Kenaf (Hibiscus cannabinus L.) as a raw material for industrial applications – a market and literature review

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Biomass Production Chain and Growth Simulation Model for Kenaf

Confidential

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1 Summary

In this first year Agrotechnology and Food Innovations (A&F) has performed a market and literature review on the application of kenaf fibre fractions in composites, building materials, nonwovens, paper & board and absorption particles.
The quality of the fibre bundles (strength) depends on the method of fibre extraction. If a traditional extraction is applied after warm water retting or dew retting, than strong fibre bundles are produced, but this method is relatively expensive. Cheaper separation can be achieved if green stems are hammer milled followed by separation of the bast and core fibres, but as in the previous EU project (FAIR) has been shown, the strength of the fibre bundles is strongly decreased by the mechanical action in this process.
In the present BIOKENAF project, the first small samples of kenaf fibres are tested at this moment and we have strong indications that the strength of the fibre bundles is seriously affected by microbiological degradation in the field period or during storage. The method of harvesting, storage and extraction determines the number of market possibilities. If the fibre bundles are weakened during these processing steps, then only those applications where strength of the fibre bundles is not important are possible. Applications like compounds for automotives and pulp for paper, that make use of the strength of elementary fibres rather than fibre bundles are possible, provided that these elementary fibres are not weakened.
Small-scale fibre extraction mills that sell their products to several markets seem to be more viable than large-scale mills that are dedicated to one product. But the bast fibres always have to compete with other natural fibres. This means that preferentially the kenaf core should to be sold for applications that bring higher revenues than for energy applications.
The research that has been carried out so far indicates that whole kenaf will not be price competitive with wood.

Composites
In the production of composites clean kenaf bast fibres are already commercially applied in composites made from nonwoven fibre mats and plastics. No extra research is needed for this application. The production of compounded granules from natural fibres and plastics is in its commercialisation stage. Weakened fibre bundles can be used in this process without noticeably affecting the quality of the granules. Extra experiments with microbiological affected fibre bundles can determine if this influences the quality of the compound. If the compound properties do not decrease, drying of the kenaf plants in the field during winter will be possible for application in compounded granules.

Paper and board
Technically it is possible to use kenaf raw material for different types of pulp and paper. However, the economics of using kenaf compared to wood as a raw material are mostly more favourable for application of wood. In spite of good prospects in applying kenaf as a raw material for high yield pulps a pulp mill has never been realised. High investment

costs and reliable supplies of kenaf, result in high risks. Large-scale applications of kenaf pulp in the western paper industry are not likely to happen in the coming decades
Kenaf cannot compete with wood in large-scale chemical pulping if sufficient wood is available, but small-scale chemical pulping of bast fibres for niche markets is possible. Because of their similarity, separated bast fibres will have to compete with jute fibres in chemical pulping for specialty papers. Jute fibres are imported in Spain at a price of euro 350 per ton.
An Alkaline Peroxide Mechanical Pulping experiment is needed to determine if whole stem kenaf has an energy consumption advantage over wood in the production of newsprint like whole stem jute has. Whole stem kenaf has to compete with wood on price. In APMP pulping an extra energy advantage may result in a higher kenaf price than for woodchips is paid.

Building materials

Kenaf bast fibre as such is considered less suitable for fibreboard production. Kenaf core applied in particleboards will not fulfil strength requirements and will not be competitive with boards entirely made from wood.
In MDF boards, substitution of wood by kenaf core is technically possible in small amounts (up to 10%), but it has to be cheaper than wood to make it profitable for the manufacturer to deal with the different properties and logistics of this extra raw material. Substitution of wood by whole stem kenaf is possible up to 30 %. Again this whole stem kenaf has to be cheaper than wood, which costs about euro 70 per ton. Application of kenaf core fibre in binderless thermal and sound insulation panels seems technically feasible and on price it will have to compete with woodchips. Extra research is needed for the production of binderless boards.
Application in thermal and sound insulation mats of kenaf bast fibre will be possible if kenaf gives comparable insulation properties as flax fibres. If technically feasible, the kenaf fibres will have to compete with the almost similar jute fibres. The import price of unprocessed jute fibres in EU is around euro 350 per ton. The suitability of kenaf bast fibres in insulation mats still has to be investigated.

