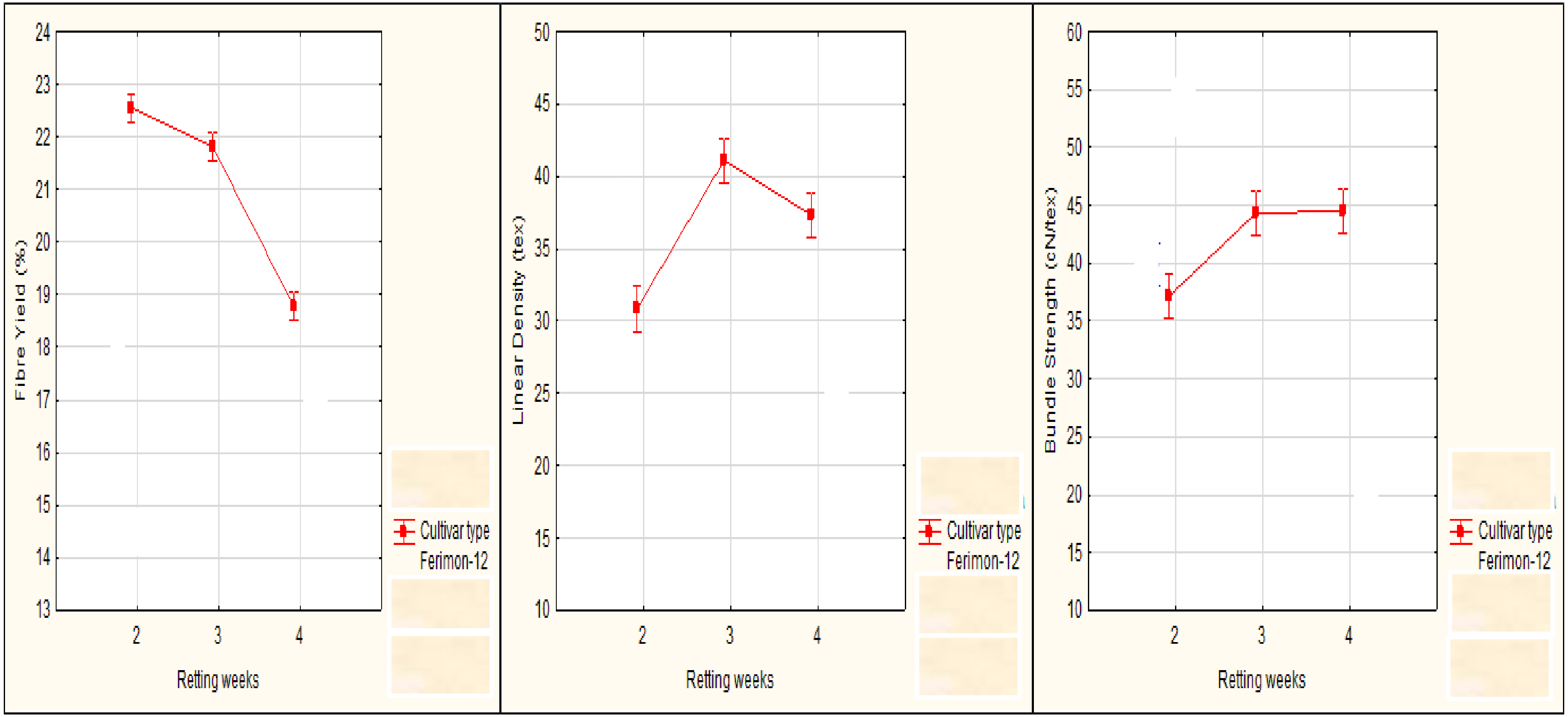

Figure 70. Effect of retting period (2 to 3 weeks) on fibre yield, linear density and bundle strength for the Ferimon-12 cultivar grown at Addo under natural plus artificial light.

A.2.2 Effect of lighting conditions (natural and artificial) for cultivars grown at Addo.

Figure 71 shows the effect of different lighting conditions (natural or artificial), on the fibre properties of the three cultivars grown at Addo and retted for 2 weeks.

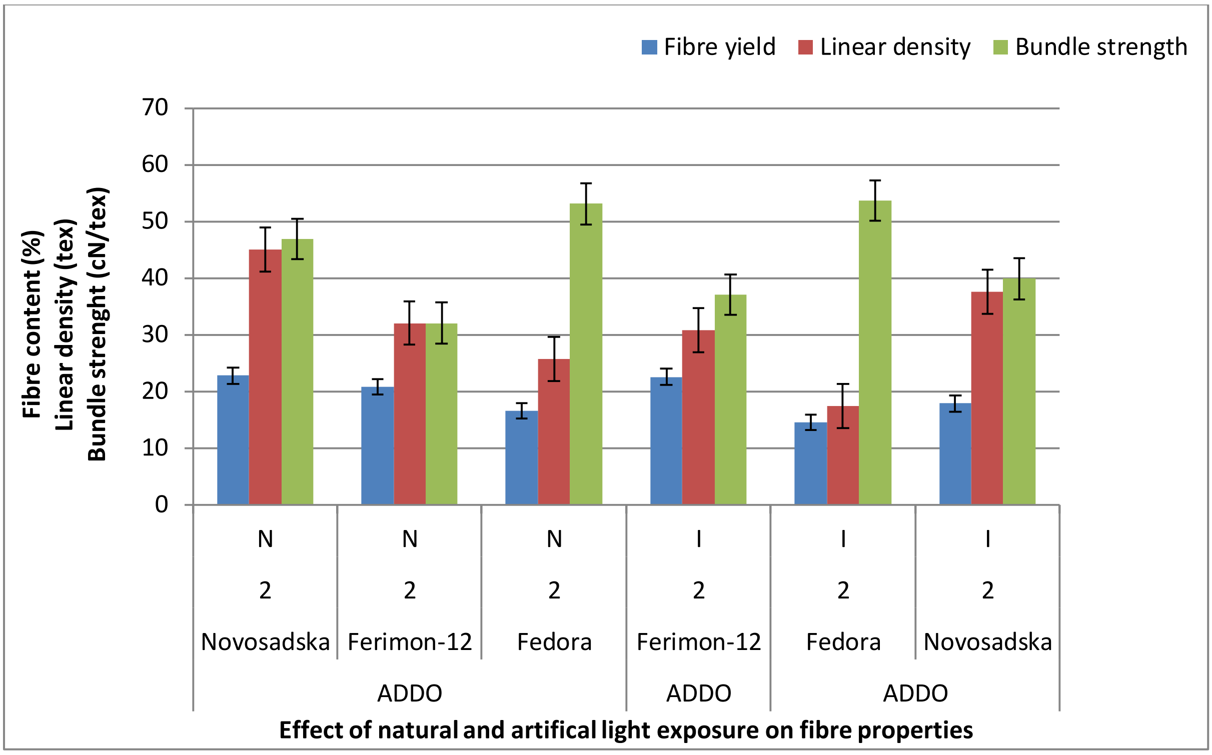

Figure 71. Effect of natural and artificial light exposure on the fibre yield and physical properties of three cultivars grown at Addo [N=natural day light; I = artificial light + natural day light; 2 = retting period in weeks].

According to the analysis of the results, plotted in Figure 71, it appeared that adding the artificial light did not affect the fibre properties of the different cultivars in a consistently beneficial manner.

B) Overall effect of planting site, cultivar, retting period and lighting conditions on linear density, bundle strength and CV

Figure 72 shows the effect of cultivar type and planting site on fibre yield (%), linear density (tex), bundle strength (cN/tex) and its CV (%), with Tables 25 & 26 showing the ANOVA and linear regression results, respectively.

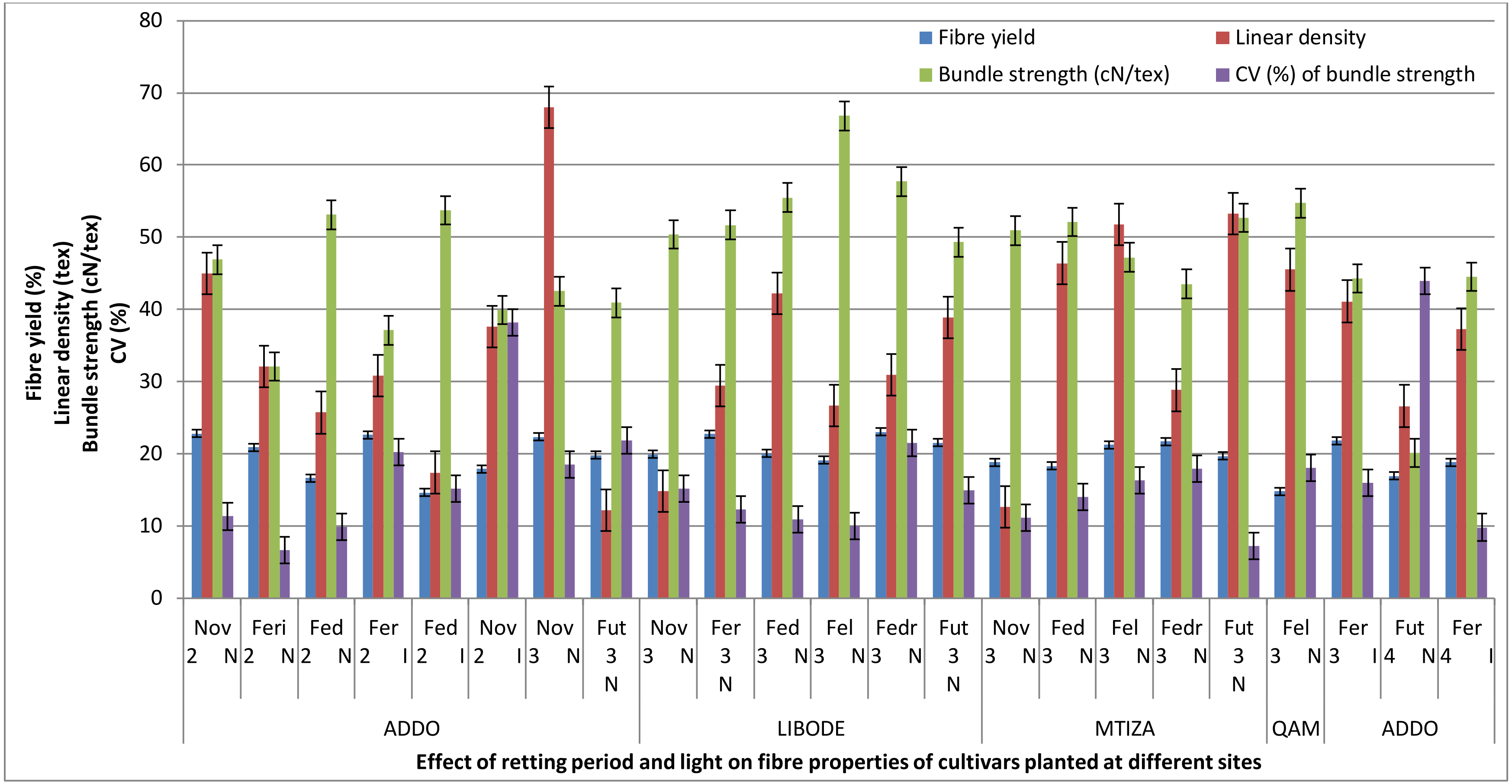

*Figure 72. Effect of cultivar and planting site on fibre yield, linear density, bundle strength and its CV [**Cultivar** (Nov = Novosadska, Fer=Ferimon-12, Fed = Fedora19, Fel=Felina-34, Fed = Fedrina-74, Fut = Futura-77); **Retting** (2,3,4 = weeks), **Lighting** (N=natural daylight & I=daylight + artificial), **Planting Site** (Addo, Libode, Mtiza and Qam = Qamata).*

Discussion

The following observations can be made on the basis of the overall results, plotted in Figure 72, concerning the effect of site, cultivar, retting period and lighting conditions on the fibre properties:

i. ***Fibre yield:*** The planting site, the retting period and lighting exposure conditions did not appear to affect the fibre yield of the different cultivars in a consistent manner.

ii. ***Linear density:*** Large differences in linear density values occurred for the same cultivar grown at different sites, e.g., Novosadska planted at Addo had a linear density of 68 tex and 12.6 tex when planted at Libode, retting being three weeks. These large variations are most likely due to the overall lack of technical expertise with respect to the overall primary hemp production management processes.

iii. ***Bundle strength:*** Similar inconsistencies in bundle strength as those for linear density were observed, as in linear density, the exception being Fedora-19, whose bundle strength of which at Addo, Libode and Mtiza, ranged only from 52.1 to 55.5 cN/tex, with no apparent influence of either the retting period or lighting conditions.

iv. ***CV of bundle strength:*** Cultivars that produced CV of bundle strength values lower than 10% were Ferimon-12 (natural and artificial lighting, and retted for 2 & 4 weeks) and Fedora-19 (natural light and 2 weeks retting) grown at Addo, and Futura-77 (natural light and 4 weeks retting) grown at Mtiza.

Statistical analysis

Table 25 shows the results of the analysis of variance (ANOVA) on the effect of planting site and cultivar on the fibre yield, linear density, bundle strength and its CV.

Table 25. Analysis of variance results for fibre linear density, bundle strength and CV

Response variable	Factor	Sum Square (SS)	Df Effect	Mean Square (MS)	F	p-value	Significance (Yes or No)
Fibre Yield	Planting Site*Cultivar	50.2	5	10.0	57.9	0.00	Yes
Linear Density	Planting Site*Cultivar	14343.2	5	2868.6	1448.4	0.00	Yes
Bundle Strength	Planting Site*Cultivar	973.2	5	194.6	77.1	0.00	Yes
CV	Planting Site*Cultivar	382.1	5	76.4	134.6	0.00	Yes

The results of the statistical analysis in Table 25, show that there were significant interactions (p-value of <0.05) between planting site and cultivar that affected the fibre properties, i.e. fibre yield, linear density, bundle strength and CV of bundle strength.

Table 26 shows the correlation matrix for fibre yield (%), linear density (tex), bundle strength (cN/tex) and its CV (%).

Table 26. Correlation matrix for fibre yield and properties

Fibre Properties	Means	Std.Dev.	Linear Density (tex)	Bundle Strength (cN/tex)	CV (%)	Fibre Yield (%)
Linear Density (tex)	35.8	16.2	1.000	-0.068	-0.079	0.048
Bundle Strength (cN/tex)	51.1	6.7	-0.068	1.000	-0.461	-0.253
CV %	15.0	4.3	-0.079	-0.461	1.000	0.179
Fibre Yield (%)	20.2	2.1	0.048	-0.253	0.179	1.000

The linear regression analysis carried out, with Bundle Strength as dependent variable (Y) and Fibre Yield, Fibre Linear Density and CV of Bundle Strength as independent variables, produced the following significant regression equation:

$$\text{Y (Bundle Strength in } cN/tex) = 59-0.467 \text{ CV(\%)}$$

According to Table 26, the bundle strength had a significant inverse relationship with both the CV and fibre yield.

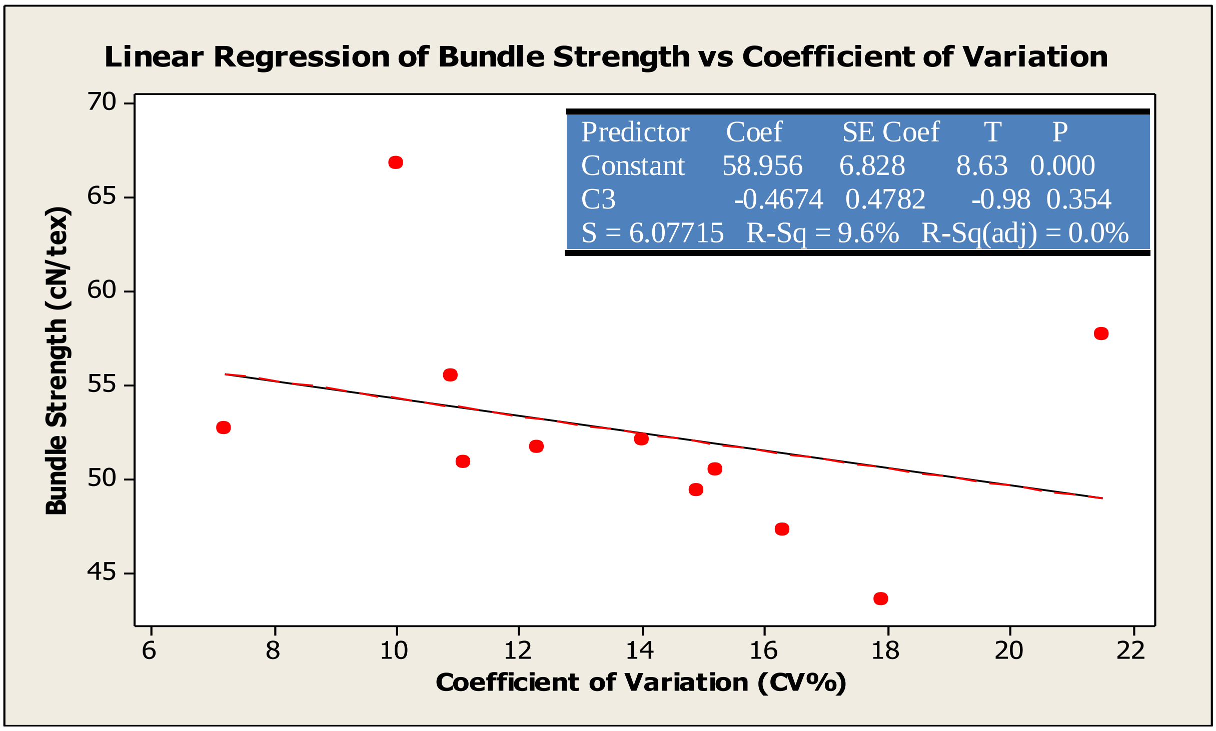

Figure 73. Bundle strength vs CVof bundle strength

The regression analysis showed that the bundle strength is mainly correlated with its CV, i.e. higher bundle strength being associated with a lower CV of collective bundle strength. The results have been plotted in Figure 73, with the regression line superimposed.

Main conclusions:

The following represent the main conclusions:

- The cultivar and agronomic conditions prevailing at the planting site had a direct effect on the fibre properties, such as fibre yield, linear density, bundle strengths and CV of bundle strength.

- A significant correlation existed between bundle strength and its CV, with higher bundle strength tending to be associated with a lower CV of bundle strength, i.e. the less variable the fibre, the higher their bundle strength tends to be.
- The lighting conditions had neither a large nor consistent effect on the various measured fibre properties.
- Retting periods of 2 or 3 weeks, did not appear to affect the properties of the fibres from the different cultivars in a consistent manner, and was found to generally produce better fibre results in terms of fibre yield and CV.

C) Subjectively assessed fibre quality

Using the colour code presented earlier, subjective assessment of the 26 fibre samples was undertaken by four CSIR researchers and the results are presented in Figure 74 and Appendix 3 Table 3.

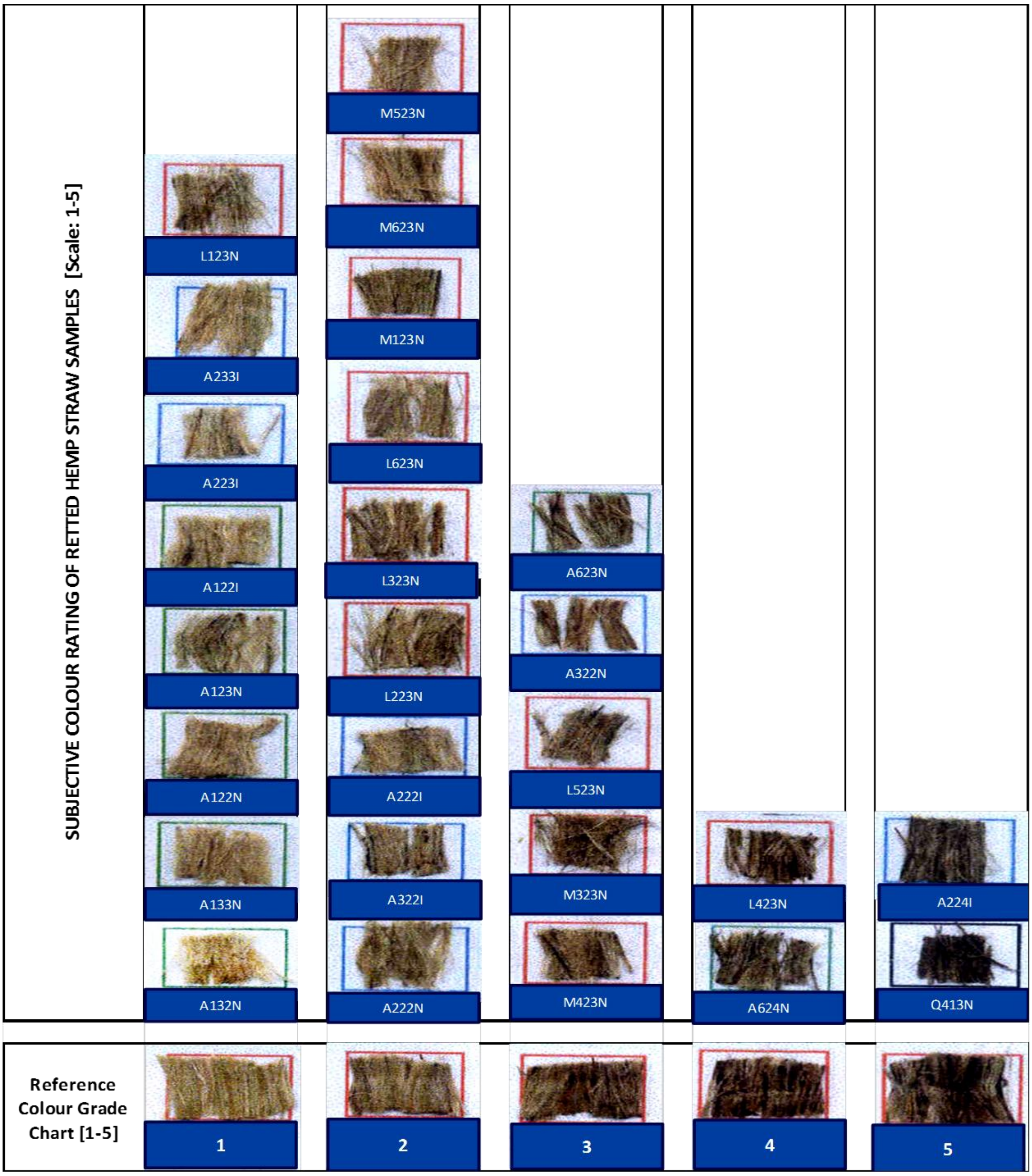

Figure 74. Photographs of retted fibre bundles placed according to their respective colour grades, as subjectively assessed [Colour Grade: 1 = very under-retted; 2 = slightly under-retted; 3 = well retted; 4 = slightly over-retted; 5 = very over-retted].

The percentage of samples in each colour grade is tabulated below.

Retting Degree (Colour Grade)	*Very under-retted [1]*	*Slightly under-retted [2]*	*Well retted [3]*	*Slightly over-retted [4]*	*Very over-retted [5]*
Percentage of samples	30.8	34.6	19.2	7.7	7.7

Figure 75 compares photographs of local inadequately retted combed fibre samples (the first 4 photos of fibre samples on the left), with those of well-prepared fibre samples received from the Institute of Natural Fibres (INF) in Poland (3 photos of hackled and carded fibre samples on the right).

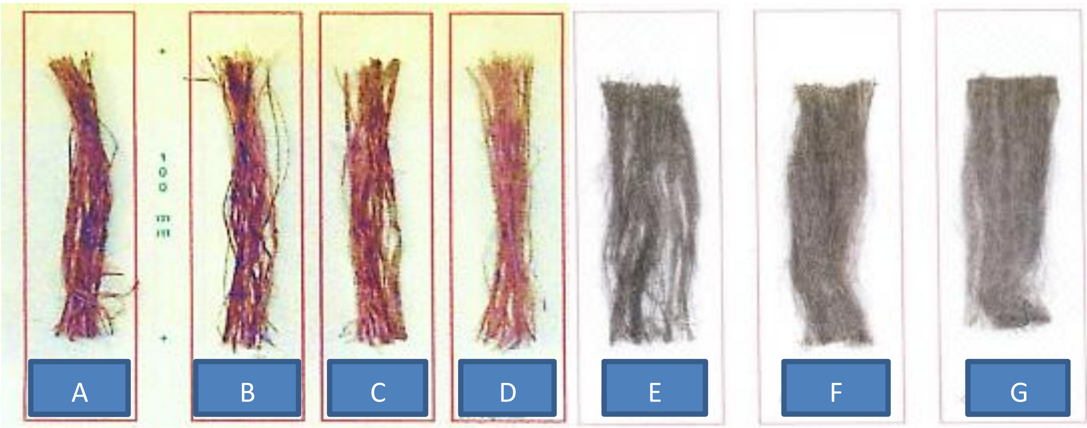

Figure 75. A comparison of inadequately retted local hemp (four photos on the left) with well retted hemp (three photos on the right).
A = Manually extracted; B = 1 x pass through machine; C = 2 x Pass through machine; D = 3 x pass through machine ; E = hackled fibres; F = carded fibres and G = 2 x (carded fibres)

Discussion

Based upon the colour grade results (Figures 74 & 75) the following conclusions may be drawn:

- The colour grade chart can be used as a **guide** to decide on the most appropriate time to stop the retting process.

- A retting period of between 2 to 4 weeks, depending on the prevailing climatic conditions, generally produced well retted straw.
- The colour rating chart can only be used as a screening tool by growers, traders and buyers to ascertain the quality and thus the price of hemp on the fields. It does not, however, replace the use of some methods and mobile testing systems to evaluate retting degree particularly suitable for rural use, and
- Appropriate experience and technical skills, relating to the primary growing and processing of hemp fibre crops are essential for the production of fibres with the specific quality requirements for various industrial applications.

Fibre Microscopy

Figure 76 shows SEM micrographs of the cross- and longitudinal sections of locally grown hemp.

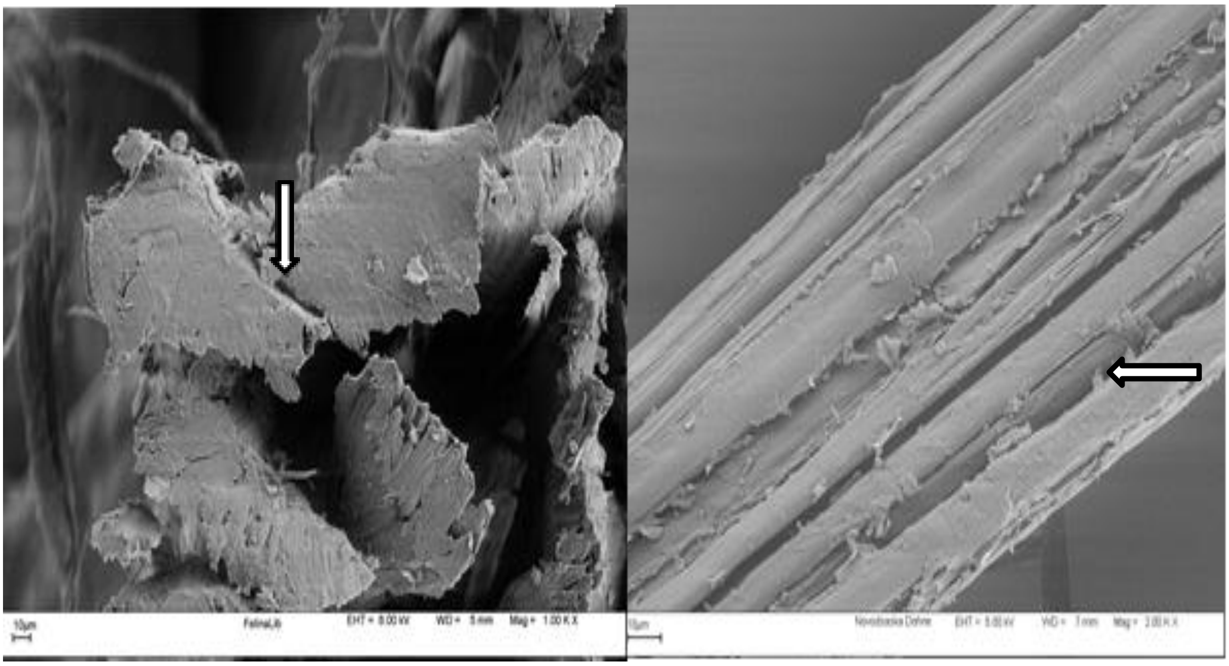

Figure 76. Examples of SEM micrographs of cross - and - longitudinal sections of locally grown hemp

Discussion

The SEM micrograph on the left of Figure 76 shows the cross-section of hemp fibre bundles with a thin cell wall, while the longitudinal one on the right shows cracks visible along the length of the fibre, as indicated by the arrows.

Analysis of the SEM micrograph in Figure 76 leads to the following observations:

- Inherent natural defects, such as cracks, occur along the length of the fibre, and
- these cracks represent weak spots which will affect the fibre bundle physical properties and thus limit their use in industrial applications.

3.2.4.2 Chemical Properties and Composition

The results of the chemical analysis (Cellulose, Hemicellulose, Moisture Regain, Ash, Aqueous Extract, Petroleum Ether Extract and Lignin) and of the elemental analysis of the fibres are given in Tables 27 and 28, respectively.

Table 27. Chemical composition of fibres after retting.

Cultivar	Locality	Cellulose & Hemicellulose (%)	Moisture Regain (%)	Ash (%)	Aqueous Extract (%)	Pet.Ether Extract (waxes) (%)	Lignin (%)
Novosadska	Dohne	68.1 & 10.1	9.3	3.0	4.9	0.37	4.4
Novosadska	Qamata	70.4 & 13.0	9.4	3.1	3.1	0.15	10.8
Futura	Libode	72.0 & 14.1	9.1	2.1	3.6	0.22	4.9
Felina	Libode	73.1 & 12.5	9.8	2.8	3.6	0.23	4.5
French Low Grade	France	72.8 & 12.0	9.0	3.3	3.1	0.37	5.5

Discussion

From the chemical composition results given in Table 27, it can be concluded that:

- The hemp fibres from different localities had cellulose content ranging from 68.1 to 73.1 %, hemicellulose content from 10.1 to 14.1%, moisture regain from 9.0 to 9.8 %, ash content from 2.1 to 3.3 %, aqueous extract levels from 3.1 to 4.9, petroleum ether extract levels from 0 to 0.37 % and lignin content from 4.4 to 10.8 %, with the Qamata site showing an unusually high lignin content of 10.8 %,
- The chemical composition of the locally grown fibres closely matched that published in the literature (see Table 21) and those of the French low grade reference hemp sample (Table 27). It can, therefore, be concluded that the chemical composition of the locally grown hemp falls within the ranges published for hemp grown overseas.
- The moisture content values were slightly higher than the published values. According to Harris and Mauersberger [166,167], the moisture content of hemp fibres is approximately 8.8 % with the moisture regain varying from 8 to 8.9 %, while here it ranged from 9.0 to 9.8%.
- The values for ash content (2.1 to 3.3%) were higher than those cited in the literature, namely from 0.82 to 1.5% [168]. According to Sadov et al [169], this discrepancy could be due to the quality and maturity of the hemp, since studies on cotton fibres have shown that immature cotton fibres have a higher ash content than more mature ones [169].
- Three of the four samples, namely Novosadska grown at Qamata, and Futura-77 and Felina-34, grown at Libode, had aqueous extract levels similar to those cited by Mathews and Mauersberger [170], namely 3.48%, the exception being Novosadska cultivar grown at Dohne, that had a higher aqueous extract level of 4.9%.

Table 28. Elemental composition (%) of hemp fibre samples

Elements	Cultivar and Planting Site					
	Novosadska *Dohne*	Novosadska *Mtiza*	Novosadska *Qamata*	Futura *Libode*	Felina *Libode*	French Low Grade Hemp *France*
Ash (%)	3.0	4.7	3.1	2.1	2.8	3.3
Sodium	0.0	0.45	0.0	0.0	0.0	0.0
Magnesium	1.4	1.7	1.8	1.1	2.3	0.48
Aluminium	0.2	0.2	0.4	0.1	0.0	0.0
Silicon	1.9	1.9	1.5	2.0	1.3	0.6
Phosphorous	0.4	0.3	1.0	0.4	0.5	0.8
Sulphur	3.3	3.9	3.4	2.1	2.3	5.1
Calcium	3.9	2.2	4.1	2.4	0.0	5.3
Potassium	1.5	4.4	2.9	0.9	2.4	4.5
Titanium	0.0	0.0	0.0	0.1	1.3	0.0
Manganese	0.0	0.0	0.0	0.3	0.2	0.0
Chromium	0.0	0.1	0.0	0.0	0.0	0.0
Iron	0.3	0.4	0.5	0.3	0.4	0.0

Discussion

The main elements found in plant fibres are minerals, such as, Calcium (Ca), Potassium (K), Phosphorus (P) and Magnesium (Mg) [168], the actual mineral content depending on various agronomic factors, including the composition of the soil. Silicon (Si) is the second most abundant element in the earth's crust, after oxygen, and thus large quantities of silicon are present in most soils and are thought to play a role in plant stiffening [171, 172].

From the elemental composition results of the fibres given in Table 28, the following conclusion may be drawn:

- The five main elements present in the ash of the various hemp samples were Calcium, Sulphur, Potassium, Silicon and Magnesium, confirming what has been reported in the literature [168].
- The elemental content levels of the locally grown hemp were similar to those found in the French sample for the five most prevalent elements, the exception being Silicon, which was higher than that of the imported French hemp fibre.
- According to the results of the locally grown cultivars and those of the imported French hemp sample as well as those published in the literature, it is reasonable to conclude that the elemental composition of the plant fibres, such as hemp, depends on both agronomic factors, notably the composition of the soil on which the cultivars are grown.

Main overall conclusions:

The following represent the main overall conclusions drawn from this part of the study:

- Planting site, retting period and lighting conditions did not affect the fibre yield of the different cultivars in a consistent manner. The low levels of fibre yield achieved could negatively impact the economic viability of the primary fibre production industry.
- Inconsistencies in the experimental results of the fibre properties, such as linear density and bundle strength, can most probably be attributed to the local lack of technical expertise on hemp crop production.
- The retting period of between 2 to 4 weeks, depending on the prevailing climatic conditions, produced well retted straw, and appeared to be optimum.
- Microscopic studies on the fibre revealed inherent natural defects, such as cracks, occurring in some spots along the fibre which could affect the fibre physical properties and which could limit their use in industrial applications.

- It can be concluded that the chemical composition of the locally grown fibres matched those published for hemp producing countries.
- The elemental composition of the locally grown hemp matched those published for hemp from traditional hemp producing countries, being dependent on agronomic factors, particularly the composition of the soil.

PART II: THE PERFORMANCE OF EUROPEAN FLAX CULTIVARS UNDER SOUTH AFRICAN AGRONOMIC CONDITIONS

3.3 Effect of Agronomic Parameters on Flax Biomass and Fibre Yield

3.3.1 Introduction

Flax (*Linum usitatissimum L*, *Linaceae*), has been grown for more than a hundred years as a source of fibres, and has found application in high-value niche consumer products as well as in natural fibre reinforced composites, technical textiles, paper/pulp, etc. The flax plant is the source of long line and short staple fibres, the long line fibres being predominantly used in the production of linen fabric. Flax can be grown in many locations, and under different agronomic and climatic conditions. An earlier report entitled *"Establishing a flax and linen industry in South Africa"* [173], indicated that certain regions in South Africa, such as the Southern Cape, are climatically and agronomically suitable for growing flax, and that flax production in the Southern Cape has the potential to enhance rural economic growth and provide a domestic source to the fibre industries of South Africa. Flax is known to grow in a cool and moist climate, such as that in the Southern Cape region.

The retting process is used to separate flax fibres from the woody-core of the plant through the biological degradation of the matrix substance holding the fibres together, and it has a great effect on the fibre quality and yield. In the past, the majority of flax producing countries in the world used two methods to ret flax for the commercial production of flax fibres, namely water and dew retting [174 - 176]. Due to environmental concerns, dew retting, which takes several weeks to complete, is still the most favoured retting practice in most flax fibre producing countries. Its disadvantages include the dependence on good climatic conditions, such as moisture and temperature, to speed up the retting process, as well as variability in fibre properties and the accumulation of dust particles on the retted straw. A number of research institutes have therefore been, and still are, involved in exploring and investigating alternative flax straw treatments to produce good quality fibres, including chemical retting, enzyme-retting and steam explosion techniques [177-179].

South Africa has a well-established flax secondary production operation which relies on imported flax sliver, which is then converted into yarn for local and export markets. There is, however, no primary production of fibre or fibre extraction operations in the country. A prerequisite for any country wishing to establish a flax industry, including South Africa, is that it should develop local expertise in crop cultivation, retting, extraction and fibre quality assessment techniques, supported by the necessary facilities, competence and technology platforms to produce a variety of flax fibre based products at a competitive price. The purpose of the research work presented here, forms part of a much broader study aimed at obtaining an objective measure of the fibre content (yield) and fibre properties of selected European flax cultivar varieties grown in the Provinces of the Eastern and Western Cape to prove that flax can be grown economically in South Africa, the agricultural trials being conducted by the ARC-IIC.

The objectives of the agronomic experiments were to evaluate the effect of planting date on the fibre yield of flax grown under South African climatic conditions. The establishment of a flax fibre primary production industry will improve the agro-processing sector of the economy through the production of a winter crop as a rotational crop to high-value summer crops, currently produced in the region. It can be used as a catalyst for rural subsistence farmers to meaningfully participate in the agriculture mainstream agro-processing economy and create a sustainable, high employment agro-industry. This will be achieved through the production and sale of flax fibres and by-products, as well as by the associated agricultural sectors (fertiliser and farm equipment), including processing facilities, related maintenance services, and seed production/distribution industries. Besides improving the agro-processing sector, the processing and utilisation of locally produced flax fibre by the local textile sector will ensure a consistent supply of quality fibre at a competitive price to replace the importation of flax fibres, thereby enhancing the global competitiveness of sectors utilising flax fibres.

Table 29, compiled from various sources [180 – 188], shows some flax data based upon experimental studies carried out in flax producing countries, and serves as a background for the assessment of the flax fibres produced in the present trials.

Table 29: Flax biomass and fibre yields compiled from various sources [180-188]

Reference	**Genotype**	**Country (*)**	**Total DM** yield (t/ha)**	**Seed yield (t/ha)**	**Straw yield (t/ha)**	**Fibre yield (t/ha)**	**Fibre (%)**
Easson, 1989	Flax	NL			3.7- 6.0	1.1- 1.8	26.5-30.9
Aufhammer et al., 2000	Linseed	De	6.8-7.4	2.0-2.3			
Eason & Molloy, 2000	Flax	NL	11	1.2	8	2	25
	Linseed	NL	8	2.2	5.2	0.7	16
Dimmock et al., 2005	Flax 30 varieties	UK	6.3-11.1	0.72	3.39-5.11	0.85-3.7	39-59
Couture et al., 2002	Flax	CA	3.0-4.4				
Sankari, 2000a,b	Linseed	FL		1.0-1.9	0.9-2.1		
Hassan & Leitch, 2001	Linseed	UK	10-11				
Marshall et al., 1989	Flax	CA	5-14	0.87-1.32			

*, NL, Netherlands; De, Germany; Ca, Canada; FL, Finland; UK, United Kingdom
** DM = dry straw biomass

3.3.2 Experimental

In the following Subsections 3.3.2.1 and 3.3.2.2, both the experimental design for the flax cultivation trials as well as the extraction of the fibres and their measurement are described.

The ARC-IIC used the approved varieties for ‘long staple’ flax production, which comprise most of those varieties which are registered as ‘flax’ types on the EU Common Catalogue and are essentially high yielding types and reasonably consistent in fibre yield [180]. Flax cultivars, originating from Netherlands, Belgium and the UK, and registered as “flax type” on the list of EU common catalogue (see Appendix 4 Table 1), were used in the agronomic experiments, and planted between May and July at the three sites, namely Outdsthoorn and Outeniqua, both in the Western Cape, and Addo in the Eastern Cape. When the plants reached maturity, they were harvested and the straw subjected to dew retting, involving the spreading of the flax straw on the field to allow indigenous aerobic fungi to degrade the stems. The lack of agronomic technical skills, retting expertise, appropriate laboratory size fibre extraction and processing technologies and universally accepted principles of fibre testing were some of the challenges experienced during the carrying out of this research.

3.3.2.1 Agricultural field trial design

Tables 30 and 31 provide the experimental design of the flax cultivation trials undertaken by the ARC-IIC.

Table 30: Experimental design for agronomic trials aimed at evaluating the performance of five European flax cultivars grown in the Western and Eastern Cape Provinces of South Africa (Field Trial 1).

Cultivars	Argos, Ariane, Diane, Elise and Viking obtained from the Netherlands, Belgium and the U.K.
Planting Sites	**Western Cape** – Oudtshoorn and Outeniqua **Eastern Cape** – Addo
Planting dates	May, June & July
Harvesting dates	October, November and December
Trial design and spacing	A randomised block design, with three to four replications, was used throughout. Plot size was 1.25 m x 4 m, with six planting rows (the four middle rows were to be harvested), each row having a length of 4m, and an interrow spacing of 0.25 m. A seed sowing density of 63 $kg.ha^{-1}$ and a sowing depth of 2 cm were used throughout.
Soil preparation and fertilisation	A basic fertiliser (50kg N, 25kg P and 125kg K) was applied per hectare, by administering 50% at planting and the balance as a top dressing, three to four weeks after planting. The soil was loosened deep down, and as fine a seedbed as possible was prepared. The planting furrows were 2 cm deep and the seed was sown evenly by hand.
Irrigation	After the seed had been sown, overhead sprinkler irrigation was applied to all the plantings to ensure the emergence of the seedlings. Thereafter, Oudtshoorn plantings were irrigated regularly while the other plantings involved dry land trials.
Measurements	Biomass and total fibre yield ($kg.ha^{-1}$) and fibre yield (%) were evaluated as a basic measure of performance under South African agronomic conditions

Table 31: Experimental design for agronomic trials aimed at evaluating the performance of six flax cultivars from the Netherlands, grown at Addo site in the Eastern Cape Province (Field Trial 2).

Cultivars	Evylin, Marylin, Electra, Viola, Hermes and Escalina
Planting Location	Addo (ARC Exp. Farm) – under irrigation in the Eastern Cape Province
Planting date	June 2003/2004
Harvesting date	November 2003/2004
Trial design and spacing	A randomised block design, with four replications was used. Plot size was 1.5 m x 4 m, with 6 plant rows (4 middle rows for harvesting), 4m in length and 0.25 m spacing between rows. A sowing density of 65 $kg.ha^{-1}$ and a sowing depth of 2 cm were used throughout.
Soil preparation and fertilisation	A firm and level seedbed was prepared. A basic fertilisation of 300 $kg.ha^{-1}$ 2:3:4 was applied to the soil before planting. A top dressing of 25 $kg.ha^{-1}$ N in the form of LAN, was applied at all the planting sites.
Irrigation and weed control	The fields were irrigated during the growing period at Addo, the pre-emergence herbicide, Dual-S, was sprayed directly after planting to control the weeds. Hand hoeing was performed during the growing season.
Measurements	Biomass and total fibre yield ($kg.ha^{-1}$) and fibre yield (%) were measured.

3.3.2.2 Mechanical fibre extraction and fibre yield determination

3.3.2.2.1 Materials

Dew retted flax straw, representing the various cultivars grown at the various trial sites, was received from the ARC-IIC for fibre yield evaluation by the CSIR. Fibres were extracted using a CMT-200M flax breaker-scutching machine of Russian origin and the fibre yield measured as described in Section 3.1.

3.3.3 Results and discussion

The results, representing the effects of the various agro-parameters on biomass and fibre yields, are summarized in Table 32 and Figure 77, the detailed (raw) results being given in Appendix 4 Table 2.

3.3.3.1 Fibre yield results for Field Trial 1

Table 32 gives the biomass (kg.ha^{-1}), mean fibre yield (%) and total fibre yield (kg. ha^{-1}) results for the different cultivars, planting dates and sites, with the fibre yield results also being illustrated graphically in Figure 77.

3.3.3.1.1 Biomass and fibre yields

Table 32: Biomass yield, fibre yield and total fibre yield for different cultivars, planting dates and sites (Field Trial 1)

Planting and harvesting dates	Cultivar	Addo			Oudtshoorn			Outeniqua		
		Biomass yield (kg.ha^{-1})	Fibre yield (%)	Total fibre yield (kg.ha^{-1})	Biomass yield (kg.ha^{-1})	Fibre yield (%)	Total fibre yield (kg.ha^{-1})	Biomass yield (kg.ha^{-1})	Fibre yield (%)	Total fibre yield (kg.ha^{-1})
May / October	1-Argos	4425	20.2	894	4488	34.1	1530	4281	35.2	1507
	2-Ariane	3981	36.1	1437	4175	28.3	1181	3988	26.0	1037
	3-Diane	4994	33.3	1663	4388	29.6	1299	5031	21.5	1082
	4-Elise	4969	22.2	1103	4569	31.0	1416	4981	28.2	1404
	5-Viking	5038	30.3	1526	4975	33.7	1677	5688	28.7	1632
June / November	1-Argos	2606	17.5	456	5169	29.4	1520	4725	24.5	1157
	2-Ariane	3713	15.4	571	5181	31.6	1637	5175	26.2	1356
	3-Diane	3794	23.0	872	5544	24.7	1369	5338	33.0	1761
	4-Elise	3750	31.9	1196	5219	32.7	1706	5750	25.5	1466
	5-Viking	3975	41.1	1633	5381	36.9	1986	6213	29.8	1851
July /December (1st harvest)*	1-Argos	3325	19.6	651	3731	30.1	1123	6169	33.2	2048
	2-Ariane	3100	24.3	753	4363	23.1	1008	5869	32.5	1907
	3-Diane	3038	23.0	698	3988	37.0	1476	5663	31.2	1767
	4-Elise	3600	25.7	925	4213	34.9	1470	5200	30.0	1560
	5-Viking	3206	22.4	718	3956	35.5	1404	5138	32.6	1675
July / December (2nd harvest)**	1-Argos	N/A	N/A	N/A	3488	36.2	1263	3563	32.1	1143
	2-Ariane				3425	27.7	948	4556	30.3	1380
	3-Diane				3663	23.9	875	4888	23.3	1138
	4-Elise				3931	25.7	1010	4331	28.6	1239
	5-Viking				3569	30.3	1081	2444	18.8	459

* denotes the early harvesting of some flax crop plants in December; **denotes the late harvesting of some flax plants in December

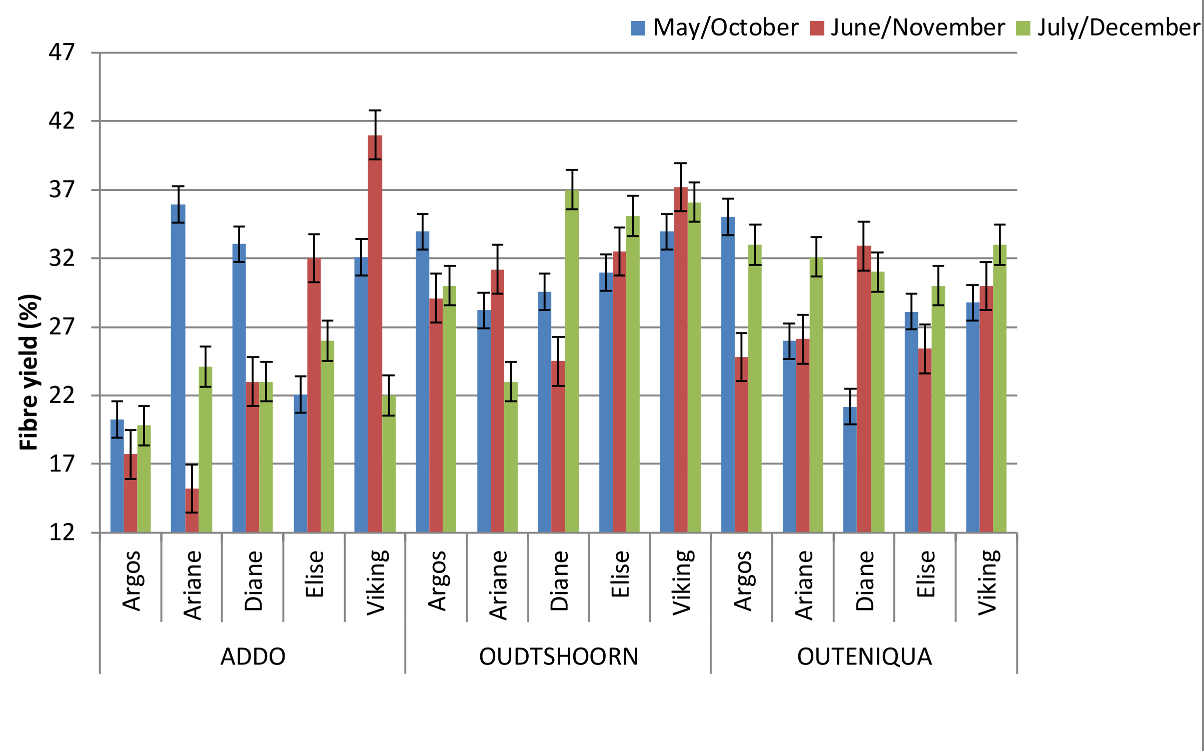

Figure 77. Effect of planting and harvesting dates on fibre yield for flax cultivars grown at Addo, Oudtshoorn and Outeniqua

Comparing the present fibre yield (%) and total fibre yield for the different planting sites and dates with the fibre yield range of 25-35% for commericial flax varieties as reported by Booth et. al [37], and listed fibre yield range of 0.85 to 3.7 tonnes per hectare as shown in Table 29, respectively, lead to the following conclusions in terms of which trials produced results within the ranges as quoted above:

- **Addo site**: For the May planting date, the Ariane (36.1%,1437 kg.ha^{-1}), Diane (33.3%, 1663 kg.ha^{-1}) and Viking (30.3%, 1526 kg.ha^{-1}), for the June planting date, Elise (31.9%, 1196 kg.ha^{-1}) and Viking (41.1%, 1633 kg.ha^{-1}), and for the July planting date, only Elise (25.7%, 925 kg.ha^{-1}), fell within the quoted ranges with the Viking planted in June being the best performing cultivar.
- **Oudtshoorn site**: All the cultivars planted at this site produced yields (fibre content and fibre yield per hectare) within the acceptable ranges, the exceptions being Ariane and Diane cultivars planted in July - first harvest of December and second harvest of

December, respectively, producing fibre yields of less than 25%, although their total fibre yield per hectare was above the lower end value of 0.85 tonnes per hectare publised in literature. The best performing cultivar of all was Viking (36.9%, 1986 $kg.ha^{-1}$), planted in June month.

- **Outeniqua site**: All the cultivars planted at this site produced yields (fibre yield and total fibre yield per hectare) within the acceptable ranges, the exception being Diane planted in May and July - second harvest of December as well as Viking second harvest of December being the worst performer (fibre yields of 18.8% and 459 $kg.ha^{-1}$), producing a fibre yield of less than 25%, although the total fibre yield per hectare was above the lower end of 0.85 tonnes per hectare published in the literature. The best performing cultivar of all was Argos (33.2%, 2048 $kg.ha^{-1}$), planted in July.
- Viking, planted in July at Addo, performed exceptionally well, giving a fibre yield of more than 40%. Furthermore, it produced fibre yields of more than 30% for all planting dates, except for the third planting date at Addo and the second harvest of the July planting date at the Outeniqua site where it performed very badly.
- Fibre yields per hectare of more than 1000 ($kg.ha^{-1}$), were achieved by all the cultivars for the third planting date (July) at Oudtshoorn and Outeniqua, with Outeniqua generally performing best for the July planting date, and Oudtshoorn the best for the other two planting dates (May and June). The Addo site first planting in June also achieved a fibre yield exceeding 1000 ($kg.ha^{-1}$), except for the Argos cultivar.
- It appears that, for Outeniqua, the third planting is best in terms of both fibre yield (%) and total fibre yield ($kg.ha^{-1}$), while this was not the case for the other two sites.

Taking an overall view of all the planting sites and dates and cultivars, it would appear as if the Viking cultivar, planted in June at all three sites performed very well, if not the best, in terms of both the fibre yield (41.1%, 36.9 and 29.8% respectively), and total fibre yield (1633, 1986 and 1851kg.ha^{-1}, respectively).

Statistical analysis

The ANOVA based results on the effect, and signifance, of the planting site and date on fibre yield, are shown in Figure 78 and Table 33, the results of the second harvest being excluded from the analysis since it was not replicated at Addo.

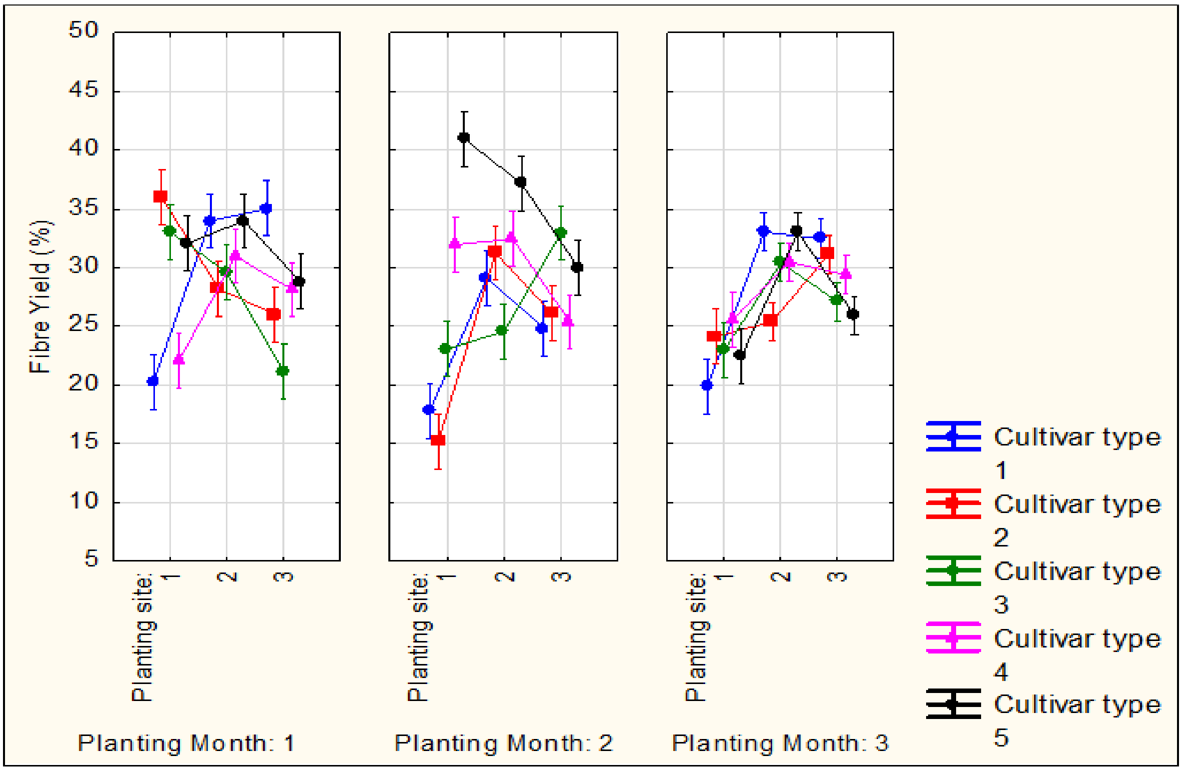

Figure 78. Fibre yield means and confidence levels for different cultivars, planting dates and sites. [Cultivar 1 =Argos, 2=Ariane, 3=Diane, 4=Elise, 5=Viking] [Planting site 1=Addo, 2=Oudtshoorn, 3=Outeniqua]

Table 33 shows the significant effects ($p<0.05$) of planting site and date and cultivar, as well as their interactions, on fibre yield.

Table 33. ANOVA results on factors affecting fibre yield (%)

FACTORS	dF	Sum Square	Mean Sum	F	p-Value	Significant (p<0.05)
Intercept	1	203184.0	203184.0	29102.8	0.000	Yes
Planting site	2	1063.3	531.6	76.2	0.000	Yes
Cultivar	4	736.9	184.2	26.4	0.000	Yes
Planting Date	2	134.2	67.1	9.61	0.0001	Yes
Planting site*Cultivar	8	1218.6	152.3	21.82	0.000	Yes
Planting site*Planting Date	4	378.9	94.7	13.57	0.000	Yes
Cultivar *Planting Date	8	1219.0	152.4	21.83	0.000	Yes
Planting site*Cultivar *Planting Date	16	2212.5	138.3	19.81	0.000	Yes
Error	230	1605.8	7.0			
Total	274	8471.6				

The ANOVA results in Table 33 show that all three factors, namely planting site, cultivar and planting date, individually and in combination, had a significant effect ($p<0.05$) on fibre yield. No further analysis was undertaken to identify at the basic level which cultivar, planting date and site contributed significantly to the highly significant p-values ($p<0.05$).

Main conclusions

The main conclusions are:

- The EU flax cultivars used in these experimental trials were adaptable to local agricultural conditions.
- The Southern Cape region had the right agronomic and climatic conditions to grow flax that produces yields comparable to those found in other flax producing countries, while the Western Cape sub-region produced consistently higher yields over the three different planting dates. It should be pointed out that these yields were derived from small plot trials and might significantly change when upscaled to commercial levels.

3.3.3.2 Fibre yield results for Field Trial 2

Table 34 shows the results for the biomass, fibre (%) and total fibre yields (kg.ha^{-1}), for the cultivars planted at Addo, the results also being illustrated graphically in Figure 79.

3.3.3.2.1 Biomass and fibre yields

Table 34. Biomass and fibre yields for the cultivars grown at Addo

Cultivar	Biomass yield (kg.ha^{-1})	Fibre yield (%)	Total fibre yield (kg.ha^{-1})
Evylin	1906	27.6	526.1
Marylin	2041	32.5	663.3
Electra	1856	28.2	523.4
Viola	1719	25.0	429.8
Hermes	2161	34.4	743.4
Escalina	2231	32.6	727.3

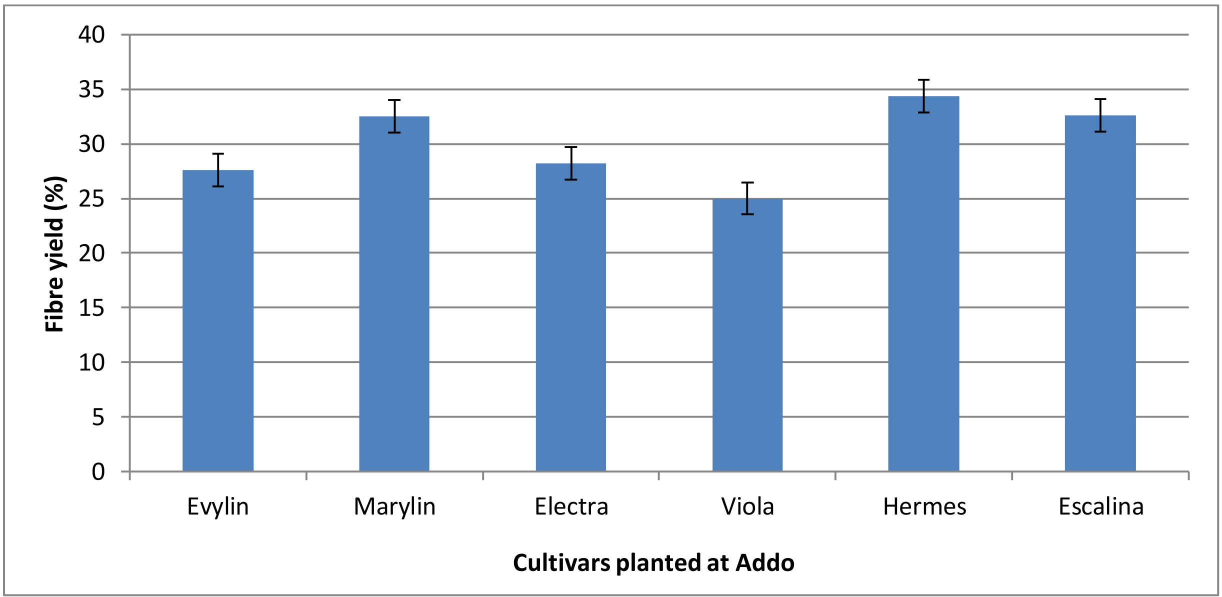

Figure 79. Fibre yields of the cultivars grown at Addo

Discussion

- The cultivars produced fibre yields ranging from 25 to 34.4%, which fall within the ranges (25 to 35%) quoted in the literature.
- All the cultivars produced total fibre yields per hectare that were less than the minimum published value of 0.85 to 3.7 tonnes per hectare. This could be as result of the application of wrong agronomic experimental design, particularly density of sowing.
- Hermes produced the highest fibre yield of 34.4%, followed by Escalina and Marylin with fibre yields of 32.6 and 32.5%, respectively, the same ranking also applying to the total fibre yield ($kg.ha^{-1}$), where Hermes again performed best.

Statistical data analysis

The ANOVA results on the effect of cultivar on fibre yield for the cultivars grown at Addo, are shown in Figure 80 and Table 35.

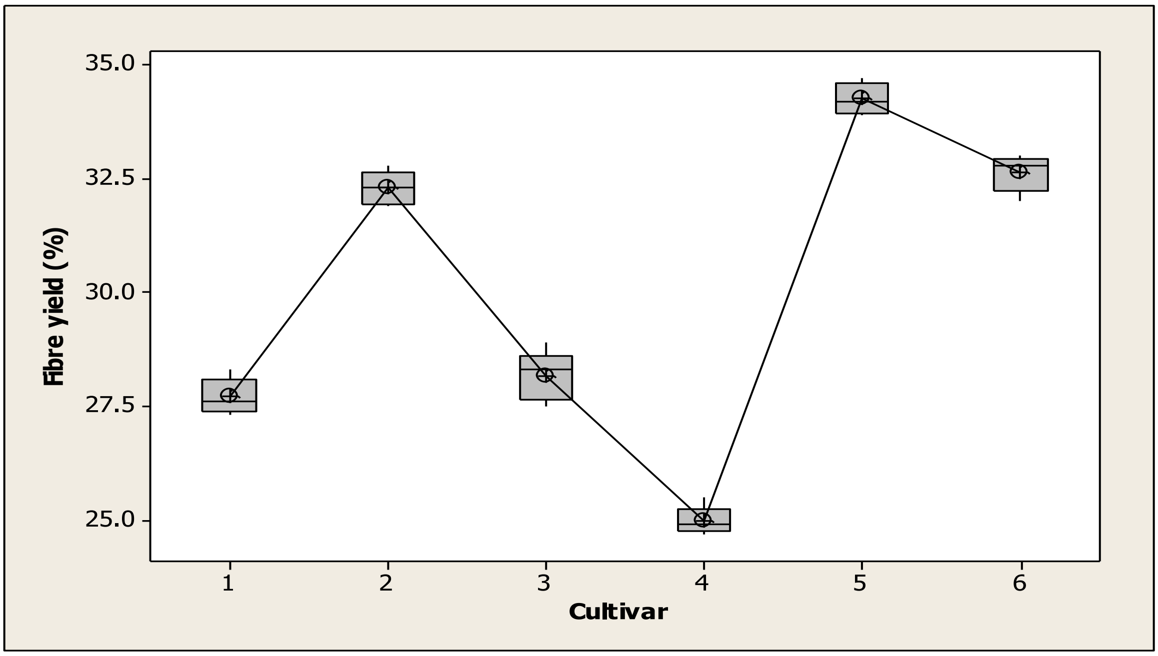

Figure 80. Effect of cultivar on fibre yield mean values and 95% confidence levels
[1= Evelyin, 2=Marylin, 3=Electra, 4=Viola, 5=Hermes and 6=Escalina]

Table 35. ANOVA results on the effect of cultivar on fibre yield

	Fibre yield (%)					
FACTOR	dF	Sum Square	Mean Sum	F	p-Value	Significant (p<0.05)
Cultivar	5	320.955	64.191	406.3	0.000	yes
Error	24	3.8	0.16			
Total	24	324.747				

The results given in Table 35 show that cultivar had a statistically significant ($p<0.05$) effect on fibre yield.