Absorption particles

Technically kenaf core is suitable as bedding material for animals and as oil sorbent and is actually sold for these purposes. The prices of these products are high, but profits will strongly depend on transportation distances. Kenaf core has to compete with flax and hemp cores, so a good comparison of the sorbent characteristics of kenaf, flax and hemp is needed.

Research topics to be addressed

A&F will focus the experiments on the application of kenaf bast fibres for insulation mats and kenaf core as absorption particles. If time and budget allows it, A&F will also carry out experiments on compounding of microbiological affected fibres, APMP refining of whole kenaf and production of binderless boards from kenaf core.

This results in the following priority list of experiments.

1. ***Insulation mats of bast fibres.***
2. ***Comparison of kenaf core with flax and hemp core as absorption material in stable bedding and as oil spill absorber.***
3. ***Compounding of microbiological partly degraded kenaf bast fibre.***
4. ***APMP comparable to already done jute experiment***
5. ***Insulation boards of core fibres.***

2 Fair project

In EU project Fair CT96 1697 different applications of kenaf were studied.
A final report is not available for this project group. The co-ordinator of this project cannot be reached and does not react on e-mails and telephone connection does not work.
The EU has only one final report in their archives and cannot release this version. Only a small executive report was found on the Internet.
Besides the A&F reports, some progress reports are available, so the results of this EU project are only partly available, more efforts will be taken to get a more clear view on the results of this project.

3 Plant morphological aspects of Kenaf (Hibiscus cannabinus L.)

The Kenaf plant is a member of the Malvaceae family and belongs to the genus Hibiscus that comprises various fibrous species. Kenaf can be grown in tropical and subtropical areas. The plant is very similar to Roselle (Hibiscus sabdariffa L.) It is possible that growers do not always differentiate between the two species. In India the common names 'Mesta' and 'Bimli' are used for both crops [1]. The transverse section of Hibiscus sabdariffa is examined by Catling and presented in Figure 1