Main conclusion

The main conclusions are:

- The cultivars grown at Addo produced fibre yields (%) which were within the acceptable international range, but produced very low biomass yields which affected the total fibre yields to such an extent that they were lower than the minimum value of 0.8 tonnes per hectare, quoted in the literature.

PART III: COTTONISATION OF FLAX AND HEMP

3.4 Flax and hemp fibre cottonisation through mechanical processing

3.4.1 Introduction

In Chapter 2, Section 2.4.4, the lack of industry structures and weak linkages were identified as critical barriers in the development of globally competitive and economically sustainable flax and hemp sectors in South Africa. Added to the necessary industrial structures and linkages, the production of flax and hemp fibres, possessing tailor-made and functional fibre properties, is the ultimate determining factor in providing a strong business case for a bast fibre industry [190].

Worldwide, a number of R&D organisations are involved in bast fibre research with a focus on the use of various treatments, popularly referred to as cottonisation, including mechanical processing, steam explosion, enzymatic, and ultrasound, for the extraction of fibres with the requisite fineness [from elementary (10-20µm) up to microfibril (4-10nm) levels] and length for high value added niche industrial applications. Bast ultimate fibres, illustrated in Figure 60 of Section 3.2.1, are estimated to have a fibre diameter of between 10 to12 µm and a staple length longer than that of cotton. The modification of bast fibres, such as flax, to produce cotton-like fibres at a price comparable to that of cotton, would not only create a potentially much greater market than the existing one but would allow such fibres to be processed on existing short staple (cotton) type machinery which predominate worldwide. More than 90% of the world's staple spinning, weaving and nonwoven production technologies are designed to handle fibres with staple length and fineness similar to those of cotton. Flax fibre cottonisation is based on the ability of the technical fibre to be split into elementary fibres, having diameters similar to those of cotton, hence the term cottonisation [191].

The global consumption of fibres is estimated at over 85.9 million tonnes per annum, of which some 90% is used to produce woven textiles. Manmade and cotton fibres are the dominant fibres in meeting the ever increasing global fibre market demand (2.5% p.a.) driven by an increase in both population and consumption per capita [191, 12]. Owing to environmental concerns relating to both cotton growing and man-made fibres production, cottonised flax fibres provide an attractive alternative raw material for the production of textile yarns.

The agronomic research that proved the suitability of climatic and soil conditions for the cultivation of the flax and hemp fibre crops in South Africa, played a significant role in defining the CSIR fibre strategy, which covers the mechanical and biotechnological modification of flax and hemp fibres for various industrial applications in support of the establishment of a local flax and hemp industry. Fibre linear density (fineness) is one of the most important fibre properties in determining the most appropriate processing system and conditions and product, including yarn and fabric manufacturing as well as the performance of the end-product. Decreasing the fibre linear density, i.e. the fibre diameter, combined with higher bundle strength and lower CV values, enhances the spinning performance (spinnability), and yarn properties of cottonised flax and hemp fibres on the short-staple spinning system. The research presented here deals with the first phase of optimising local technical competence on the cottonisation of bast fibres by determining the machine related processing parameters required to produce fibres with fineness and staple length similar to those of cotton. This research, carried out on the Temafa Linline, investigated the effect of the number of passages through the fine opener and cottoniser, respectively, on the fineness of flax and hemp fibre, with the main objective being to produce fibre with a diameter of less than 20µm. Because of its high production capacity, cottonisation has the potential of economically producing large volumes of cotton-like fibres suitable for processing in cotton mills, without incurring the additional capital expenditure necessary when processing on wet spinning machinery.

3.4.2 EXPERIMENTAL

3.4.2.1 Material

The following flax and hemp fibres were used in this study:

- Novosadska (EU cultivar) hemp fibre grown at Addo, South Africa,
- Imported French nonwoven grade hemp,
- Imported French bleached hemp slivers, and
- IDC flax (light and grey colour grades) grown at Brits, South Africa.

3.4.2.2 Description of Temafa Linline

The Temafa Linline basically consists of two sections, the one (Lomy) essentially being responsible for the initial coarse fibre opening, shortening and cleaning of the fibres, while the second (Linstar) subjects the fibres from the Lomy to a second, finer opening, cleaning, shortening and cottonising processes. Figure 81 shows a photograph of the Temafa Linline installed at the CSIR, which was used in these experiments.

The mode of operation of the two units is explained in more detail below.

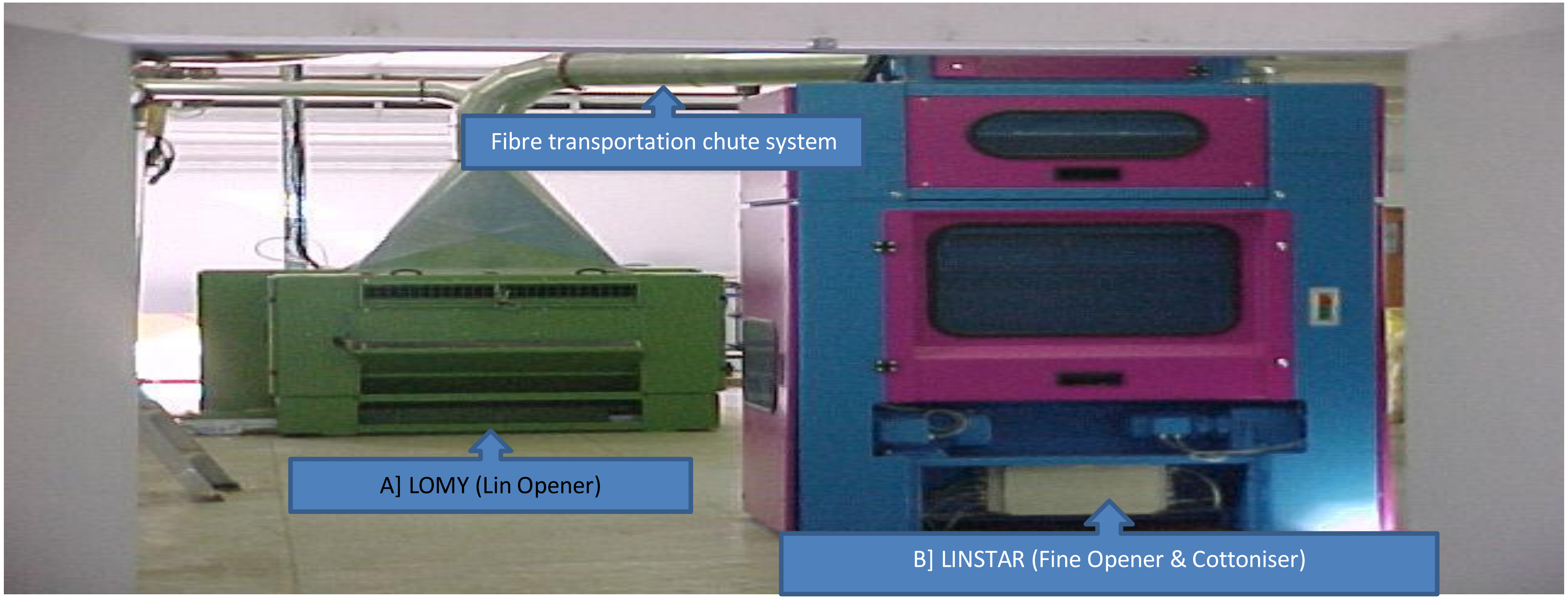

Figure 81. Temafa Linline at the CSIR (Photo source: CSIR)

a. Mode of operation of the LOMY Lin-Opener

A schematic diagram of the Temafa Lin-Opener (referred to as Lomy) designed for the opening, shortening and cleaning of natural fibres (e.g. flax and hemp) is shown in Figure 82. It has a width of 1600mm and cylinder speeds ranging from 684 to 1075 rpm, varied by manual adjustment of both the main cylinder and motor shaft using V-belt pulleys. Decorticated fibres are placed on the feed table of the LOMY unit and gripped by both the holder and draw-in roller which guides them to the main cylinder. The presence of the cut keyways on the draw-in rollers, and the contact pressure caused by pneumatic cylinders, resulting in the clamping of the fibres, thereby enabling uniform processing of the material by the main cylinder. The main cylinder cleans, opens and shortens the fibres. To regulate the fibre length, the main cylinder of the LOMY can be adjusted to three different positions (10 mm, 0 mm and – 40 mm). By lifting the main cylinder to +10 mm, the fibre length is shortened and lowering it to –40mm results in longer fibre lengths.

The impurities (trash) fall through the grid on to a traversing apron which guides them out of the machine. The processed fibres are transported through the chute system into the fibre collector bag for analysis, or directly to the storage chute of the Linstar for further fibre opening, cleaning and shortening. The fibre production is estimated at ±600kg.hr^{-1}. For these experiments, the LOMY main cylinder position and speed settings were kept constant at +10mm and 684 rpm, respectively.

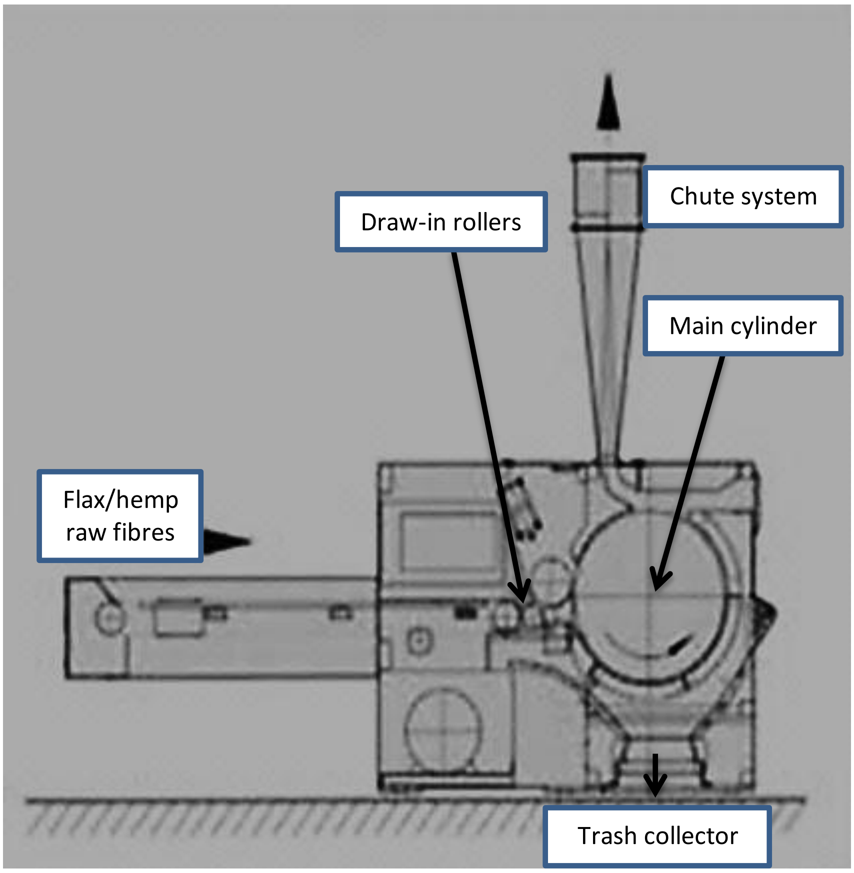

Figure 82. Schematic diagram of the Temafa Lin-Opener (LOMY)
[Source: www.temafa.com]

b. Mode of operation of the Linstar:

A schematic diagram of the Linstar (fine fibre opener and cottoniser), referred to as LINY, is shown in Figure 83. It has a width of 1000mm and total height of 4600mm, with the main cylinder speed ranging from 720 to 3000 rpm. The fine opener and cottoniser main block cylinder drums are clad in a fine and very fine card wire, respectively, and both are used for further fibre cleaning, opening and shortening to produce finer (cotton-like) fibres. The fine fibre opener and cottoniser is the same unit, except that when functioning as a cottoniser a finer main drum cylinder replaces the one used when the unit functions as a fine fibre opener.

The fibres are delivered to the Linstar directly from the LOMY, or manually via the chute system, into the storage and dosing chutes and guided by the delivery rollers into the top intake cylinder, where they are opened, cleaned and shortened. The milled channels on the draw-in roller and contact pressure caused by rubber hollow springs clamp the fibres, allowing for uniform processing by the cylinder. High centrifugal and gravitational forces, occurring during fibre processing, result in heavier fibres being separated at the integrated cutter of the respective two cylinder card segments. For these experiments, the main cylinder drum speeds of the card segments, for the fine opener and cottoniser, were at 1470 and 2840 rpm, respectively.

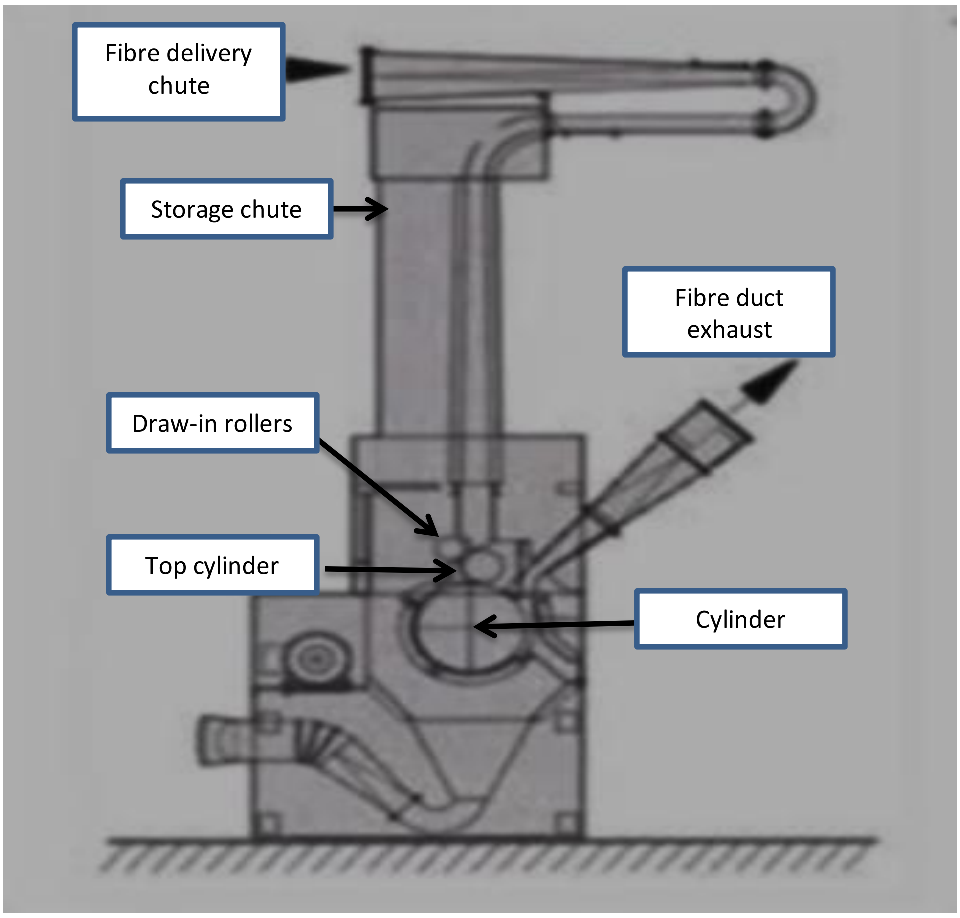

Figure 83. Schematic diagram of the Temafa Linstar
[Source: www.temafa.com]

3.4.2.3 Fibre Processing Parameters and Fibre Diameter

Ten kilograms (kg) of each fibre type were used as feedstock for the mechanical modification process which involved the following: (i) fibre opening trials using the LOMY machine at a cylinder speed of 684 rpm; (ii) thereafter passing the opened fibre once, twice and three times respectively, through the Linstar **fine opener** at cylinder speed of 1470 rpm in each case; (iii) after this, the fibres which had been passed once through the fine opener were passed once, twice and three times, respectively, through the Linstar **cottoniser** unit, at a cylinder speed of 2840 rpm. The fibre samples were weighed and tested for fineness at each processing stage. Fibre recovery was calculated from the mass after each processing stage.

Table 36 and Figure 84 illustrate the processing parameters and the schematic representation of the material flow in the processing of flax and hemp fibres (scutched, decorticated and bleached) by passing them through the Temafa Linline's various opening stages connected in series (Lin-Opener, Linstar Fine Opener and Linstar Cottoniser) to evaluate the effect of the number of processing passages at each stage the fibre properties.

Table 36. Temafa Linline processing parameters

Temafa unit type	**Processing Parameters**	
	Main cylinder position(mm)	*Cylinder Speed (rpm)*
a. Lin-Opener (LOMY)	*+10*	*684*
b. Lin-Star Fine Opener	*0*	*1470*
c. Lin-Star Cottoniser	*0*	*2840*

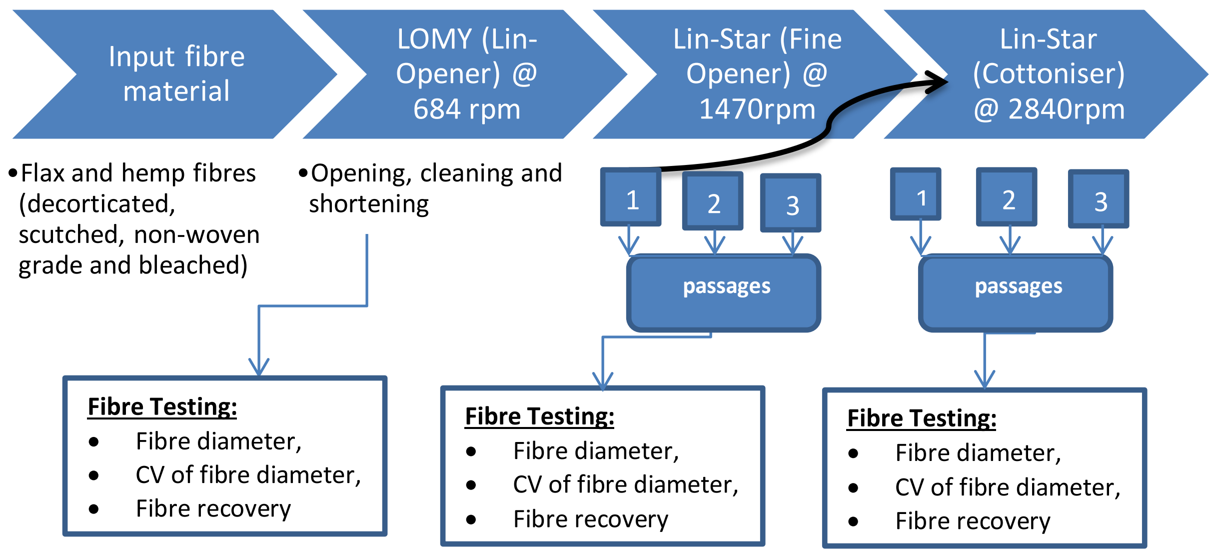

Figure 84. Temafa Linline Fibre processing flow diagram

Although, the airflow method is generally considered to be the most suitable for assessing fibre fineness for bast fibres, such as hemp, no suitably calibrated instrument was available and it was decided to use an Optical Fibre Diameter Analyser (OFDA) for this purpose, although the OFDA is generally used for measuring fibre diameter distribution of animal fibres, such as wool and mohair. Two grams of fine fibre bundles snippets of 2mm in length that were cut using the guillotine were spread on glass slide and analysed under relative humidity conditions of 65% using OFDA 100.

Statistical Analysis

An analysis of variance (ANOVA) was carried out on the data, using XL Statistician Software, to determine the effects of fibre type and the number of passages through the fine opener and cottoniser, respectively, on fibre diameter and recovery. In the ANOVA, the variation in fibre diameter explained by the number of passages and two cylinder speeds, namely 1470 and 2840 rpm were investigated, and the significance of their interactions on fibre diameter determined.

Fibre Length Distribution Chart

The flax fibre bundles subjected to different mechanical processes were laid on paper to produce a long-to-short fibre length distribution pattern in an X-Y plane, similar to the Suter Fibre Array method, commonly used for cotton fibre [192]. Normally, from these charts, fibre properties, such as effective length, mean fibre length, short fibre (%) and CV (%) can be derived, but in the present case the charts were used for qualitative evaluation only.

3.4.3 Results and discussion

3.4.3.1 Results

The effects of the different opening processes and number of passages on fibre diameter (µm); fibre recovery (%) and CV (%) of fibre bundle width referred to here as fibre diameter, are shown in Tables 37 to 39 and Figure 84, for the different fibre types. Tables 40 to 44, show the ANOVA results. The results are discussed below for each of the processing stages, namely coarse (initial) opening through the Lomy, fine opening through the Lin-Star opener and cottoniser.

a. Lin-Opener (LOMY)

Table 37. Effect of LOMY opening on fibre diameter and recovery

Fibre	Input Scutched fibre	Lomy Results		
	Fibre diameter (µm)	Fibre recovery (%)	Fibre diameter (µm)	CV (%)
SA Grown hemp	66.0	97.0	48.2	107
French nonwoven grade hemp	53.5	97.4	44.0	103
French bleached sliver hemp	43.8	97.4	38.0	96.6
IDC Flax (light colour)	45.8	97.2	28.0	97.1
IDC Flax (grey colour)	45.5	97.2	25.0	98.3

b. Linstar Fine Opener

Table 38. The effect of the number of passages through the Linstar Fine Opener on fibre diameter and recovery

Bast Fibre type	Input material fibre properties		1st passage			2nd passage			3rd passage		
	Fibre diameter (µm)	CV (%)	Fibre recovery (%)	Fibre diameter (µm)	CV (%)	Fibre recovery (%)	Fibre diameter (µm)	CV (%)	Fibre recovery (%)	Fibre diameter (µm)	CV (%)
SA Grown hemp	48.2	107	91.9	40.6	100.6	93.8	39.0	98.8	91.2	36.4	97.2
French nonwoven grade hemp	44.0	103	96.1	38.1	97.4	94.3	36.8	95.8	91.6	36.1	95.2
French bleached sliver hemp	38.0	96.6	95.1	36.7	95.2	95.5	35.0	93.8	95.9	34.3	93.0
IDC Flax (light colour)	28.0	97.1	95.1	24.0	94.2	96.5	22.6	89.0	96.0	22.0	87.4
IDC Flax (grey colour)	25.0	98.3	96.3	22.0	86.2	96.4	20.7	83.0	96.3	20.3	82.0

c. Linstar Cottoniser

Table 39. Effect of the number of passages through the Linstar Cottoniser on fibre diameter and recovery

Fibre	Input material from 1st passage Lin-Star fine opener		1st passage			2nd passage			3rd passage		
	Fibre Diameter (µm)	CV (%)	Fibre recovery (%)	Fibre diameter (µm)	CV (%)	Fibre recovery (%)	Fibre diameter (µm)	CV (%)	Fibre recovery (%)	Fibre diameter (µm)	CV (%)
SA Grown hemp	40.6	100.7	88.3	26.0	96.1	94.3	25.1	93.2	93.1	24.6	92.3
French nonwoven grade hemp	38.1	97.4	92.4	25.2	89.2	94.6	23.9	82.8	92.6	23.4	81.2
French bleached sliver hemp	36.7	95.2	94.9	23.0	87.4	95.8	21.3	79.9	96.7	20.4	72.1
IDC Flax (light colour)	24.0	94.2	95.4	20.0	85.0	95.9	19.3	83.9	93.7	19.0	83.1
IDC Flax (grey colour)	22.0	86.2	94.8	18.0	80.1	95.8	17.5	79.4	94.5	17.3	78.8

The results given in Tables 37 to 39 are presented graphically in Figure 85 by means of bar charts, with 95% confidence levels.

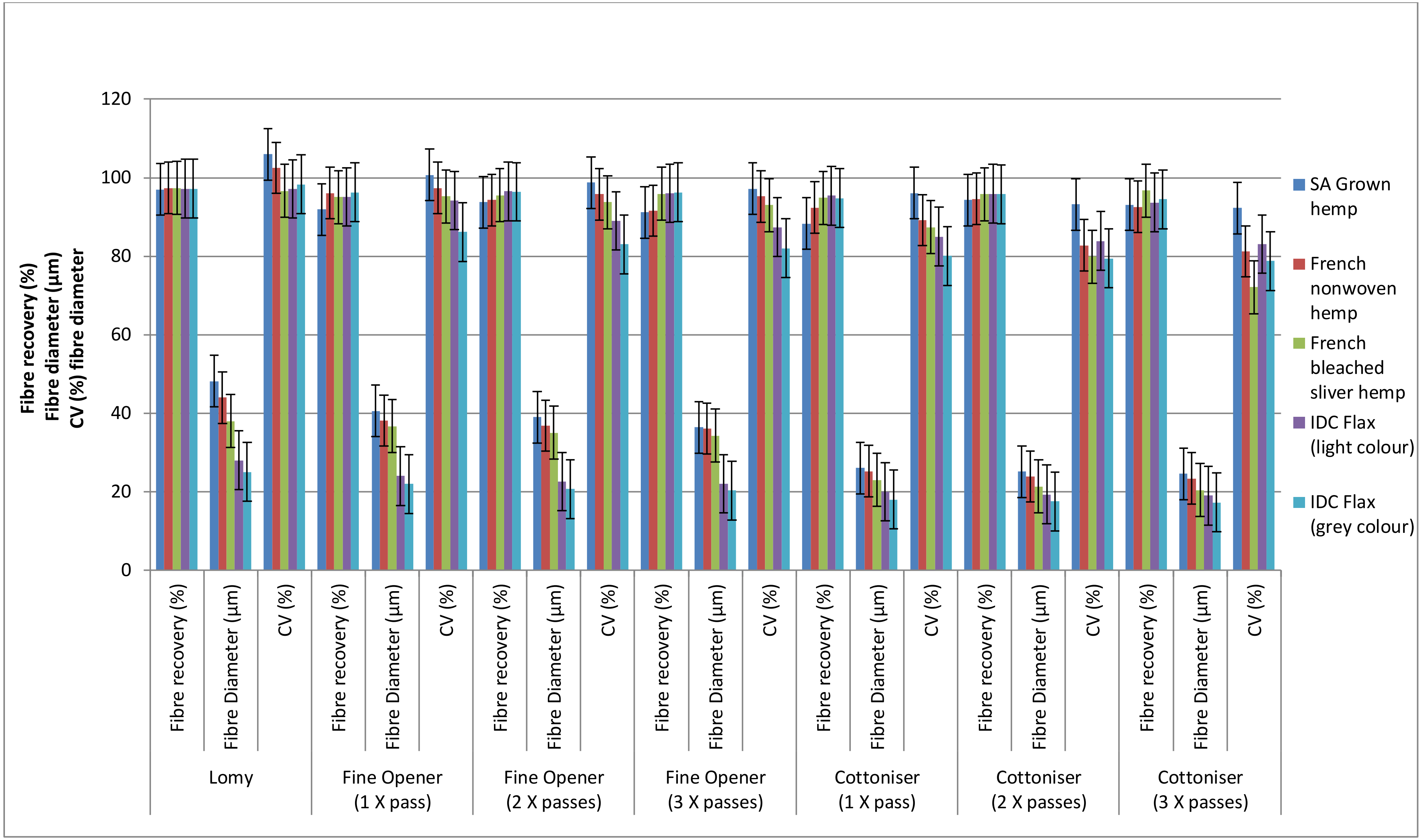

Figure 85.The effect of different processes and number of passages on fibre recovery, fibre diameter and its CV

3.4.3.2 Discussion

As can be seen from Table 37, passing the fibres through the LOMY opener reduced the fibre bundle width (referred in table as fibre diameter) by varying amounts, depending on the fibre type. For example, that of the locally grown hemp decreased from 66 to 48 µm (27.3%) while that of the imported nonwoven grade and bleached hemp fibres decreased by 17.8 % and 13.2%, respectively. Meanwhile, the fibre bundle width of the light and grey colour flax fibres deceased from about 46 µm to 28 and 25 µm, i.e. 45.6% and 39.1%, respectively, the fibre recovery being just over 97% in all cases.

According to the results given in Table 38, each passage through the Linstar fibre opener generally reduced the fibre bundle width and its CV by a small and varying amount, the magnitude depending upon the fibre type and nature. Only in the case of the IDC flax, did the fibre diameter almost reached the target value of 20 µm. The decrease in fibre diameter and its CV for the locally grown hemp after the first passage was 16% and 0.1%, respectively, and up to 24.5% and 3% for the third passage, whilst those of the nonwoven grade and bleached sliver fibre for the first passage were 13.4% and 5.4%, and 3% and 2%, respectively, and for the third passage 18% and 7.6% and 10% and 3.7%, respectively. The fibre losses for the first passage were estimated at 8% for the local, 4% for nonwoven and 5% for the bleached fibres, and for the third passage were 9%, 8% and 5%, respectively. The decrease in fibre diameter and its CV for the light and grey colour flax for the first passage were 14% and 12%, and 3% and 12%, respectively, whilst those for the third passage were 21 % and 19%, and 10% and 17%, respectively. The fibre losses for the first passage were estimated at 5% (light colour) and 4% (grey colour), and those for the third passage at 4% for both flax fibres.

From Table 39, it is apparent that, as is in the case of the Linstar fibre opener, each successive passage through the cottoniser progressively reduced the fibre diameter and its CV by relatively small amounts. Nevertheless, if the fibre diameters after the first cottoniser passage are compared with those after the first Linstar passage, which served as input material to the cottoniser, it is apparent that the first cottoniser passage reduced the diameter of the hemp fibre dramatically, by 36 % (local), 34 % (nonwoven grade) and 37 % (bleached), and those of the flax significantly by 17% (light colour) and 18% (grey colour). It is also apparent that for the locally grown flax, the second and third passages through the cottoniser have little further beneficial effect on fibre diameter and its CV, which show average improvements of 4.5 % and 2 %, respectively, with an average fibre losses at 5 %. Similar considerations apply to the locally grown hemp. It is also apparent that one passage thorough the cottoniser produced flax fibres with a diameter equal to, or better than, target value of 20µm.

Statistical analysis

Tables 40 to 44, show ANOVA results, based on the 95 % confidence level, derived from the raw data (see Appendix 4 Table 5) reflecting significant interactions between processing factors and diameter for the flax and hemp fibres.

a. Effect of Temafa processing on hemp fibres

Due to the incomplete experimental design, only the ANOVA p-values are given in Table 40 on fibre diameter and CV of fibre diameter.

Table 40. ANOVA results for fibre diameter and CV of fibre diameter

FACTORS	Fibre diameter		CV of fibre diameter	
	p-Value	Significant (p<0.05)	p-Value	Significant (p<0.05)
Linstar Cottoniser	0.000	Yes	0.000	Yes
Fibre type *Cylinder speed	0.070	No	0.000	Yes
Linstar Cottoniser *Number of passages	0.065	No	0.000	Yes
Fibre type*Linstar Cottoniser* Number of passages	0.016	Yes	0.000	Yes

Table 41. ANOVA results for fibre recovery (%)

FACTORS	Fibre recovery (%)					
	dF	Sum Square	Mean Sum	F	p-Value	Significant (p<0.05)
Linstar Cottoniser	1	2.1	2.1	1.43	0.235	No
Number of passages	0					
Fibre type *Linstar Cottoniser	2	4.8	2.4	1.651	0.198	No
Linstar Cottoniser *Number of passages	2	57.2	28.6	19.6	0.000	Yes
Fibre type *Linstar Cottoniser* Number of passages	4	17.2	4.3	2.95	0.025	Yes
Error	84	122.8	1.5			

b. Effect of Temafa processing on flax fibres

Table 42. ANOVA results for fibre diameter (μm)

FACTORS	dF	Sum Square	Mean Sum	F	p-Value	Significant ($p<0.05$)
Linstar Cottoniser	1	178.5	178.5	303.5	0.000	Yes
Fibre type *Linstar Cottoniser	1	0.01	0.01	0.014	0.91	No
Linstar Cottoniser *Number of passages	2	3.8	2.0	3.23	0.05	Yes
Fibre type *Linstar Cottoniser* Number of passages	2	0.04	0.02	0.04	0.97	No
Error	56	32.9	0.59			

Table 43. ANOVA results for CV (%) of fibre diameter

FACTORS	dF	Sum Square	Mean Sum	F	p-Value	Significant ($p<0.05$)
Linstar Cottoniser	1	409.8	409.8	160.8	0.000	Yes
Flax *Linstar Cottoniser	1	12.9	12.9	5.1	0.03	Yes
Linstar Cottoniser *Number of passages	2	43.6	21.8	8.6	0.001	Yes
Flax*Linstar Cottoniser *Number of passages	2	3.2	1.6	0.631	0.54	No
Error	56	142.7	2.6			

Table 44. ANOVA results for fibre recovery (%)

FACTORS	dF	Sum Square	Mean Sum	F	p-Value	Significant ($p<0.05$)
Linstar Cottoniser	1	17.3	17.3	11.93	0.001	Yes
Fibre type *Linstar Cottoniser	1	0.91	0.9	0.63	0.431	No
Linstar Cottoniser *Number of passage	2	6.7	3.4	2.32	0.11	No
Fibre type*Linstar Cottoniser *Number of passages	2	3.2	1.6	1.11	0.34	No
Error	56	81.2	1.5			

Discussions of ANOVA results

Tables 40 to 44 show the results of the ANOVA analysis aimed at determining whether the different processes and number of passages had a significant effect on fibre diameter (fineness), fibre recovery and CV of fibre diameter. The key factors found to have a significant effect, with $p<0.05$ values, were as follow:

a. Hemp fibres:

The following observations were made on the machine related processing factors which significantly affected the hemp **Fibre diameter** and its **CV**:

- The type of process, ie fine opening or cottonising, was significant for both the fibre diameter and CV of the fibre diameter, cottonising generally producing finer fibres.
- Interaction between hemp fibre type and process (cottoniser) was significant for CV of diameter, but not for fibre diameter.
- Interaction between process (cottoniser) and number of passages was significant for CV of diameter but not for diameter, and
- The combined interaction between hemp fibre type, process (cottoniser) and number of passages was significant for both fibre diameter and its CV.

For **Fibre recovery**, the only significant processing factors were:

- Interactions between cottoniser and number of passages, and between fibre type, cottonisation and number of passages.

b. Flax fibres

The following observations were made on the machine related processing factors which significantly affected the flax **Fibre diameter**, **Fibre recovery** and **CV** of **fibre diameter**:

- Cottonisation process on its own; and interaction between cottonisation process and number of passages had a significant effect on **fibre diameter**,
- Cottonisation process on its own as well as interactions between fibre type and process; and between cottonisation process and number of passages had significant effects on the **CV of diameter**, and
- Only the cottonisation process had a significant effect on flax fibre recovery (%).

Discussion of the result

Overall, only one passage through the **Temafa Linstar Cottoniser** unit, operating at 2840 rpm was adequate in reducing the flax fibre bundle diameter to the target value of 20µm. The fibre bundle width (referred in table as fibre diameters) of the input flax fibres used in this research were finer than those of the hemp fibres. The high fibre bundle width of the locally grown hemp and flax might have been due to both the agronomic conditions and lack of expertise in the cultivation of the two crops in South Africa. The successful production of cottonised flax fibre, using the Temafa Linstar cottoniser unit, is an important finding emerging from this research, and one which can contribute towards the mass production and spinning of cottonised flax fibres using the short staple system so prevalent in South Africa for both local and international markets. The cottonised flax fibres produced during this research were blended with cotton (30/70 and 40/60 flax/cotton) and successfully processed on the short-staple pilot plant of the CSIR to produce 32 tex yarns. This research is not reported here as it is beyond the scope of the present thesis.

Fibre Length Distribution – Qualitative analyses

Figure 86 shows photographs of fibre length distributions illustrating the effect of processing sequence in opening, cleaning and shortening the IDC flax fibres.

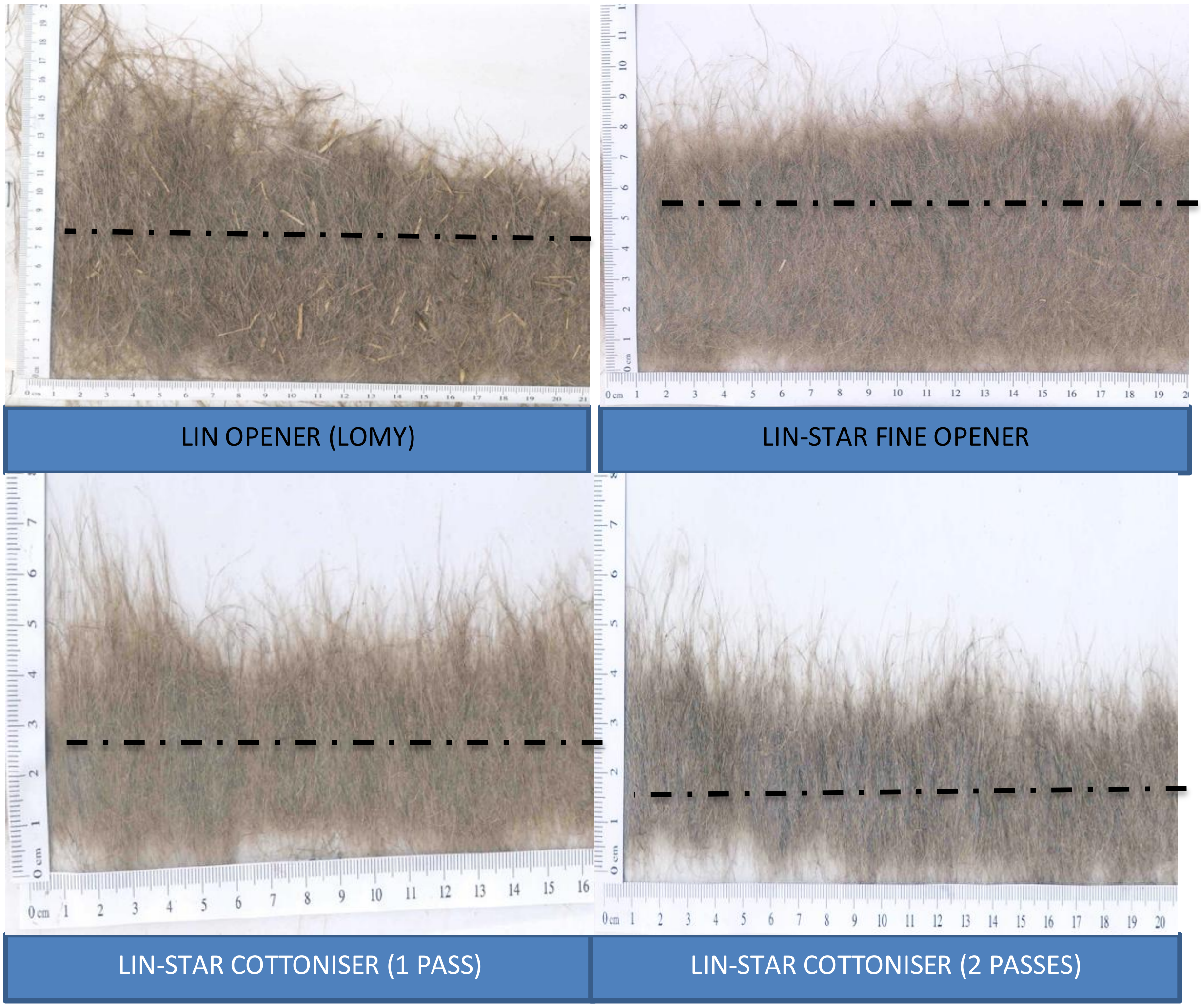

Figure 86. Photographs showing flax fibre length distributions after different processing stages

As can be seen from Figure 86 the fibres become cleaner, shorter and finer as they proceed from LOMY → LINSTAR FINE OPENER → LINSTAR COTTONISER, the fibres being reduced to an approximate length of 14 cm after one passage through the Lomy, then to an approximate average length of 9 cm after the Linstar fine opener, and to approximately 5.5 cm for 1 passage and 4.5 cm for 2 passages, respectively, through the Linstar cottoniser.

Main conclusions

The main conclusions for the Part III of this study are:

- The Temafa *Linline* fibre processing unit successfully opens, cleans and shortens locally produced flax and hemp fibres, thereby providing opportunities for the use of the fibres in various applications.
- A single passage through the Lomy, followed by a single passage through the Linstar opener and then one through the Linstar cottoniser, were sufficient to mechanically modify the scutched flax into cotton-like fibres with a diameter of less than 20µm, representing an overall fibre diameter reduction of about 20%. This processing sequence produced the following decrease in diameter of various fibre inputs covered in this research:
    - Locally grown scutched hemp fibres decreased from 66µm to 26 µm, i.e., by 60%. Fibre losses during the mechanical fibre cleaning and shortening process on Temafa lin line, based on single passage of fibres from Lomy-to-Linstar Cottoniser, was 29.9 %,
    - Nonwoven grade hemp from France decreased from 53.5 µm to 25.2 µm, i.e., by 53%. Fibre losses through mechanical processing was 14.9 %,
    - Bleached hemp fibre from France decreased from 43.8 µm to 23 µm, i.e., by 47.5%. Fibre losses through mechanical processing was 13.6 %,
    - IDC light colour scutched flax fibre grown in South Africa decreased from 45.8 µm to 20 µm. i.e., by 56.3%. Fibre losses through mechanical processing was 13.6 %, and

    - IDC grey colour scutched flax grown in South Africa decreased from 45.5 µm to 18 µm, i.e., by 60.4%. Fibre losses through mechanical processing was 12.4 %.
- Despite the relatively poor quality of the locally grown hemp fibre, i.e. under-retted and coarse, it was possible to mechanically modify it using Temafa *Linline*, and reduce the fibre diameter by 36% and achieve levels approaching those of 20µm target.

CHAPTER 4. SUMMARY AND CONCLUSIONS

The following represents the key findings of this research, and for easy reading, it is written in accordance with the main sections of this research work.

4.1. Literature Survey:

According to the literature survey, the following can cause the bast fibre industry to become one of the key global industrial sectors in terms of market size, application and revenue base, and thereby meet the world's demand for environmentally friendly products and the anticipated future global fibre supply:

- ✓ Advancement in cultivar breeding techniques to produce cultivars with a high fibre yield and which could grow under various climatic conditions, as well as improved and best farming management practices to ensure a high quality primary agricultural product resulting in a fibre of good quality.
- ✓ Improvements in fibre extraction or separating techniques, and technologies capable of reducing the lignin content of bast fibres, thus contributing towards the production of tailor-made bast fibres for various applications.
- ✓ Further progress in the "cottonisation" of bast fibres for the mass production and processing of fine and soft fibres (pure or in blends), using conventional cotton and wool systems. This would enable the development of a variety of fabrics suitable for different markets, thus enabling penetration of the textile apparel market.
- ✓ Capitalising on the significant opportunity to expand the use of bast fibres in the nonwoven sector from the current levels (<3%), by focusing on market segments identified for growth, such as filters, plant growth media (agro-textiles), insulation, geotextiles, etc.

- ✓ Bast fibres, such as flax, kenaf, hemp, etc., becoming the material of choice for all natural fibre composite applications, particularly in the automotive and construction sectors. The automotive industry's adoption of natural fibre composites is driven by government support, environmental regulations, customer acceptance, price, weight reduction and marketing incentives, rather than by technical demands, and applications other than the current ones need to be explored leading to increased demands for bast fibres, such as flax and hemp.
- ✓ Rising prices of petroleum based products, strong government support for eco-friendly products, higher acceptance and positive growth of end use industries, such as new houses.
- ✓ If, for both the developing and under-developed countries of the world, the cultivation, processing, production and manufacturing of products derived from the complete beneficiation of bast fibre plants are seen as strategic interventions for socio-economic development of rural areas and employment creation to reduce poverty, in line with millennium development goals and the Kyoto Protocol on climatic change.

4.2 Effect of agronomic parameters on the biomass and fibre yields of European hemp cultivars grown in the Eastern Cape.

The results of this study, aimed at investigating the influence of various agronomic parameters on the potential of the hemp fibre production in the Province of the Eastern Cape by utilising European cultivars, showed the following:

- ✓ That South Africa has the potential to grow a hemp crop with a fibre yield per hectare similar to that achieved in other hemp producing countries;
- ✓ Local expertise in retting hemp is required since it plays such a crucial role in achieving the desired quality of the extracted fibres.

- ✓ Planting hemp in October, using a row spacing of between 12.5 to 25 cm, with a seeding density of between 80-100 kg, and applying 50-100 kg nitrogen fertiliser, represented the optimum agricultural parameters in terms of achieving good biomass and fibre yields per hectare. The application of herbicides did not have any beneficial effect on biomass and fibre yields, a result consistent with the exceptional ability of hemp to suppress weeds, as demonstrated in various studies, thus reducing the input cost for both the subsistence and commercial farmers interested in the cultivation of hemp.
- ✓ If South Africa is seriously considering in establishing an economically viable and competitive hemp agro-industry, it will need to adopt the best agricultural practices for hemp cultivation and management, the most suitable cultivars for local conditions, the most appropriate time to plant the crop, the best crop-care management practices, train farmers in the necessary technical skills and optimise of the retting process, etc.

4.3 Hemp fibre properties

The effect of agronomic parameters (such as cultivar type, planting site, retting period and lighting conditions – both normal and artificial) on the physical fibre properties (fibre yield, linear density, bundle strength and CV) and chemical composition of the various European hemp cultivars grown in different localities in the Province of the Eastern Cape was investigated and it was concluded that:

- ✓ The fibre yields achieved here were somewhat lower than the minimum of 23 % reported in the literature, and in the majority of the cases this being attributed to the serious lack of locally available technical expertise in hemp cultivation and farming management practices. Since the main economic item in hemp fibre crop production is the fibre, the low levels of fibre yield achieved here could negatively impact the economic viability of the primary fibre production industry.

- ✓ Retting is an important process, it together with climatic conditions, having a direct effect on the properties of the extracted fibres, such as colour, strength, product uniformity and fibre yield. Both the objectively and subjectively assessed fibre properties were affected by the retting conditions, notably the duration. Despite limitations in the experimental design of agronomic trials, a retting period of two-to-three weeks appeared best for these experimental trials in producing fibres with good physical properties. Nevertheless, great care should be taken during the field retting process as it is directly influenced by environmental conditions (e.g. temperature, micro-organisms and moisture/humidity etc.) that are beyond human control, and therefore requires constant monitoring to ensure optimum degradation of the binding material that holds the fibres together.
- ✓ There was no beneficial benefit observed on fibre properties (fibre yield, linear density, bundle strength and CV) when artificial lighting was used to extend the light exposure period to 16 hours of lighting similar to that to which hemp cultivars are exposed to when grown in Europe.
- ✓ The planting site location and the cultivar were the main factors determining the fibre properties, such as fibre yield, linear density, bundle strength and CV.
- ✓ The subjective assessment of the hemp straw retting status using the colour grading chart in deciding on the correct time to remove the retted hemp straw from the field, was not a substitute for an objective measurement tool, but merely a monitoring tool. Under-and over-retting of the hemp straw resulted in fibres of poor quality and negatively affected the agro-economics in terms of growing hemp as a sustainable crop for rural farmers. Years of experience and technical skills on the primary growing and processing of hemp, particularly retting, are essential for the production of high quality fibres and which are suitable for various industrial applications.

- ✓ An inadequate experimental design and planting site management had a direct effect on the results obtained when evaluating the effects of various agronomic parameters (retting period, lighting conditions, planting site and time) on properties, such as fibre yield, linear density, bundle strength and CV of European hemp cultivars grown in South Africa. This is proven by the fact that the benchmark used by crop scientists from the ARC-IIC in measuring the success of the field trials was based on the biomass yield per hectare, using the straw weight and height, whilst the textile and material scientists from the CSIR placed emphasis on the fibre yield, uniformity, bundle strength and its CV as key performance parameters essential for industrial applications.
- ✓ Naturally occurring fibre defects, such as cracks along the fibre length, and those introduced by the action of the mechanical decortication process, as observed in the SEM micrograph, represent weak spots which could negatively affect fibre properties, processability and limit applications.
- ✓ The fibre chemical and elemental compositions of the hemp cultivars grown in the Province of the Eastern Cape were comparable to those found in hemp growing countries, the mineral elemental composition being dependent on the soil conditions at the planting sites.

4.4 Performance of European fibre flax (Linum usitatissimum) cultivars under South African climatic conditions

The following summarise the conclusions of the study on the performance of EU fibre flax cultivars when grown in South Africa:

- It was found that South Africa has the necessary climatic and agronomic conditions to grow flax, with biomass yield ($kg.ha^{-1}$) and fibre yield (%) dependent on factors such as the **planting site**, **cultivar**, **planting date** and their combinations.

- The Southern Cape region, particularly the Western Cape, has the right agronomic and climatic conditions to grow flax that produces yields comparable to those found in flax producing countries, and with the Western Cape sub-region producing higher yields in a consistent manner over the three different planting dates. Nevertheless, it is important to emphasize that these yields were derived on the basis of small plots, and might change when planted on a commercial scale. These results confirmed the conclusions in the feasibility report "Establishing a flax and linen industry in Southern Africa", the South Africa has both the climatic and agronomic conditions suitable for growing flax.
- The cultivars grown at Addo produced fibre yields (%) within the acceptable international range, but showed very low biomass yields that caused the total fibre yields ($kg.ha^{-1}$) to be lower than the normally accepted minimum of 0.8 tonnes per hectare.
- The choice of cultivar, best agronomic conditions, technical and retting expertise, availability of secondary fibre processing capabilities (skills and technology) as well as specific fibre requirements and market size, are some of the key factors that need to be considered if South Africa is to succeed in establishing an economically viable and sustainable flax fibre industry.

4.5 Flax and hemp fibre cottonisation through mechanical processing

The main conclusions from the study on flax and hemp fibre cottonisation are as follows:

- The Temafa *Linline* fibre processing unit opens, cleans and shortens locally grown flax and hemp fibres and thus opens up many opportunities for their use in various applications.

- A single passage of fibre through the Lomy, followed by the single passage through the Linstar opener and thereafter the Linstar cottoniser, was sufficient to mechanically modify the locally grown and scutched flax into cotton-like fibres, with fibre diameter of less than 20µm, representing a fibre diameter reduction of about 20%.
- Despite the poor fibre quality of the locally grown hemp, i.e. under-retted and coarse fibres, it was possible to mechanically modify them using Temafa *Linline* and reduce the fibre diameter some by 36% to levels approaching the 20µm target.
- The successful outcome of the fibre cottonisation experiments also opens up other opportunities for the CSIR to explore various fibre treatments (biotechnological, chemical, ultrasound, etc.) which could produce better separation of the meso- and micro-fibril fibres and make them suitable for high niche applications, in support of the country's newly adopted Biocomposite Strategy.

4.2 Overall conclusion

- ✓ It can be concluded that South Africa's soil and climatic conditions are suitable for growing a variety of imported flax and hemp cultivars, although not all of the cultivars performed optimally at various experimental sites, in terms of fibre yield and therefore the selection of the most appropriate cultivar is critical. A word of caution is necessary, however, namely that the results obtained in this research were based on small experimental plots, and it is possible that different results may be obtained on a commercial scale.
- ✓ The serious lack of local technical expertise in the growing and retting of flax and hemp can seriously jeopardise efforts in establishing an economically sustainable industry in South Africa.

- ✓ Pockets of technical skills, in institutions like the CSIR and ARC-IIC, exist to form core teams to build the human resources, along the entire value chain, required to make South Africa a leading bast fibre processing and manufacturing country. The lack of overall local technical skills to run industrial operations was demonstrated by the mothballing of the flax and kenaf industrial processing plants in the country.
- ✓ There exist local secondary and tertiary industries to create the necessary fibre supply demand to justify the establishment of the primary fibre production sector to create employment opportunities for people in the rural areas, thereby alleviating poverty.
- ✓ National government is fully supportive of the initiative to establish a biocomposite industry in South Africa that will utilise natural fibres, particularly locally grown flax and hemp.

CHAPTER 5. SUGGESTIONS FOR FUTURE WORK

In Chapter 4, Summary and Conclusions, it was noted that this study had revealed both serious shortcomings and opportunities, at both the institutional arrangement level and at the planning, design and implementation of the experimental cultivar adaptation field trials. These have a direct impact on deciding whether South Africa should pursue the proposed agenda towards the establishment of a vibrant and sustainable bast fibre industry. Also, the renewed global interest in the use of renewable materials in various applications has defined the global research agenda for bast fibres, such as flax and hemp, to namely replace petroleum based and high energy intensive raw materials in certain appropriate applications. The combination of all these factors forms the essence of a proposal on suggested future work that the CSIR should be involved in, as a premier R&D institute and in collaboration with other local research institutions, to advance and position South Africa favourably in the beneficiation of bast fibres. This includes:

5.1 Institutional arrangement:

Addressing the lack of industry structures, namely key stakeholders, such as government, farmers (both subsistence and commercial), private sector, R&D institute, labour and tertiary education institutions, with clear roles and responsibilities which presently undermines achieving the country's vision for bast fibre beneficiation. This entails the necessary legislative framework and policies required to support this industrial sector, appropriate government incentive programmes, R&D funding and technical training support programmes and the overall coordination of the programme. Innovate Eastern Cape, an entity of the provincial government of the Eastern Cape, has been mandated by national government departments, such as the Department of Trade & Industry (the dti), Department of Agriculture, Fisheries and Forestry (DAFF) and Economic Development Department (EDD), to facilitate the development of the South Africa Chapter on Global Natural Fibre Forum that will be responsible for setting a proper institutional framework to drive South Africa's natural fibre agenda. The Chapter's main functions are to promote the natural fibre industry to various industry participants, collect and disseminate information relating to all aspects of the industry, and coordinate research and development programmes. Its other task is to ensure that the fibre supply chain constraints arising between producers, processors and manufacturers are addressed as commercial entities place a strong emphasis on the reliability of raw material supply over the duration of their yearly production schedule so as not to negatively affect the industry production schedule and meeting market demands. The CSIR has a relationship with Innovate Eastern Cape and, together with the ARC-IIC, is expected to lead the development of the research and development programme for the Chapter.

5.2 R&D

It is forecast that global fibre demand will be 130 million tonnes by 2050, which cotton and synthetic fibre production will not be able to meet. Other than the environmental concerns, the renewed global interest in natural fibres, such as flax and hemp, forms part of the strategy to offset this fibre demand. The markets, identified as having a great potential in increasing the percentage share of the consumption of bast staple fibres, include nonwovens, natural fibre composites and as a substitute for cotton fibres in the apparel sector. In the nonwoven sector, the products identified for flax and hemp fibres use include hygienic / medical, filtration, insulation, geotextiles and plant growth media. In terms of natural fibre composites field, the sectors of fibre use include mass transportation (automotive, aerospace and locomotive), building construction, energy (wind turbines) and electrical & electronics. These future market opportunities for bast fibres, define the global R&D agenda for natural fibres in terms of finding the optimum ways to produce flax and hemp fibres with performance characteristics which match or surpass those of currently used feedstock, without adding an unacceptable costs. This global R&D consensus also informs the direction of future research and development to be carried out by the CSIR and broader South African institutions as further elaborated below:

5.2.1 Primary production

The agricultural field trials undertaken by the ARC-IIC to investigate the adaptability and performance of flax and hemp cultivars to the local conditions exposed inadequate technical collaboration between the crop scientists at the ARC-IIC and textile scientists at the CSIR. The ARC-IIC focused on biomass yield as the true determinant of crop performance, whilst the CSIR placed the emphasis on fibre physical and chemical properties since these influence the potential industrial applications of the fibres. To obviate further inconclusive results resulting from inappropriate or incomplete agriculture experimental designs, which could impact on aspects relating to fibre properties and their processability, the following minimum requirements need to be agreed upon:

A. Ensuring joint, and correct agricultural experimental design, starting with cultivar & planting site selection, seed viability tests, soil analysis, accurate recordings of daily climatic and soil conditions (day length, humidity, rain, etc), accurate recordings of plant growth (height, branching, biomass, etc), schedules for plant harvesting, farmer training schedules (pre-planting, data recording, retting, etc). Establish the impact on fibre properties (physical and chemical), using the most appropriate test methods. Pre-plan the experiments based on acceptable experimental designs, such as Box Behnken; which will not only limit the extent of the experimental work but which will also enable the statistical analysis of the data to be carried out from which meaningful conclusions can be drawn. It is recommended that in similar future studies, scientists from both the ARC-IIC, government and the CSIR should jointly undertake the experimental planning and design of such trials to mitigate against all controllable risks, such as the right harvesting time, fertiliser and herbicide treatment, retting process, recording of results, correct sampling procedure, etc. in order to produce results that are reproducible.

B. Explore new retting techniques, such as osmotic degumming, ultra-sound, steam explosion and enzymatic treatments and determine their effects on fibre properties, particularly within the context of certain specific applications.

C. Explore new fibre extraction and processing techniques, focusing on the complete beneficiation opportunities for the bast crop to enhance its economic viability across the value add chain.

5.2.2 Approaches for fibre extraction and refinement

The initial successes in the mechanical and biotechnological modification of flax and hemp fibres for the production of tailor-made fibres, e.g. "cotton-like" for application in technical textiles and natural fibre composites will inform future work at CSIR including:

- ✓ Optimisation of the mechanical modification process, using the Temafa technology, and its effect on fibre physical and chemical properties,
    - o Matching the fibre properties obtained by the mechanical modification process with the minimum specifications for different applications.
    - o Further application of both chemical and biotechnological treatments to modify the fibres and determine their effect in terms of producing ultimate fibres and the associated fibre properties.
- ✓ Using results obtained during the research to develop a quality measurement system, incorporating best practices from other research institutes that will be used by local

processors and manufacturers as a guide in assessing the quality of the raw materials they use to manufacture specific products.

References

1. Anon, 1985, Cotton spinning, "The story of the Spindle Diary and Buyers Guide," Textile Institute, Manchester, p.39.
2. R.R., Franck, 1985 "The history and present position of linen," on The Biology and Processing of Flax by H.S. Sharma and C.F. Van Sumere, M Publications, Belfast.
3. Gherzi-Consultants to the Industry, October 2011 "Newsletter," www.gherzi.com
4. Fibre2Fashion, February 2011 "Global textile sector run short of fiber," www.fibre2fashion.com
5. L. Turunen and H. Van der Werf, (2006), "Life cycle analysis of hemp textile yarn," Comparison of Three Fiber Processing Scenarios and a Flax Scenario. French National Institute for Agronomy Research.
6. Lucintel – Global Management Consulting & Market Research Firm, March 2011, "Opportunities in natural fibre composite," Lucintel Brief.
7. S. Moolman, July 2011, "Biocomposite business plan," CSIR, South Africa.
8. Trading Economics, 2012, "South Africa economic indicators," www.trading economics.com
9. Statistics South Africa, 2012 "2011 Census data," www.statssa.gov.za
10. Kyoto Protocol to the UNITED NATIONS, 1998 "Framework Convention on Climate Change," UNITED NATIONS
11. C. Vasvanathan, S. Kumar and S. Han, 2000 "Cleaner Production in Textile Sector – Asian Scenario", National Workshop on "Sustainable Industrial Development through Cleaner Production," November 2000, Colombo, Sri Lanka.
12. B.P. Singh, 2010 "Industrial Crops and Uses," CAB International, UK.
13. United Nations, 2008 "Report of the Conference of Parties on its thirteenth session, held in Bali from 3 to 15 December 2007," COP 13, Framework Convention on Climate Change, Bali, Indonesia.
14. United Nations, 2011 "Report of the Conference of Parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010," COP 16, Framework Convention on Climate Change, Cancun, Mexico.
15. United Nations, 2012 "Report of the Conference of Parties on its seventeenth session, held in Durban from 28 November to 11 December 2011," COP 17, Framework Convention on Climate Change, Durban, South Africa.
16. United Nations, 2013 "Report of the Conference of Parties on its eighteenth session, held in Doha from 26 November to 8 December 2012," COP 16, Framework Convention on Climate Change, Doha, Qatar.
17. Lenzing, 2012 "The fiber year 2012," World Survey on Textiles and Nonwovens report, Lenzing, www.lenzing.com
18. R.W. Kessler and R. Kohler, 1996 "New strategies for exploiting flax and hemp," Chemtech

Dec. p.34
19. J.E.G. van Dam, 2009 “Environmental benefits of natural fibre production and use,” Discover Natural Fibres : Proceedings of the Symposium on Natural Fibres, Rome:FAO.
20. A. Seely, 2009 “Landfill taxes : Recent developments,” SN/BT1963, UK.
21. S.M. Devall, 2010 “Textile and process for making textiles and dyes from tobacco plants,” US Pantent number US20110287681.
22. C.M. Clemons and D.F. Caulfield, 2005 “Natural Fibers - Functional fillers for plastics,” Newark, NJ: Wiley-VCH.
23. R. R. McKenzie,2006 “Flax stem cross-section,” Source: http://en.wikipedia.org/wiki/File:Labeledstemforposter_copy.
24. D. E. Akin, 2005 “Standard for Flax,” ASTM Standardization News.
25. F. Munder and H. Hempel, 2006 “Mechanical and Thermal Properties of Bast Fibers Compared to Tropical Fibers,” Institute of Agricultural Engineering, Vol 448. p.197.
26. E. Small and D. Marcus, 2002 “Hemp: A new crop with new uses for North America,” p. 284, In: J. Janick and A. Whipkey (eds.), “Trends in new crops and new uses”, ASHS Press, Alexandria, VA.
27. A. Dujardin, 1948 “The retting of flax”, Flax Development Committee, Belfast, p.194
28. P.S. Fredericksen, 1968 “Mycological investigations on field retting of fibre flax : species and distribution,” Fibra, Vol 13, p.9
29. H.S.S. Sharma, 1988b “Screening polysaccharide-degrading enzymes for retting flax stems,” International Bio-deterioration, Vol 23, p.463
30. W. Konczewicz, “Review of retting methods – Osmotic degumming,” Presentation, Institute of Natural Fibres and Medicinal Plants, Poznan, Poland, www.inf.poznan.pl
31. L.A. Allen, 1946a “Recent developments in the microbiology of retting. Part I. The microbial flora in different systems of retting,” Journal of the Society of the Chemical Industry, Vol 65, p.365
32. L. Enebo, C.G. Carlsson and H. Lundin, 1947 “On the formation of fatty acids during retting of flax,” Archives of Biochemistry, Vol 12, p.339
33. C.F. Van Sumere and D. Cowan, 1987 “Method for batchwise enzymatic-retting of flax or other rettable plants,” (21.10.85) DK (4813/85) European Patent 220913 A2 (6.5.87)
34. H.S.S. Sharma, 1998a “Micro-organisms in processing of flax,” In Biotechnology, Edited by H.J. Rehm and G. Reed, VCH, Weinheim, Vol 6b, p.746
35. S.D. Bhattacharya and J.N. Shah, 2004 “Enzymatic treatment of flax fabric,” Textile Research Journal, Vol 74, p. 622
36. C.F Van Sumere, and H.S.S. Sharma, 1991 “Analyses of fine flax fibre produced by enzymatic retting,” Aspects Appl. Biol., Vol 28, p.15
37. A. Dujardin, 1942 “Vias-roten. De Westvlaamsche Boekhandel,” s.v. Groeninghe drukkerij,

Kortrijk, Belgium.