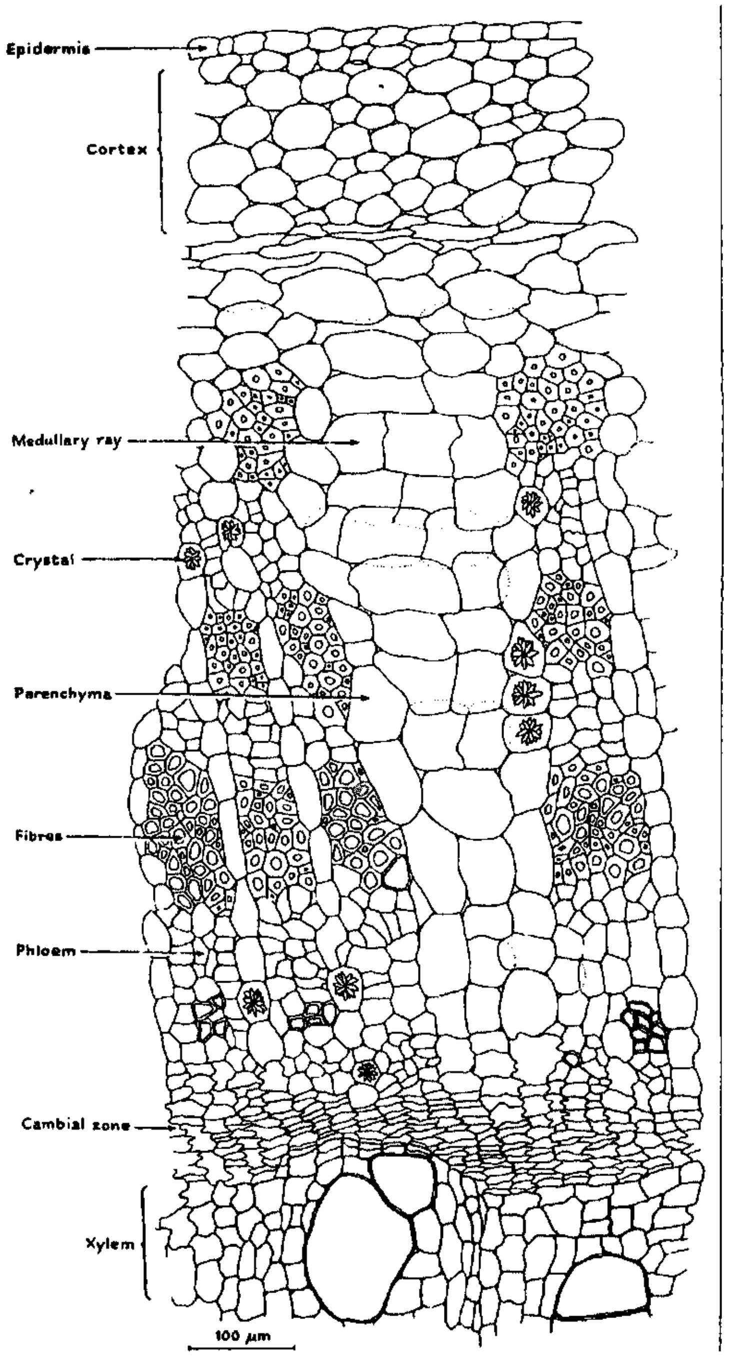

Figure 1: Transverse of H. sabdariffa stem by D. Catling

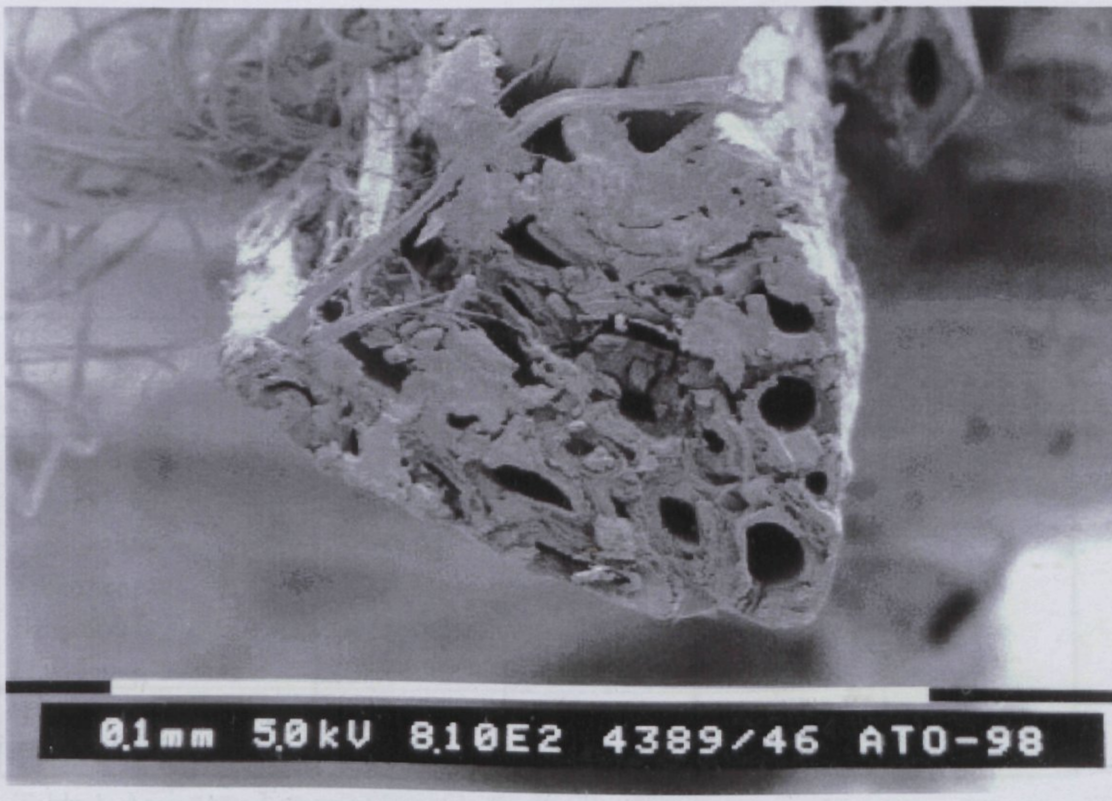

Figure 3: fracture surface of a fibre bundle

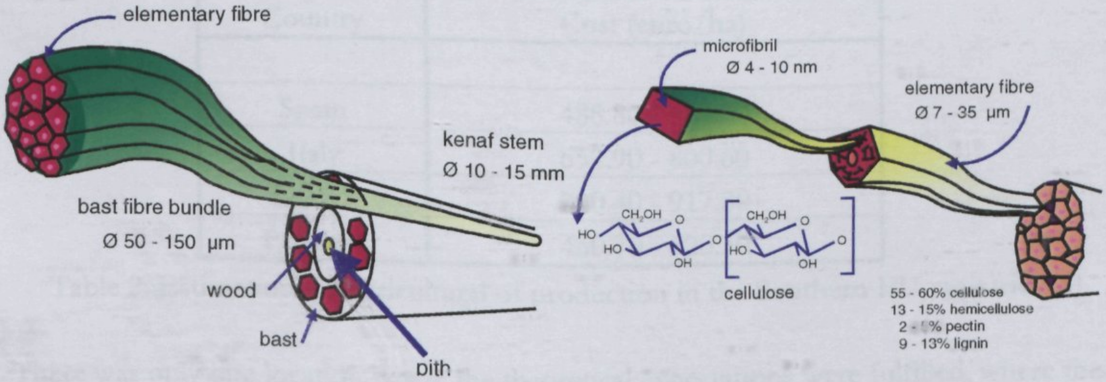

Figure 4: schematic composition of bast fibre

4 Agricultural production

In the Fair project [5]it was stated that the agricultural production costs depend on country and location. In Spain the costs largely depend on costs for fertilisers and irrigation, it ranges from euro 490 to 660 per ton (table 1). This was calculated at the price level of 1998.

	South Area		North Area	
	euro/ha	%	euro/ha	%
Preparation labours	71.00	10.8	71.00	14.5
Sowing	150.90	23.0	150.90	30.9
Fertilization	82.40	12.5	56.10	11.5
Treatments	31.90	4.9	48.40	9.9
Irrigation	159.40	24.3	53.60	11.0
Harvesting	161.70	24.5	108.80	22.2
Total	657.30	100	488.80	100

Table 1: Agricultural costs of kenaf in Spain [5]

The calculated agricultural costs in Italy and Greece was much higher than for Spain, but the costs in Portugal were estimated somewhat lower than in Spain (table 2).

Country	Cost (euro/ha)
Spain	488.80 - 657.30
Italy	652.90 - 800.60
Greece	720.40 - 917.80
Portugal	460.70 - 620.30

Table 2: Estimations of agricultural of production in the Southern EU countries [5]

There was only one location where the theoretical expectations were fulfilled, where the crop reached over 24 ton dry matter/ha. In other locations (Albacete, Almazan and Andujar), production levels reached between 9.6 and 12.4 ton/ha and were around 40% lower than the theoretical maximum. So the average yield was around 11 ton/ha [6].
On the basis of this average yield, the agricultural costs of a ton of dry kenaf stems varied between euro 42 and euro 83. No detailed combinations of local yields and costs are given.
Storage, cleaning, fibre extraction and transport of the fibres are not included in these costs.