38. F. Brühlmann, M. Leupin, K.H. Erismann and A. Fiechter, 2000 "Enzymatic degumming of ramie bast fibers," Journal of Biotechnology, Vol 76, p.43.

39. N. Mosier, C. Wyman, B. Dale , R. Elander , Y.Y. Lee , M. Holtzapple and M. Ladisch, 2005 "Features of promising technologies for pre-treatment of lignocellulosic biomass," Bioresource Technology, Vol 96, p. 673.

40. R. W. Kessler, U. Becker, R. Kohler and B. Goth, 1998 "Steam explosion of flax - A superior technique for upgrading fibre value," Biomass and Bioenergy, Vol 14 (3), p. 237.

41. R.H. Marchessault, 1988 "Steam explosion - a refining process for lignocellulosics," Steam Explosion Techniques, Gordon and Breach Science publisher S 1ff.

42. K.M. Nebel, 1995 "New processing strategies for hemp," Journal of the International Hemp Association Vol 2(1): 1, p.6

43. A. Allam, R. Kozlowski and W. Konczewicz, 2001 "Application of osmotic pressure in degumming of flax," in *Proceedings of Conference "Bast Fibrous Plants on the Turn of Second and Third Millenium,"* Special Edition 2001/2, Shenyang, China, Vol 10, p.382.

44. W. Konczewicz and R. Kozlowski, 2007 " Application of osmotic pressure for evaluation of quality and quantity of fiber in flax and hemp," Chapter 9, p 95 in " Textiles for Development" ed. R. Anandjiwala, L. Hunter, R. Kozlowski, G. Zaikov, Nova Publisher.

45. M. Duckett, 2007 "Overview of European Bast Fibre Primary Processing," Biofibres International Symposium.

46. C. Sultana, 1992 "Scutching of retted-flax straw," In: The Biology and Processing of Flax, H.S.S. Sharma and C.F Van Sumere, Eds., p.261, M Publications, Belfast.

47. T. Ross, 1992 "Preparation and spinning of flax fibre," In: The Biology and Processing of Flax, H.S.S. Sharma and C.F. Van Sumere, Eds., p.263, M Publications, Belfast.

48. Temafa Machines, "Global Blending Solutions," D-51469 Bergisch Gladbach, www.temafa.com, E-Mail: info@temafa.de

49. European Cooperative Research Network on Flax and other Bast Plants, http://escorena.fao.org/.

50. R.W. Kessler, R. Kohler and M. Tubach, "Strategy for sustainable future of fibre crops," Institut für Angewandte Forschung, University of Applied Science, Reutlingen.

51. B. Smeder and S. Liljedahl, 1996 "Market oriented identification of important properties in developing flax fibres for technical uses," Industrial Crops and Products, Vol 5: p. 149

52. ASTM International, 2005a "ASTM standard terminology relating to flax and linen (D6798)," Annual Book of Standard, Section 7.02, Textile, ASTM International.

53. ASTM International, 2005b "ASTM test method for color measurement of flax fiber (D6961)," Annual Book of Standard, Section 7.02, Textile, ASTM International.

54. ASTM International, 2005c "ASTM standard test method for assessing clean fiber fineness

(D7025)," Annual Book of Standard, Section 7.02, Textile, ASTM International.

55. ASTM International, 2005d "ASTM standard test method for measurement of shives in retted flax (D7076)," Annual Book of Standard, Section 7.02, Textile, ASTM International.

56. D. Ruys, A. Crosky and W.J. Evans, 2002 "Natural bast fibre structure," Int. J. Mater. Prod. Technol., Vol 17, p.2.

57. J. Wasko, J. Walentowska and K. Piechowiak, "Flax and Hemp Raw Materials and Products and Their Standardization," Institute of Natural Fibres, Poland .

58. A. Drieling, R. Bräumer, J. Müssig and H. Harig, 1999 "Testing strength, fineness, and length of bast fibres," Technical Textiles, Vol 42. P. 261.

59. S. Amaducci, J. Müssig, A. Zatta and G. Venturi, 2008 "An Innovative Production System for Hemp Fibre for Textile Destinations: From Laboratory Results to Industrial Validation," International Conference on Flax and Other Bast Plants, ID≠21, p.104, ISBN #978-0-9809664-0-4.

60. B.G. Bowes, 1996 "A colour Atlas of plant structure," Manson Publishing Ltd, London,p. 192.

61. I. Booth, A. Goodman, S. Grishanov and R. Harwood, 2004a "A mechanical investigation of the retting process in dew retted hemp (*Cannabis sativa*)," Annals of Applied Biology, Vol 145, p. 51.

62. J. Militky, V. Bajzik, D. Kremenakova, "Selected properties of cottonized flax," Textile Faculty, Technical University of Liberec, Czech Republic

63. I. Low, 1995a "UK Hemp Production," Proc. Bioresource Hemp Symposium, Frankfurt, Germany, p.106.

64. P.O. Olesen, D.V. Plackett, "Perspectives on the performance of natural plant fibres," Plant Fibre Laboratory, Royal Veterinary and Agricultural University Copenhagen, Denmark.

65. M. Mackiewicz-Talarczyk, J. Barriga-Bedoya, J. Mankowski and I. Pniewska, 2008 "Global flax market situation," FAO/ESCORENA 2008 International Conference on Flax and Other Bast Plants, Saskatoon, Canada.

66. Z. Jianchun, "Natural Fibres in China," Proceedings of the Symposium on Natural Fibres, The Research Center of Chinahemp, China.

67. M. Carus, S. Karst, A. Kauffmann, J. Hobson and S. Bertucelli, 2013 "The European Hemp Industry : Cultivation, processing and applications for fibres, shivs and seeds," European Hemp Industrial Association, www.eiha.org

68. Saurer Report, 2007 "The Fiber Year 2006/ 2007 : A World Survey on Textile and Nonwovens Industry," Issue 7, www.oerlikontextile.com

69. 2010 State of the industry, "A reset economy changes the business of specialty fabrics in the U.S," Specialty Fabrics Review | February 2010, http://specialtyfabricsreview.com/articles

70. G. Brook, 2008 "National industrial hemp strategy," Manitoba Agriculture, Food and Rural

Initiative Agriculture and Agri-Food Canada, The Agricola Group.
71. The Nonwoven Institute, “Nonwoven : Tutorial,” North Carolina State University, http://www.thenonwoveninstitute.com
72. K.Heller and M. Strybe, “Flax & Industrial hemp valuable plants for agriculture and Industry,” Institute of Natural Fibres and Medicinal Plants ul. Wojska Polskiego 71B, 60-630 Poznan, Poland.
73. K. van Rijswijk, W.D. Brouwer and A. Beukers, 2003 “Application of natural fibre composites in the development of rural societies,” Publishing Management Service, Information Division, FAO, Viale delle Terme di Caracalla, Rome, Italy,
74. R.D. Anandjiwala and S. Blouw, 2007 “Composites from Bast Fibres: Prospects and Potential in the Changing Market Environment,” Jo Nat Fibres, Vol. 4(2), p. 22.
75. Lucintel, 2012 “Growth Opportunities in Global Composites Industry 2012-2017,” Lucintel brief.
76. Lucintel – Global Management Consulting & Market Research Firm, “ Global passenger car industry 2012-2017 : Trend, Profit, and Forecast Analysis, August 2012,” www.lucintel.com/reports/mass_transportation_market_report.aspx
77. R. Zoboli, G. Barbiroli, R. Leoncini, M. Mazzanti, and S. Montresor., “Regulation and Innovation in the Area of End-of-Life Vehicles, 2000,” EUR 19598 EN, ed. F. Leone, Milan, Italy: IDSE-CNR.
78. Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles. Official Journal of the European Communities (21 October 2000).
79. M. Karus and C. Gahle, 2006 “Use of natural fibres in composites for the German automotive Production from 1999 till 2005,” NF Market Study, nova-Institut, Hürth im Rheinland.
80. R.C Clarke and X. Lu. 1995 “The cultivation and use of hemp (Cannabis sativa L.) in ancient China,” J. Int. Hemp Ass., Vol 4(2), p.76
81. J.W. Roulac, 1997 “Hemp Horizons: The Comeback of the World’s Most Promising Plant,” Vermont, USA: Chelsea Green Publishing Co.
82. P. de Montereau, “History of hemp fibre,” www.midrealm.org/starleafgate/pdf/Hemp_Fibre
83. L. Nissen , A. Zatta , I. Stefanini , S. Grandi, B. Sgorbati, B. Biavati and A. Monti, 2010 “Characterization and antimicrobial activity of essential oils of industrial hemp varieties (Cannabis sativa L.),” Fitoterapia, Vol 81, p. 413
84. G. Appendino, S.Gibbons, A. Giana, A. Pagani, G. Grassi, M. Stavri, E. Smith and M.M. Rahmanm, 2008 “Antibacterial Cannabinoids from Cannabis sativa: a structure–activity Study,” J Nat Prod, Vol 71, p.1427.
85. H.E. Hayward, 1948 “The structure of economic plants,” The Macmillan Company, NY. 674
86. P. Matthews, 1999 “Cannabis Culture: A Journey through disputed territory,” London, UK: Bloomsbury Publishing Plc.

87. L.L. Iverson, 2000 "The Science of Marijuana," New York, USA: Oxford University Press.
88. R. E. Schultes, W.M. Klein, T. Plowman and T.E. Lockwood, 1974 "Cannabis: An example of taxonomic neglect," Harvard University Botanical Museum Leaflets 23. p.337.
89. D.F.L. Schlechtendal, L.E. von, Langethal and E. Schenk, 1885 "Flora von Deutschland," Fünfte Auglag, Band. Gera-Untermhaus, p.304.
90. V.L. Vantreese, 1997 "Industrial Hemp: Global Markets and Prices," University of Kentucky, Department of Agricultural Economics.
91. E.C. Thompson, C.B. Mark, and N.A. Steven, 1998 "Economic Impact of Industrial Hemp in Kentucky," Center for Business and Economic Research, University of Kentucky.
92. B. Svennerstedt, 2009 "Hemp Fiber Strength and Thickness: A study of Plant Development of Swedish Grown Industrial Hemp," Journal of Natural Fibers, Vol 6(4), p.295.
93. European Industrial Hemp Association (EIHA), 2009 www.eiha.org.
94. D.W. Lachenmeier, L. Kroener, F. Musshoff and B. Madea, 2004 "Determination of cannabinoids in hemp products by use headspace solid-phase micro-extraction and gas chromatography-mass spectrometry," Anal. Bioanal. Chem., Vol 378, p.183.
95. S. Blade, R. Gaudiel and N. Kerr, 1999 "Low-THC Hemp Research in the Black and Brown Soil Zones of Alberta, Canada," Perspectives on crops and new uses. Alexandria, USA: ASHS Press.
96. R. Kozlowski, B. Przemyslaw and M. Mackiewicz-Talarczyk, 2004 "IENICA- Interactive European Network for Industrial Crops and their Applications: Report from Poland," http://www.ienica.net/reports/poland.pdf, accessed May 12th 2011.
97. H.M.G van der Werf, 2004 "Life Cycle Analysis of field production of fiber hemp, the effect of production practice on environmental impacts," Euphytica, Vol 140, p.13
98. WEA, 2000 "Energy and the Challenges of Sustainability," New York, USA: United Nations Development Programme.
99. J.M. Harris, 2002 "Environmental and Natural Resource Economics: A Contemporary Approach," Houghton Mifflin Company: New York.
100. S. Montford, E. Small, 1999 "Measuring harm and benefit: The biodiversity friendliness of Cannabis sativa," In: Global biodiversity Vol 8(4), p.2
101. S. Piotrowski and M. Carus, 2011 "Ecological benefits of hemp and flax cultivation and Products," nova-Institute, Hürth, Germany.
102. C. Brough, M. Sotana and S. Mhlontlo, 2005 "Hemp (*Cannabis sativa* L.) Production in South Africa," ARC-Institute for Industrial Crops and Eastern Cape Department of Agriculture.
103. R.C. Clarke, 1999 "Chapter 1: Botany of the Genus Cannabis," In P. Ranalli (Ed.), Advances in Hemp Research. New York, USA: Food Products Press
104. V. Mediavilla, M. Jonquera, I. Schmid-Slembrouck and A. Soldati, 1998 " Decimal code for

growth stages of hemp (Cannabis sativa L.)," J of the Int Hemp Ass, Vol 5 (2), p.68

105. S. Piotrowski and M. Carus, 2011 "Ecological benefits of hemp and flax cultivation and Products," Nova-Institute.

106. C.G. Ditchfield, T.E. Friend and P.S. Warner, 1999 "Discovering the Characteristics of Tropical/Sub-Tropical Hemp Cultivars," In C. Ditchfield (Ed.), Hemp and Other Natural Fibers. Today and Tomorrow. Brisbane, Australia: Rural Industries Research and Development Corporation.

107. E.M. Young, 2005 "Revival of Industrial Hemp: A systematic analysis of the current global industry to determine limitations and identify future potentials within the concept of sustainability," Lund University, Sweden, Revised Version.

108. FAOSTAT | © FAO Statistics Division 2012, http://faostat3.fao.org, |

109. Agriculture and Rural Development, 2012 "Industrial Hemp Production in Canada," Agriculture and Rural Development, Government of Alberta.

110. T. Mashabelo, 2012 "A strategic overview of the hemp industry," Report: Industry Development Corporation Limited of South Africa, Department of Research and Information.

111. K. Heller and M. Strybe, "Flax & Industrial hemp valuable plants for agriculture and Industry," Presentation, Institute of Natural Fibres and Medicinal Plants ul. Wojska Polskiego 71B, 60-630 Poznan, Poland.

112. Biowerkstoff-Report, 2010 "Report on Bio-based Plastics and Composites," ISSN 1867-1217, Edition 7.

113. A. Leseigneur, 1987 "Lin des Ville Line des Champs," Association pour la Valorisation du Patrimone Normad, Elboeuf, France, p.17.

114. B. Dewilde, 1983 "20 eeuwen vlas in Vlaanderen," Lannoo, Tielt, Bussum.

115. M. Balter, "Clothes make the (Hu) Man," Science, Vol 325(5946), p.1329.

116. A. Durrant, 1976 "Flax and linseed," In: N.W Simmonds, Ed., Evolution of crop plants. London, Longman, p.190.

117. W. Adugna, 2007 " Linum usitatissimum L," In: H.A.M van der Vossen and G.S. Mkamilo, Eds., PROTA 14: Vegetable oils/Oléagineux. [CD-Rom]. PROTA, Wageningen, Netherlands

118. F.E. Köhler, 1897 "Köhler's Medizinal-Pflanzen," Source : List of Koehler Images.

119. B. Dewilde, 1987 "Flax in Flanders – throughout the centuries," Lannoo Tielt, Belgium, p. 216.

120. M.D.C. Crawford, 1931 "The Heritage of Cotton," G.P. Putnam, New York, pp. XVIII.

121. J.E.G. van Dam and H.L. Bos, "The Environmental Impact of Fibre Crops in Industrial Applications," Fibre Crops. 2004 FAO, Rome.

122. G. Stephens, July 2008 "Flax in the Natural Products Market: Consumer Trends & Perspective," Natural Market Institute.

123. South African Government, August 2010 “Production guidelines for flax,” Department of Agriculture, Forestry and Fisheries, Directorate – Plant Production, Republic of South Africa.
124. “Growing Flax – Production, Management & Diagnostic Guide,” Fourth Edition, Flax Council of Canada and Saskatchewan Flax Development Commission, ISBN 0-9696073-4-2.
125. Natural Fibres, 2009 “Flax,” International Year of Natural Fibres, http://www.naturalfibres2009.org/en/fibres/flax.html
126. October 2009 “Canadian Flax Sector Overview – An Industry Profile,” Saskatchewan Flax Industry Profile.
127. S. Ortmann, November 2006 “Worldwide market and price development of natural fibres,” nova-Institut, Germany, 4th EIHA Conference.
128. Flax 2000, “The future of flax in the EC,” Communication 429; Agricultural Economics Research Institute LEI, The Hague, The Netherlands
129. IENICA, 2000 ”Summary Report – Fibre Crops,” (http://www.ienica.net/crops/flax.pdf)
130. J. Harwood, P. McCormicka, D. Waldrona and R. Bonadei, 2008 “Evaluation of flax accessions for high value textile end uses,” Industrial Crops and Products, Vol 27, p.22.
131. B. C. Suddell, “Industrial Fibres: Recent and Current Developments,” Proceedings of the Symposium on Natural Fibres, ADAS Rosemaund, UK.
132. Agricultural Utilisation Research Institute website. (http://www.auri.org)
133. IENICA (Ref 1495), August 2000 “Fibre Crops,” Summary Report for European Union.
134. MAFF funded R&D project NF303, “The industrial potential of fibre from UK – grown crops,” Scientific Report.
135. http://www.lucintel.com/calender.aspx
136. Republic of South Africa, 2010 “ Millennium Development Goals,” Country Report.
137. Agriculture Research Council – Institute for Soil, Climate and Water (ARC-ISCW), 14 March 2012.
138. Department of Health, 1965 “Medicines and Related Substances Control Act, 1965 (Act No. 101 of 1965),” Republic of South Africa, www.doh.gov.za
139. ECONOMIC SECTORS AND EMPLOYMENT CLUSTER, February 2010 “2010/11 – 2012/13 Industrial Policy Action Plan,” The Department of Trade & Industry, South African Government, www.thedti.gov.za
140. ECONOMIC SECTORS AND EMPLOYMENT CLUSTER, February 2011 “2011/12 – 2013/14, Industrial Policy Action Plan”, The Department of Trade & Industry, South African Government, www.thedti.gov.za
141. National Department of Agriculture, Directorate of Statistics - Import and Export Statistics, 2010.
142. T. Kunene, April 2010, “Concept document motivating for the establishment of hemp cultivation and processing in South Africa,” House of Hemp, South Africa.

143. R. Johnson, Hemp as an Agricultural Commodity, Congressional Research Service, January 19, 2012.
144. W. van Tonder and M.C. Dippenaar, Hemp Progress Report – 1999/2000, Agricultural Research Council-Tobacco and Cotton Research Council, May 2000.
145. M. Karus, 2005 "European hemp industry 2001 till 2004: Cultivation, raw materials, products and trends," European Industrial Hemp Association and nova-Institut.
146. M.E.L. Buys, 1978 "Duration of daylight in South Africa," Department of Agriculture Technical Services.
147. CMT-200M (crushing-scutching machine), "A test for long fibre content," Manual Instruction
148. F. Höppner and U. Menge-Hartmann, 2007, " Yield and quality of fibre and oil of fourteen hemp cultivars in Northern Germany at two harvest dates," Landbauforschung Völkenrode Vol 3 (57), p.219
149. H. L. Bos, 2004 "The potential of flax fibres as reinforcement for composite materials," Technische Universiteit, Eindhoven, the Netherlands.
150. M. D. Candilo, P. Ranalli, C. Bozzi and B. Focher, 2001, "Pre-liminary Results of Tests Facing with the Controlled Retting of Hemp," Industrial Crops and Products, Vol. 11 (2), p. 197
151. B. M. Prasad and M. M. Sain, 2003 "Mechanical Properties of Thermally Treated Hemp Fibres in Inert Atmosphere for Potential Composite Reinforcement," Materials Research Innovation, Vol. 7 (4), p. 231.
152. H. J. Purz, H. P. Fink and H. Graf, 1998 "The Structure of Natural Cellulosic Fibres. Part I: The Structure of Bast Fibres and Their Changes by Scouring and Mercerization as Revealed by Optical and Electron Microscopy," Das Papier, Vol. 6 (52), p. 315
153. H. Sankari, 2000, "Towards Bast Fibre Production in Finland: Stem and Fibre Yields and Mechanical Fibre Properties of Selected Hemp and Linseed Genotypes," Agricultural Research Centre of Finland, Plant Production Research, Crops and Soil, IN-31600 Jokioinen, Finland,.
154. K. Saijonkari-Pahkala, 2001, "Non-wood plant as raw material for pulp and paper," MTT Agrifood Research Finland, Plant Production Research.
155. A. Fahn, 1974. "Plant anatomy," 2nd ed. Page Bros (Norwich) Ltd, Great Britain. p.611
156. M.S. Ilvessalo-Pfäffli, 1995. "Fiber Atlas. Identification of papermaking fibres," Springer-Verlag, Berlin Heidelberg.
157. R.M. Rowell and H.P. Stout, 1998,"Jute and Kenaf, Handbook of Fibre Chemistry," Second Edition, Eds: M. Lewin and E.M. Pearce, Marcel Dekker, New York.
158. R.M. Rowel, 1995,"Composite Materials from Agricultural Resources," In: O. Olesen, F. Rexen, and J. Larsen (eds), "Research in Industrial Application of Non-food Crops, I : plant

fibres : Proceedings of a seminar," 1195 May; Copenhagen, Denmark, Lyngby, Denmark Academy of Technical Science, p27.

159. W.E. Morton and J.W.S. Hearle, 1993, "Physical Properties of Textile Fibres," The Textile Institute, Manchester.

160. S. Smuts and Boguslavsky, L., May 1999, "Testing Sisal Fibres : Standard test method for bundle breaking strength," Indian Textile Journal, Vol. 110 (8), p.54.

161. K.-U. Heyland, K.-H. Kromer, A. Beckmann, H. Gottschalk and M. Scheer-Triebel, 1995, "Methodenbuch Industriefaser Lein. Institut für Landtechnik der Rheinischen Friedrich-Wilhelms-Universität Bonn," Heft 18. Bonn. p.32.

162. I. Baltina, Z. Zamuska, V. Stramkale and G. Strazds, 2011, "Physcial Properties of Latvian Hemp Fibres," Environment Technology Resources, Proceedings of the 8th International Scientific and Practical Conference, Vol. II, Rēzeknes Augstskola, Rēzekne, RA Izdevniecība, p.237.

163. Technical Association of the Pulp and Paper Industry, 1993 "Test methods 1992-1993", TAPPI, Atlanta, Ga.

164. H.K. Goering and P.J. Van Soest, 1975 "Forage fibre analyses (apparatus, reagents, procedures and some applications)," Agricultural Research Service – United States Department of Agriculture, USDA Washington D.C. p.379

165. "Globe & Mail," 16 June 1994, Toronto, p. A-20

166. M. Harris, 1954,"Handbook of Textile Fibres," 1st edition, Harris Research Laboratories, Washington.

167. H.R. Mauersberger, 1954 "Matthews' Textile Fibres," 6th edition, John Wiley & Sons, New York.

168. Jyväskylä Innovation Oy, 2009 "Energy from field energy crops – a handbook for energy Producers," Jyväskylä Innovation Oy & MTT Agrifood Research Finland.

169. F. Sadov, M. Korchagin, and A. Matetsky, 1979 "Chemical Technology of Fibrous Materials," Mir Publishers, Moscow.

170. J.M. Mathews and H.R. Mauersberger,1954 "Textile fibers : Their physical, chemical and microscopic properties," John Wiley and Sons Inc., New York.

171. R. Sun, 1996 "Extraction, fractional isolation and structural characterization of polysaccharides and lignin from wheat straw," The Biocomposites Centre, School of Agriculture & Forest Sciences, University of Wales, Bangor, UK.

172. M. Sommer, D. Kaczorek, Y. Kuzyakov and J. Breuer, 2006 "Silicon pools and fluxes in soils and landscapes—a review," J Plant Nutr Soil Sci Vol 169 (3), p.310

173. A. Boguslavsky, 1996 "Establishing a flax and linen industry in Southern Africa," a baseline document, Division of Textile Technology, CSIR, South Africa.

174. H. Sharma, and C. Van Sumere (eds.), 1992 "The biology and processing of flax," M Publ., Belfast, Northern Ireland.
175. M. Elhaak, N. El-Shourbagy, and R. El-Nagar, 1999 "Effect of edaphic factors on technical properties of flax fibre," J. Agron. Crop Sci. Vol 182 (2), p.113.
176. B. Pallesen, 1996 "The quality of combine-harvested fibre flax for industrials purposes depends on the degree of retting," Ind. Crops Prod. Vol 5(1), p.65.
177. C. Van Sumere, 1992 "Retting of flax with special reference to enzyme-retting," In: H.S.S Sharma and C. Van Sumere, Eds., The biology and processing of flax. M Publications, Belfast, Northern Ireland, p. 157.
178. D. E. Akin, G. Morrison, G. Gamble, L. Rigsby, G. Henriksson, and K. Eriksson. 1997 "Effect of retting enzymes on the structure and composition of flax cell walls," Textile Res. J. Vol 67(4), p.279
179. R. Harwood, V. Nusenbaum, and J. Harwood, 2008. "Cottonisation of Flax," Textile Engineering & Materials Research Group, De Montfort University, UK.
180. D.L. Easson, 1989, "The agronomy of flax and its effect on fibre yield and quality following glyphosate dessication," Flax: Breeding an utilisation. G. Marshall. Brussels, Kluwer**, p.** 61.
181. W. Aufhammer, W. Wagner, H.P. Kaul, and E. Kubler, 2000, "Radiation use by oil seed crops - a comparison of winter rape, linseed and sunflower," Journal of Agronomy and Crop Science, Vol 184, p.277.
182. D.L. Easson, and R.M. Molloy, 2000, "A study of the plant, fibre and seed development in flax and linseed (*Linum usitatissimum*) grown at a range of seed rates," Journal of Agricultural Science, Vol 135, p. 361.
183. J.P.R.E. Dimmock , S.J. Bennett, D. Wright, G. Edwards-Jones, and I.M. Harris, 2005 "Agronomic evaluation and performance of flax varieties for industrial fibre production," Journal of Agricultural Science, Vol 143, p.1.
184. S. J. Couture, W.L. Asbil, A. Di Tommaso, and A.K. Watson, 2002, "Comparison of European fibre flax (Linum usitatissimum) cultivars under Eastern Canadian growing Conditions," Journal of Agronomy and Crop Science, Vol 188, p.350.
185. H.S. Sankari, 2000a, "Bast fibre content, fibre yield and fibre quality of different linseed Genotypes," Agricultural and Food Science in Finland, Vol 9, p.79.
186. H.S. Sankari, 2000b, "Linseed (*Linum usitatissimum* L.) cultivars and breeding lines as stem biomass producers," Journal of Agronomy and Crop Science-Zeitschrift Fur Acker Und Pflanzenbau, Vol 184, p.225.
187. F.U. Hassan, and M.H. Leitch, 2001, "Dry matter accumulation in linseed (Linum usitatissimum L.)," Journal of Agronomy and Crop Science-Zeitschrift Fur Acker Und Pflanzenbau, Vol 187, p.83.
188. G. Marshall, I. Morrison, and K. Nawolsky, 1989, "Studies on the physiology of *Linum*

usitatissimum L.: The application of mathematical growth analysis," Flax: Breeding and utilisation. G. Marshall. Brussels, Kluwer.

189. M. Andrassy, E. Pezelj and R. Šurina, "Improving the modification of technical flax fibres," Faculty of Textile Technology, University of Zagreb, Croatia.
190. M. Andrassy, E. Pezelj and R. Čunko, 2004 "Cottonisation of flax fibres under variable Conditions," World Textile Conference - 4th AUTEX Conference Roubaix, June 22-24.
191. J. E. Booth, 1986 "Principles of textile testing – an introduction to physical methods of testing Textile fibres, yarns, and fabrics," Elsevier Science & Technology Book.
192. J. M. Dempsey, 1975 "Fibre crops," University of Florida book, The University Presses of Florida, Gainesville, USA.

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APPENDIX

Appendix 1 : Tables 1 to 5 show raw data of results on effect of agronomic parameters on hemp biomass and fibre yield (%) of European hemp cultivars grown in the Eastern Cape, South Africa.

Table 1. Effect of row spacing and seeding rate on fibre yield

Fibre % Content Determination : Spacing (S) & Seeding Rate (D) Combination						
Spacing [S] & Seeding Rate [D]	***Biomasss Yield ($kg.ha^{-1}$)***	***% fibre content***	***Av % fibre content***	***Calculated Fibre Content ($kg.ha^{-1}$)***	***Standard Deviation***	***C.V.%***
S1D1 = 12,5cm ; 50kg	3436	23.6	23.44	80539.84	0.559464029	2.386791934
		22.9				
		23.4				
		23				
		24.3				
S1D2 = 12,5cm ; 80kg	10432	20.05	20.22	210935.04	0.728525909	3.602996582
		20.4				
		20.7				
		20.9				
		19.05				
S1D3 = 12,5cm ; 110kg	4482	20.43	20.952	93906.864	0.435970182	2.080804613
		20.9				
		21				
		20.8				
		21.63				
S2D1 = 25,0cm ; 50kg	7706	19.5	19.82	152732.92	0.238746728	1.204574812
		20				
		19.7				
		19.8				
		20.1				
S2D2 = 25,0cm ; 80kg	10021	21.5	21.56	216052.76	0.343511281	1.593280523
		21.7				
		21.9				
		21.7				
		21				
S2D3 = 25,0cm ; 110kg	4197	21.2	21.4	89815.8	0.418330013	1.954813146
		21.9				
		21.5				
		21.6				
		20.8				
S3D1 = 50,0cm ; 50kg	9319	23.1	23.1	215268.9	0.158113883	0.684475684
		22.9				
		23.2				
		23				
		23.3				
S3D2 = 50,0cm ; 80kg	7074	19.6	20.56	145441.44	0.581377674	2.827712423
		20.5				
		20.7				
		20.9				
		21.1				
S3D3 = 50,0cm ; 110kg	3990	23.4	23.3	92967	0.85732141	3.67949103
		23.7				
		23.3				
		21.9				
		24.2				

Table 2. Effect of weed control treatment on fibre yield

Treatment	***Biomass (kg.ha⁻¹)***			***Fibre % of Cultivar Type***		
	Novosadska	*Felina-34*	*Futura-77*	*Novosadska*	*Felina-34*	*Futura-77*
Accotab	**580**	**650**	**1040**	23.1	22.1	*21*
				23.4	22.6	21.1
				22.7	22.5	21.4
				21.4	22	20.2
				24.8	21.9	21.8
Frontier	***400***	***850***	***1020***	20.7	20.7	20.4
				20.5	21	19.9
				20.7	21.2	20
				20.3	21.5	21
				22.7	20.9	20.1
Afalon	***820***	***1050***	***790***	24	20.5	20.6
				23.8	19.7	20.2
				23.5	20	20
				23.6	19.5	19.7
				23	20.2	20.3
Dual S	***1240***	***700***	***770***	21.1	22.6	23.1
				21.4	22.1	22.9
				21	22.9	23
				21.3	21.9	22.8
				21.2	22	23.4
Control	***480***	***860***	***760***	22.3	21	21.4
				22.1	21.3	21
				22	21	21.2
				22.1	21.3	21.6
				22.5	21.1	21.4

Table 3. Effect of the planting date on fibre yield – October planting

Cultivar	***Biomass Yield (kg.ha⁻¹)***				***Fibre Content % per Locality***			
	ADDO	*DOHNE*	*LIBODE*	*QAMATA*	*ADDO*	*DOHNE*	*LIBODE*	*QAMATA*
Novosadska	***15892***	***17467***	***15583***	***26875***	24.2	19	23.7	24.1
					24.1	19.3	23.5	24.3
					24.3	19.2	23.6	24.5
					24.3	19.6	24	24.7
					24.2	19.2	23.7	24.3
Felina-34	***8842***	***18533***	***11208***	***25333***	21.7	17.3	23.6	24.2
					21.5	17.8	23.5	24.3
					21.4	17.4	23.2	24.6
					21.3	17.6	23.4	24.3
					21.6	17.9	23.6	23.2
Futura-77	***13058***	***19817***	***16375***	***31208***	23.3	19.4	24.1	22.6
					23	19.5	24.5	22.3
					23.5	19.8	25	22.7
					23.1	19.9	24.4	23
					23.5	19.5	25.3	22.9
Kompolti	***18325***	***21267***	***16917***	***35583***	23.6	17.1	25.7	22.7
					23.1	17	25.5	22.9
					23.5	17.6	25.8	22.4
					23.2	17.5	26	23
					24	17.6	25.3	22.8

Table 4. Effect of the planting date on fibre yield – November planting

Cultivar	Biomass Yield (kg.ha⁻¹)				Fibre Content % per Locality			
	ADDO	DOHNE	LIBODE	QAMATA	ADDO	DOHNE	LIBODE	QAMATA
Novosadska	3853	3189	3700	6450	22.8	17.5	25	22.4
					22.7	17.6	24.5	22.5
					22.4	17.3	24.9	22.8
					22.3	17	25	23.5
					22.6	17.5	25	22.9
Felina-34	1923	3193	2645	6143	19.7	18.5	24.4	23.6
					20	18.6	24.2	23.5
					19.8	18.9	24.9	23.7
					19.5	19	25	23.3
					19.8	18.7	24.5	23.1
Futura-77	3042	3850	4257	7068	22.3	20.1	25.4	22.4
					21.9	20	25.2	22.5
					22.5	20.5	25.3	22.7
					23	20.3	25.8	23
					21.7	20.8	25	22.6
Kompolti	4333	3630	4356	8077	22.2	22.6	25.2	23.1
					22.6	22.5	25.4	23
					21.8	22.7	25.2	23.3
					23	22.9	25.2	23.5
					21.5	22.2	25.3	23.1

Table 5. Effect of fertilization on fibre yield

Nitrogen [N] & Potassium [K] application (Kg).	Biomasss Yield (kg.ha⁻¹)	% fibre content	Av. fibre content %	Standard Deviation	C.V.%
N1K1 = 0kg: 0kg	3436	27.3	26.82	0.342052628	1.27536401
		26.8			
		26.5			
		27			
		26.5			
N1K2 = 0kg:120kg	10432	22.3	22.22	0.164316767	0.739499403
		22			
		22.1			
		22.4			
		22.3			
N2K1 = 50kg:0kg	4482	28.6	28.68	0.248997992	0.868193835
		28.3			
		28.7			
		28.9			
		28.9			
N2K2 = 50kg:120kg	7706	23	22.9	0.212132034	0.926340761
		22.7			
		22.9			
		23.2			
		22.7			
N3K1 = 100kg:0kg	10021	23.5	23.42	0.192353841	0.821322974
		23.1			
		23.6			
		23.4			
		23.5			
N3K2 = 100kg:120kg	4197	23.1	22.92	0.164316767	0.716914342
		22.8			
		22.7			
		23			
		23			
N4K1 = 150kg:0kg	9319	24	23.94	0.151657509	0.633490012
		23.7			
		23.9			
		24.1			
		24			
N4K2 = 150kg:120kg	7074	25	24.94	0.270185122	1.083340504
		24.5			
		24.9			
		25.1			
		25.2			

Appendix 2. Tables 1 to 5 show of results fibre yields (% content and $kg.ha^{-1}$) on the effect of various agronomic experimental treatment on hemp cultivars grown in the Eastern Cape, South Africa as reported in Section 3.1.2.

Table 1. Results on effect of row spacing (cm) and seeding rate density (kg.ha⁻¹) on fibre content, total dry mass of hemp straw and calculated fibre content per hectare (kg.ha⁻¹)

Spacing* (cm) & Seeding Density** ($kg.ha^{-1}$) Combination	Mean Fibre Yield (%) & Std Deviation	CV (%)	Mean Fibre Yield (%)	Mean Straw Biomass ($kg.ha^{-1}$)	Total Fibre Yield ($kg.ha^{-1}$)
S1D1 = 12,5cm : 50kg	23.4 (0.6)	2.4	23.4	3436	805.4
S1D2 = 12,5cm : 80kg	20.2 (0.7)	3.6	20.2	10432	2109.4
S1D3 = 12,5cm : 110kg	20.9 (0.4)	2.1	20.9	4482	939.0
S2D1 = 25,0cm : 50kg	19.8 (0.2)	1.2	19.8	7706	1527.3
S2D2 = 25,0cm : 80kg	21.6 (0.3)	1.6	21.6	10021	2160.5
S2D3 = 25,0cm : 110kg	21.4 (0.4)	2.0	21.4	4197	898.2
S3D1 = 50,0cm : 50kg	23.1 (0.2)	0.7	32.1	9319	2991.4
S3D2 = 50,0cm : 80kg	20.6 (0.6)	2.8	20.6	7074	1454.4
S3D3 = 50,0cm : 110kg	23.3 (0.9)	3.7	23.3	3990	929.7

*Spacing denoted by S;

**Seeding density denoted by D.

Table 2. Effect of weed control treatment on fibre yields of hemp cultivars grown at Addo.

Herbicide Treatment	Cultivar type mean fibre yield (%) and CV (%)			Mean Straw Biomass ($kg.ha^{-1}$) and Total Fibre Yield ($kg.ha^{-1}$)		
	Novosadska	*Felina-34*	*Futura-77*	*Novosadska*	*Felina-34*	*Futura-77*
Accotab	23.1 (5.3)	22.2 (1.4)	21.1 (2.8)	5800 (1339.8)	6500 (1443)	10400 (2194.4)
Frontier	20.9 (4.7)	21.1 (1.4)	20.3 (2.2)	4000 (836)	8500 (1793.5)	10200 (2070.6)
Afalon	23.6 (1.6)	19.9 (1.9)	20.2 (1.7)	8200 (1935.2)	10500 (2098.5)	7900 (1595.8)
Dual S	21.2 (0.7)	22.3 (1.9)	23.0 (1.0)	12400 (2628.8)	7000 (1561)	7700 (1771)
Control	22.2 (1.0)	21.1 (0.7)	21.3 (1.1)	4800 (1056.6)	8600 (1814.6)	7600 (1618)

Table 3. Effect of planting period and site on the % fibre yields of hemp cultivar

Hemp Cultivar type	Mean fibre yield (%) and CV(%) [October planting]				Mean fibre yield (%) and CV(%) [November planting]			
	Addo	*Dohne*	*Libode*	*Qamata*	*Addo*	*Dohne*	*Libode*	*Qamata*
Novosadska	24.2 (0.3)	19.3 (1.1)	23.7 (0.8)	24.4 (0.9)	22.6 (1.0)	17.4 (1.4)	24.9 (0.9)	22.8 (1.9)
Felina-34	21.5 (0.7)	17.6 (1.4)	23.5 (0.7)	24.1 (2.2)	19.8 (1.0)	18.7 (1.1)	24.6 (1.3)	23.4 (1.0)
Futura-77	23.3 (1.0)	19.6 (1.1)	24.7 (2.0)	22.7 (1.2)	22.3 (2.3)	20.3 (1.5)	25.3 (1.1)	22.6 (1.0)
Kompolti	23.5 (1.5)	17.4 (1.7)	25.7 (1.1)	22.8 (0.9)	22.2 (2.7)	22.6 (1.1)	25.3 (0.4)	23.2 (0.9)

Table 3. Effect of planting period and site on straw biomass and fibre content yields for hemp cultivar

Hemp Cultivar Type	Mean Straw Biomass Yield ($kg.ha^{-1}$) for 1st and 2nd Planting respectively				Total Fibre Yield ($kg.ha^{-1}$) for 1st and 2nd Planting respectively			
	Addo	*Dohne*	*Libode*	*Qamata*	*Addo*	*Dohne*	*Libode*	*Qamata*
Novosadska	15892	17467	15583	26875	3846	3371	3693	6558
	3853	3189	3700	6450	871	555	921	1471
Felina-34	8842	18533	11208	25333	1901	3262	2634	6105
	1923	3193	2645	6143	381	597	651	1437
Futura-77	13058	19817	16375	31208	3043	3884	4045	7084
	3042	3850	4257	7068	678	782	1077	1597
Kompolti	18325	21267	16917	35583	4306	3701	4348	8113
	4333	3630	4356	8077	962	820	1102	1874

*Table 4**:** Effect of different fertiliser treatment on hemp % yield.*

Nitrogen [N] & Potassium [K] application in (kg).	Mean Biomasss Yield ($kg.ha^{-1}$)	Mean fibre yield(%) and CV (%)
N1K1 = 0kg: 0kg	3436	26.8 (1.3)
N1K2 = 0kg:120kg	10432	22.2 (0.7)
N2K1 = 50kg:0kg	4482	28.7 (0.9)
N2K2 = 50kg:120kg	7706	22.9 (0.9)
N3K1 = 100kg:0kg	10021	23.4 (0.8)
N3K2 = 100kg:120kg	4197	22.9 (0.7)
N4K1 = 150kg:0kg	9319	23.9 (0.6)
N4K2 = 150kg:120kg	7074	24.9 (1.1)

Table 5. p-Factor values relating to the effect of planting site on fibre yield (%).

Interactions (cell)	Planting Site	Cultivar	{1}	{7}	{8}	{9}	{10}	{11}	{13}	{14}	{15}	{17}	{18}	{20}	{21}	{25}	{26}
1	1	Novosadska		0.000149	0.000149	0.967952	0.000149	0.000149	0.313172	0.272605	0.000149	0.000149	0.008321	0.662126	0.000149	0.000149	0.000149
7	1	Futura-77	0.000149		1.000000	0.000149	0.999814	0.357098	0.000149	0.000149	0.047589	0.000185	0.000308	0.000149	1.000000	0.000149	0.000149
8	2	Novosadska	0.000149	1.000000		0.000149	1.000000	0.145840	0.000149	0.000153	0.013149	0.000154	0.000999	0.000149	0.999994	0.000149	0.000149
9	2	Ferimon-12	0.967952	0.000149	0.000149		0.000149	0.000149	0.995783	0.005209	0.000149	0.000149	0.000185	0.031489	0.000149	0.000149	0.000149
10	2	Fedora-19	0.000149	0.999814	1.000000	0.000149		0.047589	0.000149	0.000176	0.003241	0.000150	0.004117	0.000151	0.997829	0.000149	0.000149
11	2	Felina-34	0.000149	0.357098	0.145840	0.000149	0.047589		0.000149	0.000149	0.999814	0.172200	0.000149	0.000149	0.504941	0.000149	0.000149
12	2	Felina-34															
13	2	Fedrina-74	0.313172	0.000149	0.000149	0.995783	0.000149	0.000149		0.000215	0.000149	0.000149	0.000149	0.000800	0.000149	0.000149	0.000149
14	2	Futura-77	0.272605	0.000149	0.000153	0.005209	0.000176	0.000149	0.000215		0.000149	0.000149	0.987069	0.999999	0.000149	0.000149	0.000149
15	3	Novosadska	0.000149	0.047589	0.013149	0.000149	0.003241	0.999814	0.000149	0.000149		0.712401	0.000149	0.000149	0.085364	0.000149	0.000149
16	3	Ferimon-12															
17	3	Fedora-19	0.000149	0.000185	0.000154	0.000149	0.000150	0.172200	0.000149	0.000149	0.712401		0.000149	0.000149	0.000238	0.000149	0.000150
18	3	Felina-34	0.008321	0.000308	0.000999	0.000185	0.004117	0.000149	0.000149	0.987069	0.000149	0.000149		0.804048	0.000215	0.000149	0.000149
20	3	Fedrina-74	0.662126	0.000149	0.000149	0.031489	0.000151	0.000149	0.000800	0.999999	0.000149	0.000149	0.804048		0.000149	0.000149	0.000149
21	3	Futura-77	0.000149	1.000000	0.999994	0.000149	0.997829	0.504941	0.000149	0.000149	0.085364	0.000238	0.000215	0.000149		0.000149	0.000149
25	4	Felina-34	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149		0.978272
26	4	Felna-34	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000150	0.000149	0.000149	0.000149	0.978272	

*Denoting those significant interactions for which the p-value is <0.0.5

**Denoting those interactions for which the p-value is >0.05 and therefore not significant.

Planting sites [1=Addo, 2=Libode; 3=Mtiza and 4=Qamata]

Appendix 3. Tables 1 -3 show raw data of results on Hemp Properties Evaluation as described in Section 3.2.4.1

Table 1.

Site	Cultivar	Planting Date	Retting Weeks	Daylight	Sample Code	Fibre content (%)	Fibre yield (kg/ha)	Fibre Linear Density (tex)	Zero Gauge Bundle Tenacity Mean (cN/tex)	Zero Gauge Bundle Tenacity CV (%)
ADDO						22.5		44.9	45.5	11.4
						22.8		45	46	11
	Novodsaska	November	2	N	A122N	22.9	14484	45.4	47	11.3
						23.1		46.1	49.3	10.9
						22.7		43.7	46.5	11.9
						20.8		32.7	48.1	6.4
						20.9		32.3	45.7	6
	Ferimon-12	November	2	N	A222N	21	2679	32.6	461	6.3
						20.4		30	46	6.9
						21.2		33	50.1	7.3
						16.9		25.1	53.1	9.5
						17		25.9	52.6	10
	Fedora	November	2	N	A322N	16.5	1775	26	53	10.1
						16.3		26.3	52.9	10.3
						16.5		25.5	54	9.7
						22.1		30.3	36.5	20.9
						22.4		31	37	20
	Ferimon-12	November	2	I	A222I	22.5	6191	30.4	37.7	19.2
						23.1		30.9	38	19.3
						22.7		31.5	36.5	21.5
						15		17.6	54.5	14.6
						14.6		17	53	15
	Fedora	November	2	I	A322I	14.3	4613	17.4	53.9	15.3
						14.2		17.1	54.1	15.1
						14.9		18	52.9	16.1
						17.5		37.6	39.8	37.8
						18		37	40	38.2
	Novodsaska	November	2	I	A122I	17.8	4125	38	39.9	39
						18.1		38.6	41.5	38.7
						17.9		36.6	38.1	37.5
						22.3		67.1	41.5	18.8
						22		69.2	42	18.3
	Novodsaska	November	3	N	A132N	22.4	11278	68.9	43.1	18
						21.8		70.4	43.7	19.6
						22.8		64.3	42.3	17.9
						19		11.1	39.8	21.2
						19.6		12	40	22
	Futura-77	November	3	N	A623N	20	535	12.5	41	21.6
						20.5		13.3	42.1	21.7
						19.7		11.9	41.5	22.7
LIBODE						20		14.8	49.7	15.5
						19.6		14.2	50	15.2
	Novodsaska	November	3	N	L123N	19.8	2760	15	50.8	15
						20.6		14.7	51.1	15.8
						19.4		15.2	50.5	14.7
						22		29.2	51.8	11.5
						22.5		28,9	50.3	11.9
	Ferimon-12	November	3	N	L223N	22.8	3608	29	51	12.5
						23.5		28.9	53.5	13.3
						22.5		30.5	52.1	12.5
						19.8		42.1	55.3	10.3
						20.1		41.6	54	11
	Fedora-19	November	3	N	L323N	19.7	2891	43	57.7	10.4
						20.9		42.5	56.1	10.9
						19.5		41.7	54.5	11.7
						19		26.5	63.1	9.1
						18.9		27.1	65	10
	Felina-34	November	3	N	L423N	19.4	1881	25.9	67.9	10.5
						18.8		26.6	69.9	9.8
						19.2		27.5	68.3	10.6
						23		30.1	57.1	20
						22.8		29	56.5	22.1
	Fedrina-74	November	3	N	L523N	23.1	3427	29.5	59	23.5
						22.7		30.3	58.2	21.5
						23.3		35.5	57.8	20.3
						21.7		40.4	48.4	14.2
						22		39.4	47	14.3
	Futura-77	November	3	N	L623N	21.5	3081	37.9	50	15
						21.3		38.9	51.7	15.3
						21.1		38	49.3	15.9

MTIZA	***Novodsaska***	***November***	3	N	**M123N**	18.5	3746	11.4	51.5	10.3
						19.1		13	50.9	10.5
						18.7		12.5	52	11
						19		12.8	50	*12.1*
						18.8		13.5	49.9	*11.5*
	Fedora-19	***November***	3	N	**M323N**	17.9	1343	47.1	52.2	14.2
						18.2		46	51.7	13
						18.5		45.8	51.5	13.1
						18.7		46.3	52.1	*14.9*
						18		46.9	53.2	*15*
	Felina-34	***November***	3	N	**M423N**	21.1	2242	52	46	15.9
						20.6		50	44.2	16.5
						21.4		54	47	16.9
						21.8		49.7	48.7	*15.7*
						20.9		53.4	50.3	*16.7*
	Fedrina-74	***November***	3	N	**M523N**	21.3	2664	27.9	44.2	17.9
						21.4		28.5	43	17
						21.9		29.4	41	18.3
						22		30	43.1	*17.3*
						21.8		28.2	46.3	*18.9*
	Futura-77	***November***	3	N	**M623N**	20.4	2729	54.1	52.8	6.6
						19.8		53	53.2	7.2
						19.3		50	50.9	7.9
						19		53.7	51.1	*7.4*
						20		55.5	55.4	*6.9*
QAMATA	***Felina-34***	***November***	3	N	**Q423N**	14.2	1509	46.8	51.1	17.1
						14.5		44	54.8	18.4
						15		43.1	53.2	19
						14.8		45.5	56.2	*17.3*
						15.3		48.1	58.1	*18.4*
ADDO	***Ferimon-12***	***November***	3	I	**A223I**	21.5	6023	38	40.4	15
						22		41	41.3	17
						21.8		45	46	16.5
						22.2		42.4	49.2	*15.7*
						21.6		39.1	44.7	*16.1*
	Futura-77	***November***	4	N	A624N	16.8	473	25.1	19.2	41.9
						17.1		26.7	19.9	43
						17		27.2	20.4	46.9
						17		28.1	20.1	*42.5*
						16.6		25.8	20.9	*45*
	Ferimon-12	***November***	4	I	**A224I**	18.7	5239	38	41.2	9.2
						19		34	44	10.1
						18.5		35.3	46.3	9.3
						18.6		40	42.3	*10.5*
						19.1		39.4	48.7	*9.8*

Table 2. p-values of the effects of various agronomic conditions and their interactions on fibre Properties

	Planting Site	Cultivar	{1}	{7}	{8}	{9}	{10}	{11}	{13}	{14}	{15}	{17}	{18}	{20}	{21}	{25}	{26}
1	1	Novodsaska		0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149
7	1	Futura-77	0.000149		0.209503	0.000149	0.000149	0.000149	0.000149	0.000149	1.000000	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149
8	2	Novodsaska	0.000149	0.209503		0.000149	0.000149	0.000149	0.000149	0.000149	0.522458	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149
9	2	Ferimon-12	0.000149	0.000149	0.000149		0.000149	0.229352	0.897807	0.000149	0.000149	0.000149	0.000149	1.000000	0.000149	0.000149	0.000149
10	2	Fedora-19	0.000149	0.000149	0.000149	0.000149		0.000149	0.000149	0.036942	0.000149	0.001334	0.000149	0.000149	0.000149	0.263017	0.022497
11	2	Felina-34	0.000149	0.000149	0.000149	0.229352	0.000149		0.001771	0.000149	0.000149	0.000149	0.000149	0.569196	0.000149	0.000149	0.000149
13	2	Fedrina-74	0.000149	0.000149	0.000149	0.897807	0.000149	0.001771		0.000149	0.000149	0.000149	0.000149	0.569196	0.000149	0.000149	0.000149
14	2	Futura-77	0.000149	0.000149	0.000149	0.000149	0.036942	0.000149	0.000149		0.000149	0.000149	0.000149	0.000149	0.000149	0.000152	0.000161
15	3	Novodsaska	0.000149	1.000000	0.522458	0.000149	0.000149	0.000149	0.000149	0.000149		0.000149	0.000149	0.000149	0.000149	0.000149	0.000149
17	3	Fedora-19	0.000149	0.000149	0.000149	0.000149	0.001334	0.000149	0.000149	0.000149	0.000149		0.000157	0.000149	0.000149	0.935257	0.998635
18	3	Felina-34	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000157		0.000149	0.947268	0.000149	0.516463
20	3	Fedrina-74	0.000149	0.000149	0.000149	1.000000	0.000149	0.569196	0.569196	0.000149	0.000149	0.000149	0.000149		0.000149	0.000149	0.000149
21	3	Futura-77	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.000149	0.947268	0.000149		0.000149	0.084086
25	4	Felina-34	0.000149	0.000149	0.000149	0.000149	0.263017	0.000149	0.000149	0.000152	0.000149	0.935257	0.000149	0.000149	0.000149		0.750613
26	4	Felna-34	0.000149	0.000149	0.000149	0.000149	0.022497	0.000149	0.000149	0.000161	0.000149	0.998635	0.516463	0.000149	0.084086	0.750613	

Table 3. Average colour grade (rating) as assessed subjectively.

Planting Site	Sample Code	Colour Grade Rating Score [1 – 5]*	
		Mean	***Standard Deviation***
ADDO	A122N	1.2	0.2
	A123N	1.5	0.4
	A132N	1.0	0.0
	A133N	1.1	0.3
	A122I	1.1	0.1
ADDO	A222N	1.9	0.1
	A222I	1.9	0.1
	A223I	1.2	0.3
	A224I	4.2	0.3
	A233I	1.5	0.5
ADDO	A322I	2.3	0.2
	A322N	3.0	0.7
LIBODE	L123N	1.6	0.3
	L223N	2.2	0.8
	L323N	2.3	0.5
	L423N	3.7	0.7
	L523N	2.8	0.6
	L623N	2.1	0.3
MTIZA	M123N	2.3	0.4
	M323N	2.9	0.2
	M423N	2.9	0.3
	M523N	1.9	0.3
	M623N	2.2	0.2
QAMATA	Q413N	5.0	0.2

**Sample code [Site, Cultivar, Planting date, Retting week and Lighting period (natural or extended artificial lighting as in Table 1 above])*

Appendix 4. Agronomic conditions on performance of EU flax cultivars grown in Southern Cape, South Africa as reported in Section 3.3.2

Table 1. Flax varieties on the EU Common Catalogue

Adelie	Escalina	Melina
Agatha	Evelin	Merkur
Alizee	Helmi	Modran
Argos	Hermes	Nike
Ariane	Ilona	Raisa
Artemida	Jitka	Selena
Atena	Jordán	Sofie
Aurore	Kastyčiai	Super
Belinka	Laura	Suzanne
Bonet	Lea	Tábor
Bonita	Liflax	Texa
Caesar Augustus	Liviola	Venica
Diane	Loréa	Venus
Diva	Luna	Veralin
Drakkar	Marilyn	Viking
Electra	Martta	Viola
Elise	Marylin	

Table 1. Effect of agronomic conditions on performance of EU flax cultivars grown in Southern Cape Region

Site	Cultivar	First Planting (October)			Second Planting (November)			Third Planting (December)			Third Planting (December)		
		Biomass Yield (kg.ha⁻¹)	*Fibre Content (%)*	*Fibre Yield (kg,ha⁻¹)*	*Biomass Yield (kg.ha⁻¹)*	*Fibre Content (%)*	*Fibre Yield (kg,ha⁻¹)*	*Biomass Yield (kg.ha⁻¹)*	*Fibre Content (%)*	*Fibre Yield (kg,ha⁻¹)*	*Biomass Yield (kg.ha⁻¹)*	*Fibre Content (%)*	*Fibre Yield (kg,ha⁻¹)*
ADDO	*Argos*	4425	20.2	893.9	2606	17.5	456	3325	19.6	651.7			
			20.3			17.9			20				
			20			18			20.1				
			20.5			17.6			19.8				
			20.3			17.7			19.7				
	Ariane	3981	36.1	1437	3713	15.4	571.8	3100	24.3	753.3			
			35.8			15.3			24				
			35.7			15			24.5				
			36			15.2			23.9				
			36.1			15.1			23.8				
	Diane	4994	33.3	1664	3794	23	872.6	3038	23	698.7			
			33.1			23.4			22.8				
			33			23			22.9				
			32.8			23.1			23.2				
			33			22.9			23				
	Elise	4969	22.2	1103	3750	31.9	1196	3600	25.7	925.2			
			22			32			25.4				
			22.1			32.1			25.6				

			21.9			31.8			25.3				
			22.1			32			25.8				
	Viking	5038	30.3	1526.5	3975	41.1	1633.7	3206	22.4	718			
			30			40.8			22.3				
			29.9			41			22				
			30.4			40.9			22.7				
			39.8			41			22.6				
OUDTSHOORN	*Argos*	4488	34.1	1530	5169	29.4	1519.7	3731	30.1	1123.3	3488	36.2	1262.7
			34			28.9			29.8			35.8	
			33.9			29			30.2			36	
			33.8			29.1			30			35.8	
			34			28.9			30.3			35.9	
	Ariane	4175	28.3	1181	5181	31.6	1637.2	4363	23.1	1007.8	3425	27.7	948.7
			28.1			31.1			22.8			28.1	
			28.3			31.3			23			27.7	
			28			31.2			23.1			28	
			28.4			31			22.8			27.9	
	Diane	4388	29.6	1298.8	5544	24.7	1369.4	3988	37	1475.6	3663	23.9	875.5
			29.5			24.2			36.7			23.6	
			29.6			24.5			37.1			24.1	
			29.6			24.6			36.8			24.1	
			29.5			24.6			36.9			23.9	
	Elise	4569	31	1416.4	5219	32.7	1706.6	4213	34.9	1470.3	3931	25.7	1010.3
			30.8			32.2			35			26	

			31.1 30.9 31			32 32.4 33			35 35.3 35.2			26.1 25.8 25.8	
	Viking	4975	33.7 34 34 34.2 33.9	1676.6	5381	36.9 37.5 37.5 37 37	1985.6	3956	35.5 36 36 35.9 36.9	1404.4	3569	30.3 29.6 30 30.4 29.8	1081.4
	Argos	4281	35.2 34.9 35 35 35	1507	4725	24.5 25.1 24.8 24.9 24.8	1157.6	6169	33.2 33 32.9 33 32.8	2048.1	3563	32.1 32 31.8 32 31.9	1143.7
OUTENIQUA	*Ariane*	3988	26 25.8 26.2 25.9 26	1036.9	5175	26.2 26 25.9 26.1 26.1	1351.1	5869	32.5 31.9 32 32 32.1	1907.4	4556	30.3 30.4 30.4 29.8 30	1380.5
	Diane	5031	21.5 21 21.1 21.3 21	1081.7	5338	33 32.8 33 32.9 33	1761.5	5663	31.2 31 31 30.8 31	1766.9	4888	23.3 23.1 23.1 23.4 23	1138.9

	Elise	4981	28.2	1404.6	5750	25.5	1466.3	5200	30	1560	4331	28.6	1238.7
			28			25.3			29.8			29	
			28			25.4			30			29	
			28.1			25.7			30			28.8	
			28.3			25			29.8			28.8	
	Viking	5688	28.7	1632.5	6213	29.8	1851.5	5138	32.6	1675	2444	18.8	459.5
			28.6			30			33			19.1	
			28.6			30.1			33			18.9	
			29			30			32.9			18.9	
			29			30			32.9			19.1	

Appendix 5. Raw data of results for Cottonisation experiment reported on Section 3.4.2

Table 1. LOMY results

Bast fibre sample type	Input material (kg)	Scutched mean fibre length (mm)	Fibre Diameter (µm)	Lomy Fibre Preparation			OFDA Analysis Results	
	Sample mass (kg)			Speed (rpm)	Main cylinder position (mm)	% Fibre recovery	Mean fibre diameter (µm)	CV (%)
SA Grown hemp	10	±760	66	680	-40	97	47.4	105.8
			65			98	48.3	104
			67			96	49	106
			66			97	48.4	107.4
			66			97	48	107
French nonwoven grade hemp	10	±600	53.2	680	-40	98	43.7	101.5
			53			98	44.1	102.3
			54			96	43.9	101.9
			54.2			97	44.3	103
			53.2			98	44	104
French bleached sliver hemp	10	±560	40.1	680	-40	99	37.5	96.7
			43			96	38	98
			42			97	38.3	95
			46			97	37.9	97.3
			48			98	38.1	95.8
IDC Flax (light colour)	10	±580	42.1	680	-40	98	28.2	100
			44			97	27.9	97
			45			97	28.3	96
			48			96	28	94.3
			50			98	27.8	98
IDC Flax (grey colour)	10	±575	40.3	680	-40	98	24.6	100.2
			51			97	24.8	98.2
			47			96	25.3	95.7
			46			98	25	99.4
			43			97	25.1	97.9

Table 1. Lin-Star Fine Opener Results

Lynstar Fine Opener Fibre Processing									
Fine opener main cylinder speed (rpm)	***1st pass OFDA Analysis Results***			***2nd pass OFDA Analysis Results***			***3rd pass OFDA Analysis Results***		
	mean fibre diameter (µm)	CV (%)	% Fibre recovery	mean fibre diameter (µm)	CV (%)	% Fibre recovery	mean fibre diameter (µm)	CV (%)	% Fibre recovery
1470 (SA grown hemp)	39.7	102.3	92	38	100.4	93	37.2	99.5	90
	40.3	99	91.8	39	98	94.2	36.3	96	89
	40.8	101.3	92.1	39.2	98	93.9	35.9	97.3	92
	39.8	100.5	91.8	38.9	98.8	94	36.1	96	93
	42.3	100.4	92	39.9	98.7	94	36.5	97	92
1470 (French nonwoven grade hemp)	37.5	98.3	95	36.9	96.8	95	36.1	95.8	93
	38.2	98	95.6	37.1	96.9	94.3	36.5	96	92
	37	96.3	94.5	36.1	95	93.3	35.4	94.1	90
	39.3	97.6	97.3	37.8	95.1	94	37	94.2	91
	38.5	97	98.2	36.3	95.4	95	35.6	95.7	92
1470 (French bleached sliver hemp)	36.1	95.4	97	35.2	95	98	34.8	94.6	98
	38	96.7	95	35.6	94.3	96.2	35	95	95
	37.2	93.3	94.1	35.1	93	93	34.4	91.3	97.3
	35.3	96.7	95.5	33.8	93.6	95	33	92	94.2
	36.7	94	93.8	35.2	92.9	95.3	34.3	92	95
1470 (IDC flax-light colour)	24	89	96	22.1	86	98	21.9	85.2	97
	23.7	96.1	95.4	21.7	89.4	96.8	21.2	87	96.1
	24.9	94.9	94.3	23.5	88.3	95	22.8	86.3	95.3
	23.3	93.8	93	22.6	90	97	22	87.8	94
	24.5	97	96.7	23.1	91.2	95.5	22	90.5	97
1470 (IDC flax-grey colour)	21.2	85.1	97	19	83	98	19	82.1	98
	22	85	97	20.4	83.7	96.7	20	83	97
	21.7	86.1	93.4	20.8	82	95	20.1	81.1	95.5
	22.3	87.3	98	21.2	83.2	96	20.8	82	94
	23	87.3	96	22.1	83.3	96.4	21.6	81.9	97

Table 1. Lin-Star Cottoniser Results

Lynstar Cottonisation Fibre Processing									
Cottoniser speed (rpm)	***1st pass OFDA Analysis Results***			***2nd pass OFDA Analysis Results***			***3rd pass OFDA Analysis Results***		
	mean fibre diameter (µm)	CV (%)	% Fibre recovery	mean fibre diameter (µm)	CV (%)	% Fibre recovery	mean fibre diameter (µm)	CV (%)	% Fibre recovery
2840 (SA grown hemp)	25.4	95.7	85	24.8	91.3	94	24.1	90	93
	25.2	96	89.1	24.9	93	93.2	23.9	92.1	94
	26.1	94.9	90.3	25	92.5	93	24.3	92	92.4
	26	97.1	88.3	24.9	94.2	95.2	24.5	93.2	93
	27.5	97	89	26	95	96	26.1	94.3	93.2
2840 (French nonwoven grade hemp)	24.3	90.3	91	23.1	83.1	94	22.8	82.2	92
	25.2	89.9	92	23.2	84	95	22.6	81.9	92
	24.9	88.7	94	23.8	83.5	94	23.3	80.5	93
	26	88	92	24.5	82	96	23.8	80.9	94
	25.7	89	93	24.9	81.2	94	24.3	80.3	92
2840 (French bleached sliver hemp	22.2	87.5	94	20.9	77.9	97	19.6	69	96
	23	89	94.5	20.3	80.3	96	19.7	74.3	97
	23.3	86.3	94	21.5	80	94	21	72	98
	22.5	87	95	21	81.2	95.6	20.3	73	97.5
	24	87.4	97	22.8	80	96.4	21.4	72.3	95
2840 (IDC flax-light colour)	19	83	96	18.8	82.4	94	18.7	82.1	92
	18.7	85.1	95	18	83.7	95.6	17.6	82.6	93.4
	20.1	84.2	96.4	19.5	83.3	97.4	19.1	82.4	94
	21.7	85.1	95.5	21	83.8	95.4	20.8	83	94
	19.8	87.5	94	19.4	86.4	97	19	85.6	95
2840 (IDC flax-grey colour)	17.6	79	93	17.3	78.4	96	17	78.1	95
	17.9	80.3	96.5	17.2	79.4	95	17	79	95
	18	80.1	94.5	17.6	79.2	96.5	17.2	78.7	93.3
	18.3	81.2	96	18	80.6	96	17.7	79.3	94
	18	80	94	17.6	79.4	95.4	17.4	78.9	95

Appendix 6. List of publication

1. S. Blouw and M. Sotana, 2007, "Performance of four European cultivars cultivated under different agronomic conditions in the Eastern Cape Province, South Africa", Textile for Sustainable Development, Ed, R, Anandjiwala, L. Hunter, R. Kozlowski and G. Zaikov, Nova Publishers.
2. R.D. Anandjiwala and S. Blouw, 2007 "Composites from Bast Fibres: Prospects and Potential in the Changing Market Environment", Jo Nat Fibres, Vol. 4(2), p. 22.