If bast fibres are not separated from the core fibres, whole stem kenaf has to compete with wood as a raw material. The costs of wood chips delivered to the mill are nowadays euro 70 per ton of dry weight [7]. Taking in account this wood price level and the reported agricultural average production costs of euro 60 per ton, that are uncorrected for inflation during the past years, it is clear that with the present agricultural yield, kenaf fibres as such can not compete on price with wood. So in the competition with wood as a raw material kenaf has to bring substantial quality improvement or reduction in processing costs. Only with a strong increase of the yield it would be possible to compete on price. This improvement in yield is one of the major challenges for the other partners in the project.

In applications that make use of the specific bast fibre properties a process step that separates the bast from the core fibre is necessary. The separation of bast and core fibres has always been a very costly processing step. Within the Fair project the "Instituto Poligrafico E Zecco Dello Stato" (IPSZ) developed a dry cleaning-separation plant. It is based on hammer milling and sieving. Separation costs were estimated at around euro 24 per ton of fibre, which was comparable with working separation systems in the USA [5]. If due to quality demands green decortication is not possible than retting of the stems is necessary. Dew retting on the field is the most economical way of retting. If climate and field conditions do not allow dew retting in the field than warm water retting is the only option. But the costs of warm water retting will increase the cost price of the fibres strongly and will make the competition with other bast fibres extremely difficult.

In the Fair project, the bast fibre part of the whole stem varied between 18.8 and 26.6%. The highest long fibre yield was achieved with Tainung 1 [8]. If no additional outlet can be found for the core fibres, the raw material part of the cost price of bast fibres is 4 to 5 times the estimated costs of kenaf stems. Depending on country and location this can vary between euro 190 and euro 440 per ton (including green decortication). The average inflation in the EU was 2 % in the period of 1999 to 2002 [9] If these prices are corrected for inflation with 10%, the costs for the production of kenaf bast fibres will range from euro 210 to euro 480 per ton (transport not included).