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Chapter 1

PART 1: FIBER PRODUCTION AND PROPERTIES. PERFORMANCE OF FOUR EUROPEAN HEMP CULTIVARS CULTIVATED UNDER DIFFERENT AGRONOMIC CONDITIONS IN THE EASTERN CAPE PROVINCE, SOUTH AFRICA

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ABSTRACT

The purpose of this work was to obtain information on the performance of four European hemp cultivars piloted at four different sites in the Eastern Cape (South Africa), by assessing the fiber content of each cultivar grown under different agronomic experimental design. The southern region of the Eastern Cape is characterized by long day-length periods compared to other regions in south Africa and it should be an ideal area for hemp cultivation in South Africa.

According to the objectives of the project selected hemp straw samples from the four hemp pilot sites were investigated to determine their hemp fiber content. The experimental results gave information about the fiber yield in general and in accordance to the agricultural parameters as documented in the report on "Hemp cultivar adaptation trials in the Eastern Cape" by the Agriculture Research Council – Institute for Industrial Crops ARC-IIC. It also gave an indication of the best performing cultivars of the four piloted in the Eastern Cape Province.

After dew retting the hemp fiber was extracted from the stems using a simple and relatively inexpensive decorticating turbine.

For each hemp cultivar piloted, the fiber yield was objectively evaluated in terms of both the long and short fibers. The relationships between the fiber content of the European hemp cultivars as determined by the agronomic experimental design was evaluated and used to establish the performance of the individual cultivars and how each adapted to the Eastern Cape conditions.

Keywords: European hemp cultivars; decortication; fiber content.

INTRODUCTION

South Africa has a very high level of unemployment, hovering around 36%, and both the National and the Provincial Governments have initiated a number of programmes aimed at creating conditions conducive for stimulating employment creation opportunities [1]. The Eastern Cape Provincial Government identified the establishment of a fiber agro-crop industry, e.g., flax, hemp and kenaf, as one such program that will help revitalise the agricultural potential of the province. Hemp imports (fibers, yarns and fabric) in South Africa for January – November 2003 amounted to close on U$2million [2].

The growing popularity worldwide of this high value cash crop has resulted in great interest in the crop from farmers, agricultural organisations, industries and co-operatives in South Africa. The commercial production of this crop is labour intensive, and has great potential for job creation in rural areas. However, the ethical complexity, limited knowledge and expertise in the production and processing of this crop make it difficult for farmers and other entrepreneurs to benefit from the increasing demand for hemp products.

It is this recognition of the economic opportunities presented by hemp for emerging farmers and industries alike that led to the launch of a pilot initiative for hemp cultivation in the Eastern Cape Province in 1999/2000.

The Agriculture Research Council – Institute for Industrial Crops (ARC-IIC) and the Döhne Agricultural Development Institute were partners responsible for all the agronomic related activities, i.e., experimental design, planting, crop-care, harvesting and retting. For this purpose, four European hemp cultivars, namely; Novodsaska, Felina-34, Futura-77 and Kompolti were used in this research and piloted at four sites in the province.

Retted hemp straw was sent to the CSIR for the determination of the fiber yield of the cultivars grown under different agronomic conditions, in order to evaluate their performance and adaptation to conditions in the Eastern Cape Province. The results of the work are presented in this paper.

DESCRIPTION OF WORK CARRIED OUT

Agronomic Hemp Pilot Trials

The agronomic trials were undertaken on plots located at the two agricultural research stations, i.e., Addo and Döhne as well as at two community sites (Libode and Qamata). At the Döhne research station the experimental trials covered:

spacing and density[1], and
weed control, both using only the Novodsaska cultivar.

The experimental trials at Addo and the two community sites focused on hemp cultivar adaptation and performance when planted a month apart (see table1).

Table 1. Experimental agronomic parameters for hemp cultivar pilot trials in the Eastern Cape Province

Experiment 1. Hemp spacing and density trials at Döhne		
Objective: Determination of optimum row spacing , seeding rate, and population density		
Cultivar	*Spacing factor (cm)*	*Density factor (kg)*
Novodsaska	S1 = 12.5	D1 = 50
	S2 = 25	D2 = 80
	S3 = 55	D3 = 110
Experiment 2: Weed Control trials at Döhne		
Objective : To identify and select suitable herbicide and weed control methods for hemp		
Cultivar	*Treatment*	*Method*
Felina - 34 , Futura - 77 and Novodsaska	Chemical	Accotab, Basagran, Gallant Super, Afolan SC, Diuron, Frontier , and Dual S
	Non Chemical	Weed removal by hand
	Control	No weed removal
Experiment 3: Hemp cultivar adaptation trials Addo, Libode and Qamata		
Objective: To evaluate adaptation of hemp cultivars to Eastern Cape Province conditions		

[1] Density (density factor) means the seed quantity per unit area.

Cultivar	*Seeding rate (kg) / hectare*	*Spacing (cm)*
Felina-34	50	25
Futura-77		
Novodsaska		

Fiber Extraction

Since hemp is a bast fiber crop, with the most valuable fibers contained within the bark of the stem, fiber extraction involves the separation of the bark from the core, a process known as decortication. The fibers were removed using the hemp breaker-scutching unit available at the centre. A random sample of 20 retted hemp stems (figure 1) from each cultivar grown under each of the different agronomic parameters, were weighed and decorticated by the crushing mechanism of the fluted steel rollers of the breaker.

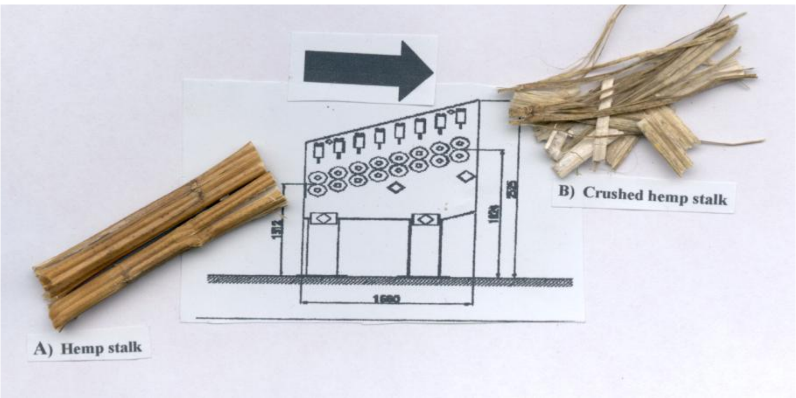

Figure 1. Hemp breaker used to crush retted hemp stems.

After successive cycles of crushing of the retted stems from the same sample, a steel comb was used to remove the plant debris still attached to the fibers. The weight of the sample fibers was then recorded in order to determine the total fiber content.

RESULTS AND DISCUSSION

The results of the total fiber yield of *European* hemp cultivars grown under different agronomic conditions in the Eastern Cape Province to determine cultivar adaptability and performance are given for all the parameter used.

Experiment 1. Hemp spacing and density trial at Döhne

Spacing (S) and seeding rate (D) combination	FibreYield (%)
S1D1 = 12,5cm ; 50kg	23.7
S1D2 = 12,5cm ; 80kg	20.1
S1D3 = 12,5cm ; 110kg	20.4
S2D1 = 25,0cm ; 50kg	19.6
S2D2 = 25,0cm ; 80kg	21.5
S2D3 = 25,0cm ; 110kg	21.2
S3D1 = 50,0cm ; 50kg	23.1
S3D2 = 50,0cm ; 80kg	19.6
S3D3 = 50,0cm ; 110kg	23.1

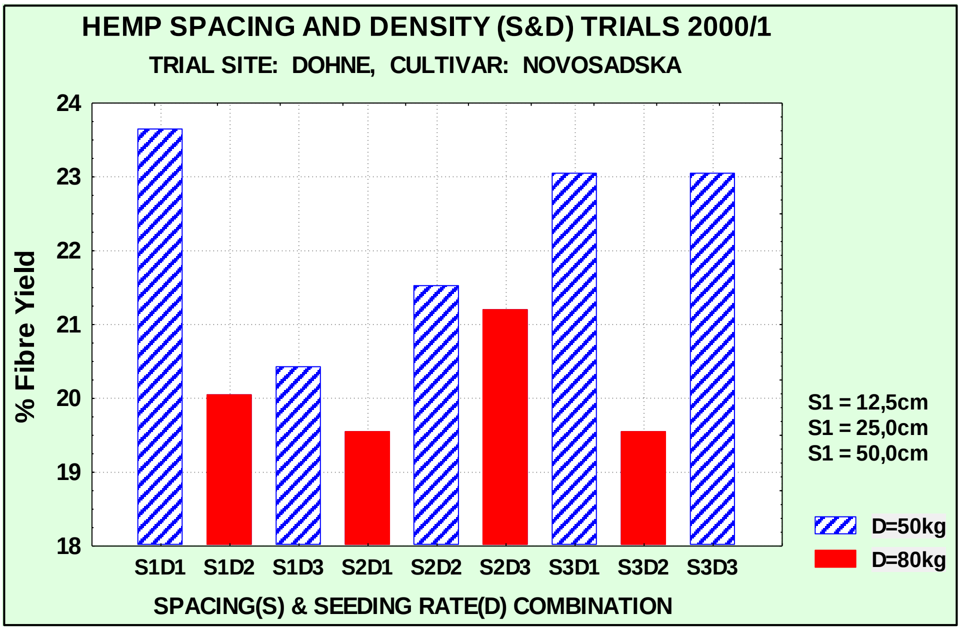

Figure 2. Fiber yield for different hemp spacing and density combinations.

There was a marginal variation in the total fiber yield, ranging from around 19.55 to 23.65% for the same cultivar grown under different spacing and seeding rate. The S1D1 spacing and density combination showed a higher fiber yield compared to the other combinations.

Experiment 2. Weed Control trials at Döhne

Treatment	Fibre Yield (%)		
	Novosadska	Felina-34	Futura-77
Accotab	23.1	22.1	21
Basagran	24.5	21.6	20.3
Gallant Super	25.2	20.1	22.3
Afalon SC	24	20.5	20.6
Diuron	21.3	20.3	22
Frontier	20.7	19.9	20.4
Dual S	21.1	22.6	23.1
Control (weeded by hand)	24.1	22	20.3
Control (no treatment)	22.3	21	21.4

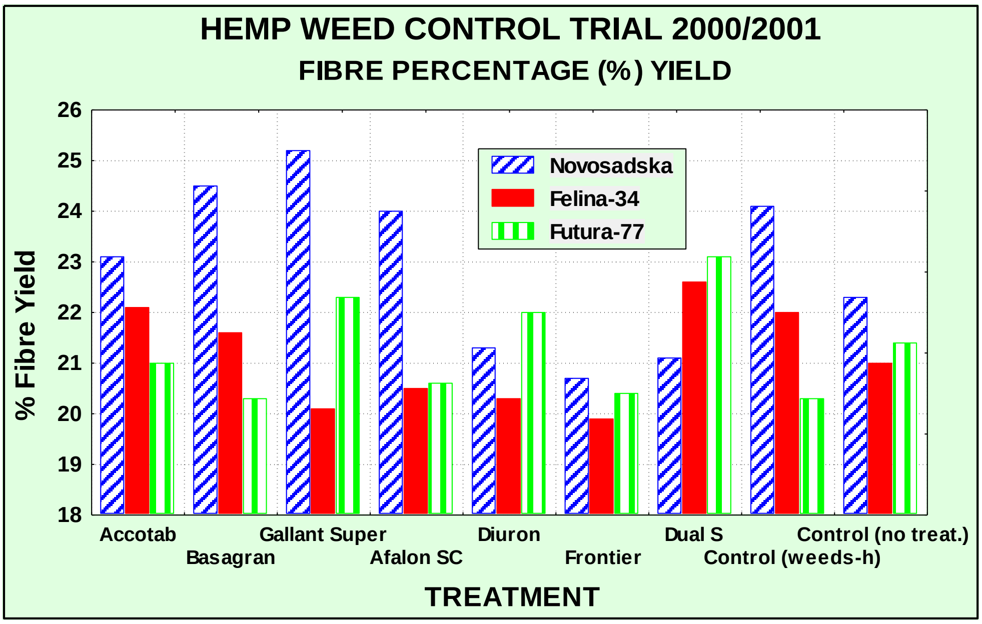

Figure 3. Table and graph on results of hemp weed fiber yield obtained under different control conditions.

The fiber yield of the different hemp cultivars grown under different weed control conditions, i.e., chemical, mechanical and no treatment, ranged from 19.9 to 25.2%. The different cultivars performed as follows:

Novosadska responded positively overall to most of the treatments, except for Diuron and Dual, with the fiber yield ranging from 20.7 to 25.2%.
Felina-34 fiber yield varied from 19.9 to 22.6%
Futura-77 fiber yield varied from 20.3 to 23.1%

These results show no significant difference in the fiber yield of the chemically treated and untreated cultivars. The treatment does not appear to influence the fiber yield of different hemp cultivars relative to the control experiments.

Experiment 3. Hemp cultivar adaptation trials at Addo, Libode and Qamata

HEMP CULTIVAR ADAPTATION TRIALS				
1st planting 2000				
CULTIVAR	Fiber Yield (%)			
	ADDO	DOHNE	LIBODE	QAMATA
Novosadska (Yoguslavia)	24.3	17.7	23.8	24.1
F - 34 (French)	21.8	17.0	23.6	24.3
F - 77 (French)	22.3	19.4	25.0	22.7
Kompolti (Hungarian)	21.1	16.5	25.8	22.7

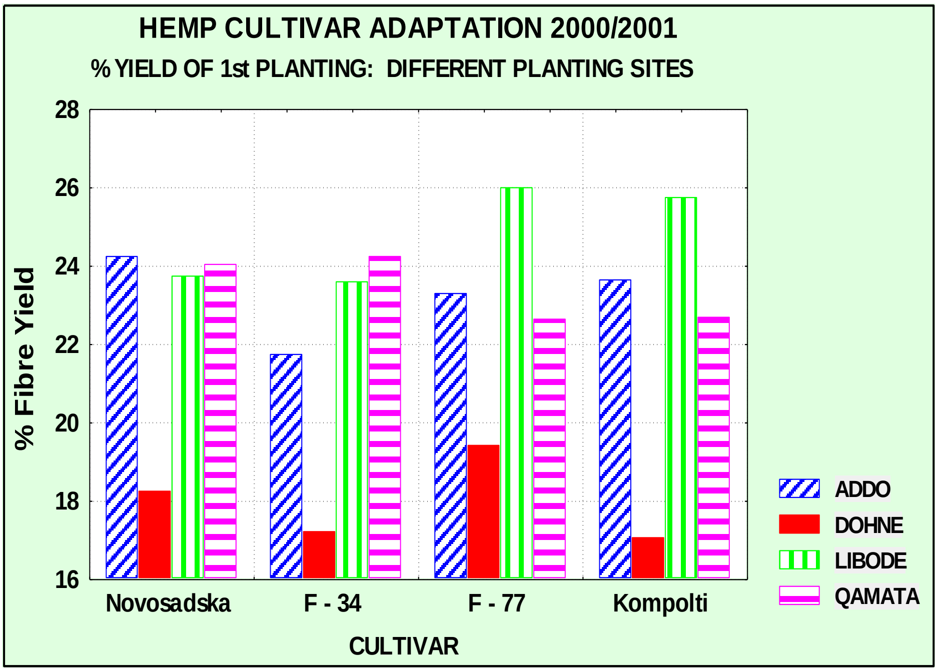

Figure 4(a). Fiber yield during hemp cultivar adaptation trials - 1st planting.

HEMP CULTIVAR ADAPTATION TRIALS (2000/2001)				
2nd PLANTING				
CULTIVAR	FIBER % YIELD			
	ADDO	DOHNE	LIBODE	QAMATA
Novosadska (Yoguslavia)	22.8	17.5	25.0	22.4
F - 34 (French)	19.7	18.5	24.1	23.6
F - 77 (French)	22.4	19.0	25.3	22.4
Kompolti (Hungarian)	22.3	22.6	25.3	23.2

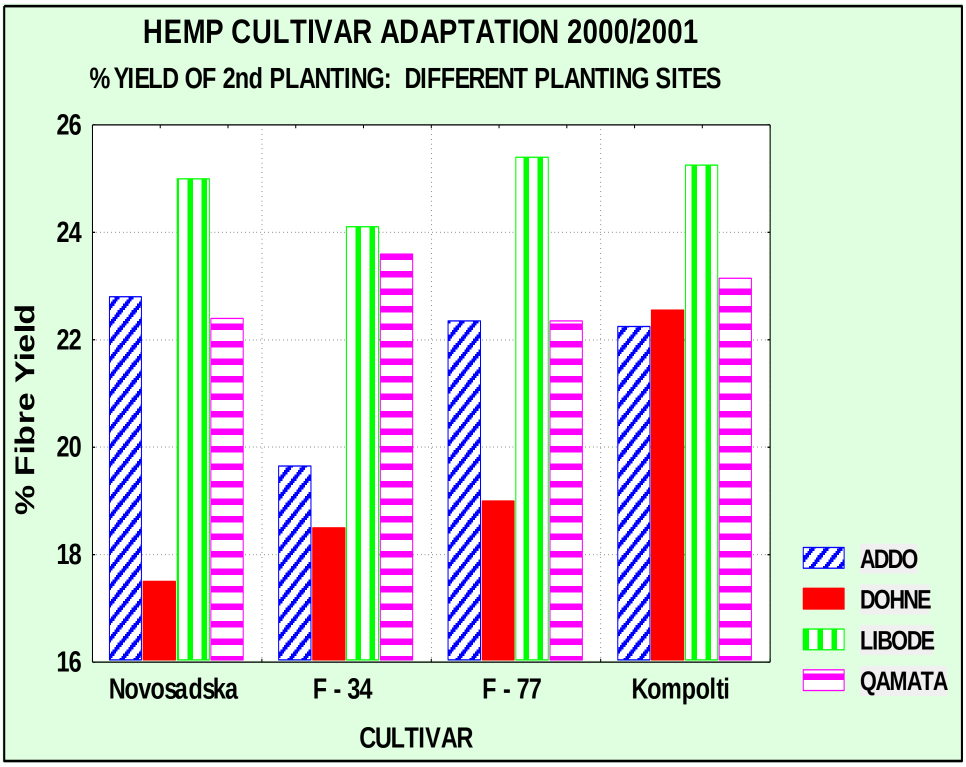

Figure 4(b). Fiber yield results for hemp cultivar adaptation trials – 2nd planting.

A comparison of the effect of different sowing dates, a month apart, on the performance (adaptability) of the different hemp cultivars piloted in the Eastern Cape was made on the basis of the fiber yield which ranged from 16.5 to 25.8.

There were no significant differences in the fiber yield of cultivars grown on the same pilot site but sowed on different dates. The fiber yield results from the Döhne pilot sites were lower for both sowing dates than those of the other three sites, except for Kompolti which performed better with the second sowing date.

Conclusion

The potential to develop a hemp industry in South Africa was investigated by the cultivation of four different cultivars under different agronomic conditions.

This study has shown that:

Hemp can be grown successfully in South Africa, with a fiber yield comparable to that found in other countries.

To achieve a slender hemp straw that will yield a high fiber yield using minimum spacing and density combinations thereby resulting in an easy decortication process, the spacing and density combination found to be appropriate was 12,5cm and 50kg respectively.

The application of herbicide did not cause any improvement in the fiber yield when compared to the untreated control.

The most appropriate time of the year for the cultivation of hemp in the Eastern Cape Province is October – November.

FURTHER WORK

Further research on the best farming practices for the cultivation of hemp, i.e., crop care, harvesting method and retting process by the agricultural research partners continues. Other cultivars sourced from different parts of the world will be evaluated in terms of their suitability for cultivation in the province and country.

The CSIR will continue to evaluate the fiber properties (physical and chemical) of the different hemp cultivars as well as undertaking product developmental via different spinning and nonwoven technologies.

ACKNOWLEDGEMENTS

The work reported has been undertaken as part of a wider investigation into “Feasibility of cultivation of hemp in the Eastern Cape Province” championed by the National Hemp Foundation consisting of the following partners:

- Agriculture Research Council-Institute of Industrial Crops, Rustenburg, for all activities related to agronomic research.
- Döhne Agricultural Development Institute, Eastern Cape Provincial Department of Agriculture, Stutterheim, for providing research and extension services for this initiative as well as supplying the CSIR with samples of hemp straw for fiber yield evaluation.
- The Eastern Cape Provincial Department of Economic Affairs, Environment and Tourism, for supporting this initiative.
- The communities of Qamata and Libode for their enthusiastic labour as well as providing security to prevent crop theft from the pilot sites.
- The CSIR for investing research funds in this research work and for fiber evaluation.

REFERENCES

1. Statistics South Africa, Labour Force Survey, March 2005
2. Booth, I; Harwood, R.J; Wyatt, J.L; Grishanov, S. A Comparative Study of the Fibre Characteristics of Fibre- Flax (Linum usitatissimum), De Montfort University, 2002.
3. Müssig, J; Martens, R. Quality Aspects in Hemp Production – Influence of Cultivation, Harvesting and Retting, *Journal of Industrial Hemp,* 2003, 8, Number 1,
4. Kaniewski, R; Konczewicz, W; Cierpucha, W. New Trends in Harvesting, Processing and Utilizing Hemp, *Natural Fibres,* 2000, XLIV.
5. Shekhar Sharma, HS; Van Smere, CF. The Biology and Processing of Flax, M Publications, Belfast.
6. Garcia-Jaldon, C; Dupeyre, D; Vignon, MR. Fibres from Semi-Retted Hemp Bundles by Steam Explosion Treatment, *Biomass Bioenergy*, 1998, 14, 251-260.
7. Kautto, K; Hakkarainen, E; Pasila, A; Pehkonen, A. Harvesting and Processing of Fibre Hemp, *Publication Agricultural Engineering,* 2001, 31, University of Helsinki.
8. Sankari, H.S. Comparison of Bast Fibre Yield and Mechanical Fibre Properties of Hemp (Cannabis sativa L) cultivars, *Industrial Crops and Products,* 2000, 11, 73-84.
9. ARC, CSIR, DALA, Progress Report on Hemp Research 2000/2001, National Hemp Foundation – a report, 2001
10. Mankowski, J; Rynduch, W. Cottonized Hemp Fiber as a Component of Blended Yarns, Proceedings of the 4th European Workshop on Flax, Rouen, 1996.

COMPOSITES FROM BAST FIBRES - PROSPECTS AND POTENTIAL IN THE CHANGING MARKET ENVIRONMENT

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ABSTRACT

Composite materials reinforced with natural fibres, such as flax, hemp, kenaf and jute, are gaining increasing importance in automotive, aerospace, packaging and other industrial applications due to their lighter weight, competitive specific strength and stiffness, improved energy recovery, carbon dioxide sequestration, ease and flexibility of manufacturing and environmental friendliness besides the benefit of the renewable resources of bast fibres. The market scenario for composite applications is changing due to the introduction of newer bio-degradable polymers, such as PLA synthesized from corn, development of composite making techniques and new stringent environmental laws requiring improved recyclability or biodegradability for industrial applications where stress bearing capacities and micro-mechanical failures dictate serviceability. Bast fibre reinforced composites, made from bio-degradable polymers, will have to compete with conventional composites in terms of their mechanical behaviour. Bio-composites, in which natural fibres, such as kenaf, jute, flax, hemp, sisal, corn stalk, bagasse or even grass are embedded in a biodegradable matrix, made as bioplastics from soybean, corn and sugar, have opened-up new possibilities for applications in automotive and building products. Obviously, new approaches to research and development will be required to improve their mechanical properties, such as tensile, bending and impact resistance to match their performance and commercial competitiveness against petroleum based products. The research community has to look at the various possibilities of combining natural fibers, such as sisal, flax, hemp and jute with polymer matrices from non-renewable and renewable resources to develop cost effective biocomposites. This paper will review the newer products and techniques that can improve the properties of bast fibre based composites as well as potential structural and non-structural applications which can increase their market share.

Key Words: Fibre-reinforced composite, biodegradable, natural fibres, bast fibres, hemp, flax, kenaf, particle boards, automotive components, biocomposites, thermoset, thermoplastic.

INTRODUCTION

A *composite material* is a heterogeneous combination of two or more different constituents (reinforcing elements, fillers and binders), differing in form or composition on a macroscale. The combination results in a composite material that maximizes specific performance properties not attainable in the individual constituents. The constituents do not dissolve or merge completely and therefore normally exhibit an interface between one another.

The fierce competition in the fibre reinforced composites market has compelled the manufacturers to be innovative, adopt newer production techniques, utilize cheaper resins and fillers while maintaining performance in terms of strength, temperature resistance, fracture and resilience. Essentially new products are developed for existing and newer applications by utilizing different fillers and combinations of fillers and reinforcements. Traditionally, most synthetic fibres, such as carbon, E-glass, boron, aramid, and Kevlar, have been widely used as reinforcing medium in composites. For example, commonly used resins include polypropylene for automotive applications, such as air cleaner housings, nylon for transmission gears, polyphenylene sulphide (PPS) for electrical components, polycarbonate (PC) for household applications, polyethylene, and polyethylene ethyl ketone (PEEK) for flexible circuit boards. Due to the increased pressure from environmental activists and attendant stringency of laws passed by most developed countries, the composite manufacturing industry has to search for plant based natural fibre reinforcements, such as flax, hemp, jute, kenaf, sisal, henequen, pineapple, and banana. Therefore, accelerated development efforts have taken place over the past two decades in the field of natural fibre based composites.

The market for fibre-reinforced plastics has increased in leaps and bounds over the past four decades. Almost 1.0 billion kilograms of reinforced composites were produced worldwide in 2002 and the market is forecast to increase by some 3.5% per annum, with the production reaching about 1.2 billion kilograms, with a value of US$ 6.5 billion in 2007. Figure 1 shows the distribution of the market for fibre – reinforced composites according to application (Business Communication Company, Inc., 2002).

[Insert Figure 1 Here]

Automotive, construction, marine and electronic applications account for the major proportion of composites. Thermoset composites account for about 62% of the total volume produced in 2002 and it is expected to dominate over fibre-reinforced thermoplastic composites despite the popularity of the latter due to their recyclability. Long-fibre thermoplastic composites and nanocomposites are likely to play an increasingly important role in the coming years, as research and development will mature (Business Communications Company, Inc., 2002).

To strike a balance between cost, quality, performance, environmental regulations and supply of natural fibres, such as, flax, hemp, jute, kenaf and sisal, a number of composite manufacturers are developing new facilities for utilizing alternative fibres (Karnani et al, 1997; Marsh, 2003). To augment the resource driven approach and strategy for finding new applications for the available natural fibres, the automotive industry has taken the leadership. The automotive sector requires reasonably durable materials which must biodegrade at the end of their service life. Reinforced composites made from lingo-cellulosic plant materials offer attractive opportunities because of their strength resulting from the strength of fibre bundles. The applications of such bast fibre reinforced composites in load bearing components as opposed to conventional composites based on wood fibre may turn out to be one of the material revolutions of the twenty first century (Rowell, et al, 1998).

The advantages and disadvantages of natural fibre reinforced composites may be listed as follows:

Advantages:

- Reduction in density of products from 10-30% in comparison to conventional metallic parts.
- Acceptable specific strength, toughness and stiffness in comparison to glass fibre reinforced composites.
- Ease of shaping into complex shapes in a single manufacturing process.
- Reduced tool wear.
- Most thermoplastic based natural fibre reinforced composites are recyclable and they are earth friendly as a sustainable renewable raw material is utilized.
- Lower energy consumption from fibre growing to finished composites, in comparison to synthetic and glass fibre based composites. For example, very high thermal energy is required during spinning of synthetic fibres.
- Bast fibres are CO_2 neutral as oxygen is emitted back into the environment during degradation. The possibility of thermal recycling in contrast to the combustion process for glass fibres make them environmentally friendly.

- The manufacturing processes are relatively safe when compared to glass fibre based reinforced composites. The glass fibres emit small airborne glass particles during manufacturing, thus causing the problem of occupational safety.
- Reduced dermal and respiratory irritation.
- Possibility of recycling the cuttings and wastage produced during manufacturing and moulding.
- No emission of toxic fumes when subjected to heat and during incineration.
- The production of natural fibres can be started with a low capital investment and with a lower cost, thus offering great potential to poor and developing nations for the generation of employment.
- Bast fibres exhibit good thermal and acoustic insulation properties.

Disadvantages:

- Lack of consistency of fibre quality, high level of variability in fibre properties depending upon source and cultivars.
- Preparation of fibre is labour intensive and time consuming.
- Poor compatibility between the fibres and matrix which requires surface treatment of fibres.
- Lower impact strength of bast fibre reinforced composites.
- High moisture absorption which brings about dimensional changes in composite materials.
- Poor fire resistance which restricts applications where risk due to fire is possible. Fire retardants have to be bonded to the fibre cell wall to improve the fire resistance of the composites.

- The availability of suitable fibres is uncertain and supply is rather irregular. The uncertain of supply is sometimes influenced by national agricultural policy and politics.
- Low density of bast fibres can be disadvantageous during composite processing application because fibres tend to migrate to the surface rather than getting mixed with the matrix.
- Fluctuation in price depending upon the global demand and production.
- Problem of storing raw material for extended time due to possibility of degradation, biological attack of fungi and mildew, loss in colour, and foul odour development.
- Lower resistance to ultra violet radiation, which causes the structural degradation of the composites.

FIBRES FOR COMPOSITES

The compatibility between polymers, fibre surface, and composite manufacturing processes employed will determine the properties of composite materials. Important natural plant materials used in composite materials is classified in Figure 2.

[Insert Figure 2 Here]

Wood fibres have been traditionally utilized in some composite applications as they are uniform, inexpensive and abundant; nevertheless, they are very short which limits their reinforcing ability. Bast fibres alone account for some 4 million tons of global fibre production and represent a vast and sustainable raw material source. Other natural fibres from leaf (sisal, banana, palm, pineapple) and seed (cotton, coir, kapok) of plants are also utilized as reinforcement in composite materials; however, they are out of the scope of the present paper. The physical, mechanical and chemical properties of major bast fibres, as well as the widely used E-glass fibre, are compared in Table 1.

[Insert Table 1 Here]

The bast consists of a woody core surrounded by a stem. The stem consists of a number of fibre bundles, each containing individual fibre cells or filament like fibres. Chemically, the fibres are made of cellulose and hemicellulose and they are bonded together by a matrix containing lignin or pectin. The pectin surrounds the bundle of fibres and bonds it to the stem. The pectin is removed during the retting process which enables the separation of fibre bundles from the rest of the stem.

From Table 1 it is evident that the density of glass fibres is higher than all the bast fibres. The tensile strength of all bast fibres is lower than that of glass fibre, nevertheless, the elastic modulus, E, of hemp and flax fibres is comparable to that of glass fibre. Due to the lower density of bast fibres, their specific strengths are comparable to that of glass fibre. The dimensional properties of bast fibres are highly variable due to their natural origin, retting process and fibre separation techniques employed. The moisture absorption of bast fibres is far higher than that of glass fibre which is somewhat disadvantageous in certain composite manufacturing processes. Special pre-treatments are required to control the moisture during the composite manufacturing processes.

COMPOSITE PROCESSES

The applications of bast fibres in composites include particle boards, automotive components, electronic circuit boards, household appliances and packaging products. Most of these applications involve compression moulding technology in which usually medium to long bast fibres in the form of nonwoven mat or felt are used. Compression moulding was specifically developed with a view to replace metal components with composite parts. The moulding process can be carried out with either thermosets or thermoplastics. However, most applications today use thermoset polymers and in fact, compression moulding is the most common method of processing thermosets (El-Sheikh et al. 1997).

As natural fibres do not possess thermoforming properties the addition of polymer as binder is necessary. The composite can be formed by coating, impregnating or compounding the bast fibres with polymer and then setting/curing the matrix to form a solid material which can be moulded into the desired shape. The process employed is dependent upon the type and characteristics of the polymer. Thermoplastic polymers, such as polypropylene, polyester and their bi-components are used for thermoforming the natural fibres. In the thermoset process, the natural fibre mat or fabric is coated or impregnated with epoxy resins or polyurethane. It is then moulded into the desired finished products. All bast fibres, such as flax, hemp, jute and kenaf, can be used to produce thermoset or thermoplastic moulded components using compression moulding techniques.

Injection moulding is the process in which the polymer matrix is reinforced with short natural fibres in the desired proportion. A hot, molten polymer is injected into a cold mould. A screw apparatus, either a single or twin screw type, is used to inject the polymer into the mould. After the mould cools and solidifies, it is opened and the part is ejected. The short bast fibres are compounded with a polymer, such as polypropylene, and then also extruded into granules for subsequent injection moulding (Karmaker and Youngquist, 1996).

Pultrusion technology for making bast fibre based composite is gaining very wide acceptance these days. Bast fibres can be easily converted into strands and cords due to their spinnability. Pultrusion technology can utilize the thread-like material to form the reinforced composite. Pultrusion is a continuous process for manufacturing composites that have a constant cross-sectional shape. The basic process usually involves pulling continuous fibres — reinforcing material — through a resin impregnation bath containing catalyst and then into pre-forming fixtures where the section is partially pre-shaped and excess resin is removed. It is then passed through a heated die, which determines the sectional geometry and finish of the final product (Mittal and Biswas). The primary reinforcement in pultrusion is in the longitudinal fibre direction whereas in filament winding it is in the hoop direction. These materials are generally used in structural applications. Commonly used reinforcements in pultrusion are glass, carbon and aramid fibres. The matrix material must cure quickly, not only because of the high speed of material production but also because it is a continuous process. The technology can be employed for developing high end structural composites from bast fibres as substitutes for man-made fibre based materials (Richardson and Zhang, 2001).

OPPORTUNITIES FOR BAST FIBRES

Bast fibre based composites may offer a profitable return if the selection of raw materials; both fibre grade and polymer, utilisation of the right manufacturing technique in view of the end-use characteristics, and right strategy of value addition through performance improvement features are employed judiciously. The development of new markets by offering products with improved properties, and substituting the existing glass fibre based products by bast fibre based composite can offer opportunities. Major products from bast fibres are summarised here below:

- Particle boards and fibre boards (composite lumber)
- Automotive Components
- Housing and infrastructure products
- Bio-composites

Particleboards and Fibreboards:

Particle and fibre boards constitute major applications of bast fibre based composite materials. In conventional wood based boards, the waste wood or wood chips mixed with saw dust are mixed with phenolic resins and then pressed between two hot plates. Subsequently they are subjected to grinding and polishing for finished products. Low, medium and high density fibre boards are made depending upon the end-use requirement. Hemp, flax, kenaf, either alone, or with other cellulosic waste, such as wood chips and dust, are most widely used with the appropriate binders. Traditionally, isocynate and melamine are the best and the most cost-effective binders for bast fibres and woody matters which provide adequate strength and performance for most exterior applications. Since isocynate releases no formaldehyde during manufacturing and use, which makes it safe. Considerable recent research on binder, the use of inexpensive core of bast as substrate and the improved adhesion with substrate due to pre-treatments, has reduced the cost to make them economically attractive and thus viable.

However, such composite boards are susceptible to destruction due to fire and therefore their use can be limited particularly in public and high-rise buildings. The application of special fire retardant coatings is required to make them non-ignitable. A number of studies have been reported in which fire retardant chemicals, mineral particles as fillers and non-flammable binders are added during the production process (Kozlowski et al, 1999). In this research, a three-layer non-flammable composite particle board, based on lignocellulosic particles and mineral filler, was used with urea – formaldehyde resin as a binder (Kozlowsky et al, 1999). These authors have reported production technologies for making such boards and have produced non-flammable boards with sufficient strength and durability. The technique can be used for raw materials, such as wooden particles, bast fibres and shives (Kozlowski et al, 1999). This research group further developed fire resistant upholstery using fire-retardant flax nonwoven. The non-woven used in the composites plays the role of fire barrier which reduces the vulnerability of the filling material to the development and spread of fire (Kozlowski et al, 2004). In a recent study, encompassing many applications, the flame retardancy of biodegradable polymers and biocomposites was investigated. For comparison, flame retardant ligno-cellulosic fiber reinforced biocomposites were prepared using polypropylene (PP), polyurethane (PUR) and fully biodegradable starch matrices. The phosphorus additives in flame retardant polyurethane biocomposites comprising waste bio-fillers and recycled polyol proved to be very effective because both the matrix and the filler components contribute towards the mechanism of flame retardancy (Matkó et al. 2005).

In another interesting study, it was reported that hemp fabric treated with flame retardants showed a high limiting oxygen index and char yield which indicated that the flame retardancy of treated hemp was improved (Xu et al. 2002).

The use of alternative binders arises from the market demand to reduce the cost of the product and comply with newer environment laws. Lignin, a natural binder in plant materials, is also offering potential in developing completely bio-based fibre boards. However, this approach has achieved limited success to date. Other bio-based binders, such as soybeans based adhesives and resins derived from natural source, are under study currently.

The economic viability of bast fibre based particle and fibre board is yet not well established due to their cost of production. The raw material is relatively expensive in comparison to conventional wood based particle boards. The technical feasibility conducted by various researchers on the use of bast fibres, such as kenaf, hemp and flax, in furnishing-based panel and particleboards applications indicate that bast fibres can either supplement or replace conventional wood, provided products are planned to exploit their special properties, such as strength and toughness (Marsh, 2003; Lloyd and Seber, 1996).

Automotive Components:

Automotive components offer unprecedented opportunities for bast fibres. During the past 10 years the use of natural fibre composites in automotive interior components has increased in leaps and bounds. Due to the availability of different manufacturing technologies and the proximity of raw materials in Europe, hemp and flax fibres are utilized in such applications. Jute, grown in sub-tropical regions, such as India and Bangladesh, and Kenaf in

USA are also now-a-days utilized in automotive components. Decorticated bast fibres, such as flax, hemp, jute and kenaf, are particularly suitable as reinforcement for polymeric resins, thermoplastic and thermoset composites, most prevalent in automotive components. The rapid increase in bast fibre based composites in automotive industries is also attributed to the production of lighter and fuel efficient cars, the requirement for reduced air pollution and the difficulty associated with recycling glass, carbon, and aramid fibre reinforced composites from polyester, epoxy and similar resins, besides the high level of energy expended in the entire value-addition chain. One ton of natural bast fibres require only 12% of the energy required to produce the equivalent amount of glass fibres (Marsh, 2003).

A logical beginning should be to utilize easily available recyclable resins, such as, polypropylene, polyolefin, polyethylene, polyamide and polyurethane, in combinations with biodegradable plant fibres. Thanks to high production nonwoven technologies that can provide nonwoven mat or felt at relatively low price. The nonwoven mat can be produced by the most prevalent needle-punching or air laying or hydroentanglement technology. The compression moulding technology can be utilized with appropriate binders to make thermoset or thermoplastic composites. Nonwoven mat from hemp fibres as reinforcing medium in phenolic resin have been studied (Richardson and Zhang, 2001). The introduction of two layers of nonwoven fabrics into resin improved the panel flexural strength from 11 MPa to 25 MPa and stiffness by 23%. The impact resistance of phenolic resin without reinforcement is quite low due to its brittleness, the addition of hemp as reinforcement improved it markedly due to transfer of impact force from matrix to fibres. The introduction of bast fibre based mat in also reduces the number and size of voids formed due to curing of thermoset attributed to the hydrophilicity of bast fibres which absorbs moisture produced by the curing (Richardson and Zhang, 2001).

The applications of bast fibre reinforced composites in automobiles is so far limited to interior items, such as door panels, inner trim parts, parcel compartments, shelves, headliners, and roof liners, where conventional glass fibre and synthetic fibre based composites far exceed the strength requirements for such applications. This provides a great opportunity for bast fibres as more and more vehicle manufacturers are recognising their cost-benefit advantage and the need to comply with new recycling legislations.

The major drawback of a bast fibre reinforced composite is its poor impact strength, although the properties of bast fibre reinforced composites from thermoplastic and thermosetting resins have proved to be adequate in non- and semi-structural applications, research aimed at improving their impact strength will be very useful for developing structural applications. This requires research on interfacial properties to improve impact strength. Pre-treatment of bast fibres before the composite making process is a key to improve interlaminar strength. For example, in a recent study a treatment of bast fibres with alkali and diluted resin improved adhesion between fibres and epoxy interlaminar strength almost by 100%. Recent invention specifically overcomes past difficulties involving compounding and injection moulding of composite specimens with bast fibre reinforcements. In one form, ultrasonic energy is applied to decorticated bast fibres to cause fibrillation which improves their adhesion to polymer matrix (Krishnaswamy, US Patent No: 6767634, July 27, 2004).

Housing and Infrastructure Products:

Housing and infrastructure applications require structural composite materials and the use of natural fibres based composites can play an important role in this segment as new emerging materials. The construction industry accounts for almost 32% of the total demand for reinforced composites today. It is important that better and affordable houses are built from ‘green’ materials to reduce the impact of erosion of trees for ecological and climatic conditions. For 21st century housing affordable alternative materials are needed and researchers are focused on biobased structural composite materials. The manufacturing technologies leading to the hybridization of different constituents, such as fibre reinforced composite and biobased plastic, at structural levels can help (Drzal et al., 2001, Riedel and Nickel, 1999).

Conventional fibre reinforced plastic, whether from natural or petroleum origin, are not suitable for load bearing housing applications due to their low strength, low bending resistance, low thermal stability and poor dimensional stability. Polyester is the most widely used material in composites for the housing industry. Natural fibres and polyester fibre based nonwoven mats in the proportions of 90% and 10%, respectively, have been tried as reinforcement in unsaturated polyester resin. Blends of unsaturated polyester resin and vegetable oils were also tried as the matrix in a 30% by volume fraction of the reinforcing medium. The mechanical and thermal properties were far superior to conventional petroleum based composite systems (Drzal, 2001). Performance of wood-based or fibre based composites can be improved by suitable chemical modification techniques to modify fibre properties, such as surface characteristics, dimensional stability, resistance to biological and ultraviolet exposure and resistance to chemicals. It can be also treated with conventional fire retardants to improve its fire resistance (Rowell, 1995).

Plant fibres are used as reinforcing medium in the production of cement based composites. The wood fibre reinforced products are widely used as they offer the high tensile strength, impact resistance and workability of wood with the fire resistance, durability, dimensional stability and weather resistance of cement based materials. Research in utilizing alternative fibres and new processes continues to develop cement-based composites with a view to offer balance of performance and aesthetic characteristics at competitive cost for low cost housing (Olesen and Plackett, 2002).

Bio-composites:

The regulatory pressures generated by the recent end-of-life of vehicles (ELV) laws of the European Union require the automotive manufacturers to ensure that all new vehicles are 95% recyclable by 2015. This new regulation has placed serious responsibilities on the automobile manufacturers to be the front-runners in developing new biodegradable composites. Conventional thermoplastic resins, such as polypropylene, polyolefin, polyethylene, polyurethane and polyamide, are the most widely used in fibre reinforced composites; however, they are recyclable but not biodegradable. The composite matrix is very stable and poses considerable problems with respect to reuse or recycling after the product has reached the end of its service life. A simple landfill disposal is becoming unacceptable in view of increasing environmental awareness. To comply with new stringent laws require new strategies for developing composites from natural reinforcing medium and polymeric matrix also derived from natural materials, say plants (Riedel and Nickel, 1999; Drzal, 2001; Marsh, 2002).

Biocomposite products are now commercially produced made from 100% biobased raw materials, both for reinforcement and as polymer. Thermoplastic biopolymers available include polylactic acid (PLA), poly hydroxyl alkanoate, Cellulosic Plastic and Starch Plastic, soybean and corn based polymer resins. Some of these biopolymers have properties similar to petroleum based thermoplastic resins, such as polyester, and they are on their way to full-scale commercialization. New soybean and corn-based polyurethane-type resins are used in making a composite called HarvestForm™[1] having adequate strength, flexibility, corrosion resistance and endurance and being 25% lighter than steel. The composite panels produced by means of this technology are being tested in various agricultural machinery of the company. The research on developing low and high performance polyurethanes from soybeans is

[1] Registered trademark of John Deere and Co.

continuing and multidisciplinary programme encompassing genetic engineering, composite manufacturing and soy-based liquid moulding is underway at the University of Delaware, USA. Researchers have produced full biocomposites incorporating natural bast fibres. However, the success of these biopolymers in the fibre reinforced composite market will be dependent upon the possibility to achieve their chemical modifications and ease of processing besides their ability to provide the required toughness and strength in the final products.

Cellular biocomposite cores fabricated from industrial hemp or flax fibres with unsaturated polyester were hybridized with woven jute, chopped glass, and unidirectional carbon fabrics. Material characterization showed improved stiffness, strength, and moisture-absorption stability, while flexural tests on laboratory-scale demonstrated improved structural behavior. These hybrid cellular biofiber-based composites were found to provide an economic and environmentally friendlier alternative to entry-level synthetic composites (Burguen˜o et al. 2005)

Scientists at the Affordable Composites from Renewable Resources (ACRES) program at the University of Delaware in USA investigated the mechanical properties of glass/flax hybrid composites based on a novel modified soybean oil matrix material. Composites with different ratios of glass/flax fibres and different fibre arrangements were prepared using a modified soybean oil based matrix. The fibre arrangement was varied to make symmetrical and unsymmetrical composites. The latter were tested in different modes in flexural and drop weight impact tests. The mechanical properties of the composites were found to depend upon the ratio of glass to flax fibres and the arrangement of fibres in the composite. On proper selection of the arrangement of fibres in the composite, the glass fibres and flax fibres were found to act synergistically resulting in an improved flexural and impact resistance (Morye et al. 2005).

The success of bast fibre reinforced biocomposites will be dependent upon appropriate processing techniques, modification of fibres to improve the adhesion between fibre and the biopolymer, matrix modification and after treatment to improve performance. Maybe, hybrid biocomposites, containing a high proportion of natural bast fibres and only a small proportion of glass fibres (~ 6%), may offer near term solution while research on 100% biocomposite matures and resolves some of the outstanding problems related to their mechanical properties and dimensional stability (Mishra, 2003).

Future Research Directions:

- Research effort should mainly be directed to the improvement of the interfacial properties between the fibre and the matrix. The surface treatment of fibres can improve adhesion between two different constituents (phases), thereby improving the mechanical properties, fracture and fatigue performance.
- New methods of fibre extraction should provide more elemental and technical fibres for effective embodiment into composite matrix.
- Further exploitation of nonwoven technologies, both in terms of fibre laying and web bonding.
- Composites, resins and adhesives made from renewable resources should be developed. Search for new and improved bioresins to replace standard petroleum based resins should be continued to fully meet with future environmental goals. Multidisciplinary research, involving agricultural, biotechnology, polymer and composite manufacturing aspects should be carried out.
- Composite manufacturing technologies should be refined and made suitable for the new bioresins.

- A paradigm shift with respect to the concept of biodegradability should be thoroughly researched; the research should be directed to 'triggered' biodegradability. The biocomposite should start degradation only in the presence of certain triggers to control and initiate the process of biodegradation. This research will have two advantages, namely, preventing the degradation of the product during use, thus preserving essential properties until the end of the product's useful life and thereafter allow accelerated degradation of the product for quick disposal.
- In the light of the current trend on nanocomposite, research efforts should be directed to derive nanofibres and whiskers from bast fibres and other lignocellulosic materials. This will help in incorporating natural fibres in nano-clays.

REFERENCES:

Burguen˜o, R., Quagliata, M.J., Mohanty, A.K., Mehta, G., Drzal, L.T., Misra, M., Hybrid biofiber-based composites for structural cellular plates, Composites: Part A 36, 581, 2005**.**

Business Communication Company, Inc., RP-178 Composites: Resins, Fillers, Reinforcements, Natural Fibres and Nanocomposites, Report, September 2002.

Centre for Lightweight Structures, TUD - TNO, Netherlands, the Project on Natural Fibre Composites from Upholstery to Structural Components. www.clc.tno.nl

Drzal, L.T., Mohanty, A.K., and Mishra, M. Biocomposites From Engineered Natural Fibres For Housing Panel Applications, National Science Foundation Partnership for Advancing Technologies in Housing (NSF-PATH), 2001. Award No: 0122108.

Drzal, L.T., Mohanty, A.K., Bugueno, and Mishra, M., Biobased Structural Composite for Housing and Infrastructure Applications: Opportunities and Challenges, Pre-publication Communications. Source: www.pathnet.org/si.asp?id=1076

Ellison, G.C., and McNaught, R., The Use of Natural Fibres in Nonwoven Structures for Applications as Automotive Component Substrates, Report Ref. No. NF0309, February 2000, MAFF – Industrial Materials, U.K.

El-Sheikh, E., Penney, C., Liu,R., Kamel,A., McCullough, R., Sticklen, J., Leveraging Computer Technology for Training in Liquid Molding, Technical Reinvestment Project, Source : islnotes.cps.msu.edu/domsite/PubsPres/ISLPubs.nsf, 1997.

Karmaker, A.C. and Youngquist, J.A., Injection Moulding of Polypropylene Reinforced with Short Jute Fibres, J. Applied Polymer Science, Vo. 62, 1147-1151, 1996.

Karnani, R., Krishnan, M., and Narayan, R., Biofibre-Reinforced Polypropylene Composites, Polymer Engineering and Science, Vol. 37, No. 2, 476-483, 1997.

Lloyd, E.H. and Seber, D., Best Fibres Applications for Composites, BioComposite Solutions, WA, USA.

Kozlowski, R., Mieleniak, B., Helwig, M., and Przepiera, A., Flame Resistant Ligno-cellulosic-mineral composite particleboards, Polymer Degradation and Stability, Vol. 64, 523-528, 1999.

Kozlowski, R., Muzyczek, M., Mieleniak, B., Journal of Natural Fibers, Upholstery Fire Barriers Based on Natural Fibers, Journal of Natural Fibers, Vol.1, 85, 2004

Marsh, G., Next Step for Automotive Materials, Materials Today, Elsevier Science Ltd., April 2003, pp 36-43.

Matkó, S., Toldy, A., Keszei, S., Anna, P., Bertalan, G., Marosi, G., Flame retardancy of biodegradable polymers and biocomposites, Polymer Degradation and Stability 88, 138, 2005.

Mishra, S., Mohanty, A.K., Drzal, L.T., Misra, M., Parija, S., Nayak, S.K. , and Tripathy, S.S., Studies on Mechanical Performance of Biofibre/Glass Reinforced Polyester Hybrid Composites, Composite Science and Technology 63: 1377-1385, 2003.

Mittal, A., Soumitra, B., Pultrusion of Composites - An Overview, News and Views, Source: www.tifac.org.in/news/pultr.htm, 2004

Morye, S.S., Wool, R.P., Mechanical properties of glass/flax hybrid composites based on a novel modified soybean oil matrix material, Polymer Composites, 26, 407, 2005.

Narayan, R., in Emerging Technologies for Materials and Chemicals from Biomass, Rowell, R.M., Schultz, T.P., and Narayan, R. (Eds.), ACS Symposium Series, 476, 1992.

Olesen, P.O. and Plackett, D.V., Perspectives on the Performance of Natural Plant Fibres, Plant Fibre Laboratory, Royal Veterinary and Agricultural University, Copenhagen, Denmark, 2002.

Richardson, M. and Zhang, Z., Nonwoven Hemp Reinforced Composites, Reinforced Plastics, Vol. 45, April 2001.

Riedel, U. and Nickel, J., Natural Fibre-reinforced Biopolymers as Construction Materials – New Discoveries, 2nd International Wood and Natural Fibre Composites Symposium, June 28-29, 1999, Kassel, Germany.

Rowell, R.M., and Stout, H.P., Jute and Kenaf, Handbook of Fibre Chemistry, Second Edition, Eds: Lewin, M. and Pearce, E.M., Marcel Dekker, New York, 1998.

Rowell, R.M., Composite Materials from Agricultural Resources, IN: Olesen, O, Rexen, F., and Larsen, J. (eds.), Research in Industrial Application of Non-food Crops, I: plant fibres: Proceedings of a seminar; 1995 May; Copenhagen, Denmark, Lyngby, Denmark Academy of Technical Science: 27-41.

US Patent No: 6,767,634, Krishnaswamy, P., July 27, 2004.

Xu, J.Z., Gao, M., Guo H.Z., Liu, X.L.,Li Z., Wang, H., Tian, C., Study on the Thermal Degradation of Cellulosic Fibers Treated with Flame Retardants, Journal of Fire Sciences, 20, 227-235, 2002

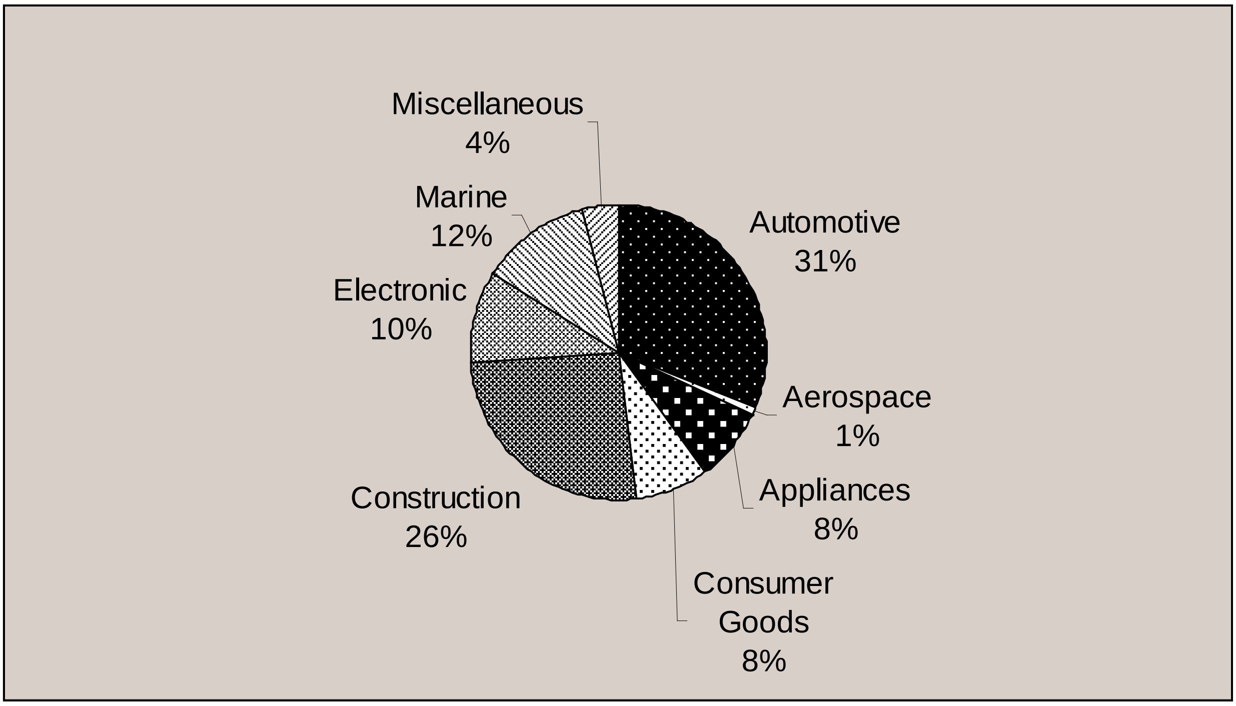

Figure 1: Distribution of fibre-reinforced composites by application (2002).

Source: Business Communication Company, Inc., 2002.

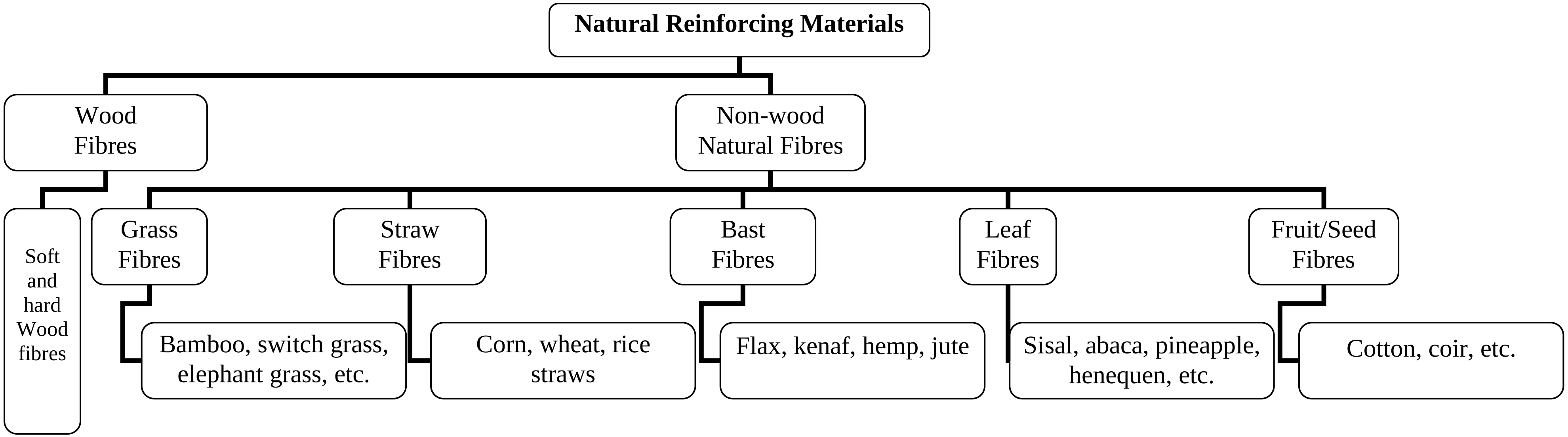

Figure 2: Natural Reinforcing Medium for Composites

Table 1: Physical, mechanical and chemical properties of bast fibres (Source 2-5, Rowell, 1995).

Properties	Flax	Hemp	Jute	Kenaf (bast)	E-Glass Fibre
Single Fibre Length (mm)	10 – 70 (range) 32 (average)	7 – 55 (range) 25 (average)	2-5 (range)	1.4 – 5 (range) 2.6 (average)	-
Bundle Fibre Length (mm)	250-1200	1000-4000	1500-3600	1500 – 4000	-
Mean diameter (μm)	19	25	20	21	
Density (g/cm^3)	1.4	1.48	1.46	1.2	2.55
Moisture Absorption (%)	7	8	12	12	-
Tensile Strength (N/m^2)	800-1500	550-900	400-800	275-450	2400
Young's Modulus, E (GPa)	60-80	70	10-30	-	73
Specific E/density	26-46	47	7-21`	-	29
Elongation at break (%)	1.2-1.6	1.6	1.8	-	3
Cellulose (%)	78.5	68.1	58-63	60.8	-
Hemi-Cellulose (%)	9.2	15.1	21-24	20.3	-
Lignin (%)	8.5	10.6	12-14	11.0	-
Pectin (%)	2.3	3.6	#	3.2	-
Ash (%)	1.5	2.5	0.5	4.7	-

Note: Properties of natural fibres vary and depend upon the fibre preparation, test specimen, testing method, origin of fibres, agricultural parameters, etc. # no authoritative value available. The table is compiled from various sources.