5 Application of kenaf fibres in composites

Kenaf bast fibre can be used in composite materials, but they have to compete with other agricultural fibres like flax, hemp and jute in quality and price. In fibre composites, the production of automotives from natural fibres is an increasing market. In this application, nonwoven mats of these fibres form the basis of the automotive part. Kenaf and the similar type of jute fibre are already used in this application, but the amount of kenaf that is used is unknown. In the past years a compounding process of natural fibres and plastics was developed by A&F. The process is patented and it is now in its commercialisation stage. Producing automotives from compounded fibres and plastics will reduce production costs significantly. These natural fibre compounds can also be used in all kind of other products.

5.1 Technical aspects

Within the Fair project warm retted fibres and green decorticated fibres (from IPSZ) were tested by A&F for different fibre properties [8].
Analyses of the green decorticated kenaf showed that the shive content was 1.5% and more than 80% of the fibre bundles had a length between 10 and 50 mm.

The fibre tensile strength of retted fibres is superior to green decorticated fibres. The strength of the retted fibres ranged from 556 to 682 MPa which make them competitive with other types of fibres. The strength of green decorticated fibres was weakened due to the mechanical treatment and cutting to 175 to 435 MPa. The tensile strength of retted fibres is comparable with jute sliver, but the fineness of jute sliver is superior.

Retting does not affect the chemical composition strongly. About 2.5 % of pectin and about 1 to 1.5% of xylan is removed, which raises the cellulose content a few percent.

Compounds of kenaf with high-density polyethylene (HDPE) and polypropylene (PP) were made with a batch kneading process. Kenaf improves the mechanical properties of HDPE compounds and are suitable as reinforcements of HDPE composite materials. Compared to jute sliver the kenaf fibres perform better in the flexural modulus, but less in flexural strength, elongation and impact strength. In contrast with the fibre strength, the green decorticated fibres showed only a slight reduction of strength in composites. Compared with HDPE composites made from retted fibres the strength was only 8% lower. A compatibilizer improves the flexural strength and the impact strength.

Kenaf also improves the mechanical properties of compounded PP composite materials. Again the green decorticated fibres result in a slightly smaller improvement than retted fibres. Compared to jute sliver the kenaf fibres perform better in the flexural modulus, but less flexural strength. Flexural elongation and impact strength are at the same level.

For this type of compounded composites both retted and green decorticated kenaf bast fibre are suitable as reinforcement fibres for HDPE and PP. The mechanical performance of these kenaf fibres is comparable with other agricultural fibres like flax, hemp and jute.

If composites are made with fabrics, the use of green decorticated kenaf is not possible. In that case long and strong fibre bundles are needed. In this application only retted fibres will fulfil the requirements.

So the FAIR project showed that kenaf fibres can technically compete with other natural fibres in compounded composites and that the strength of the fibre bundles is less important than in the production of composites with fibre mats or fabrics.

Due to weather and soil conditions harvesting of the kenaf plants in autumn is not possible in some areas.
In those areas the kenaf plants have to stay in the fields during wintertime. Depending on the wet conditions, the fibres are subject to microbiological attack and degradation. An advantage of this extra period in the field will be that the leaves will fall off and stay behind as a fertiliser. In experiments with frost kill kenaf Ramaswamy found that the strength of the kenaf fibres was affected by fungal degradation. Fibres from the base of the stems suffered most of this fungal attack [10].
While in this compounding process the fibre bundles are broken down to elementary fibres, degradation of the fibre bundle does not have to result in lower strength of the compounds.
No research has been done yet with kenaf fibres which are affected by microbiological degradation during the field period or storage. An extra experiment with this affected fibre is needed to establish if this degradation is harmful for the quality of compounds.

5.2 Economical aspects

The use of agricultural fibres in the automobile industry is increasing. In a growing number of car parts (automotives), glass fibres are replaced by natural fibres [11]. In Western Europe 25000 tons of natural fibres was used in this industry, from which 2/3 was applied in Germany and Austria (Figure 5). This market is growing and if all 16 million cars that are produced would contain the usual amount of 5 to 10 kg of these natural fibres, the market potential would be 80 to 160 thousand tons each year.

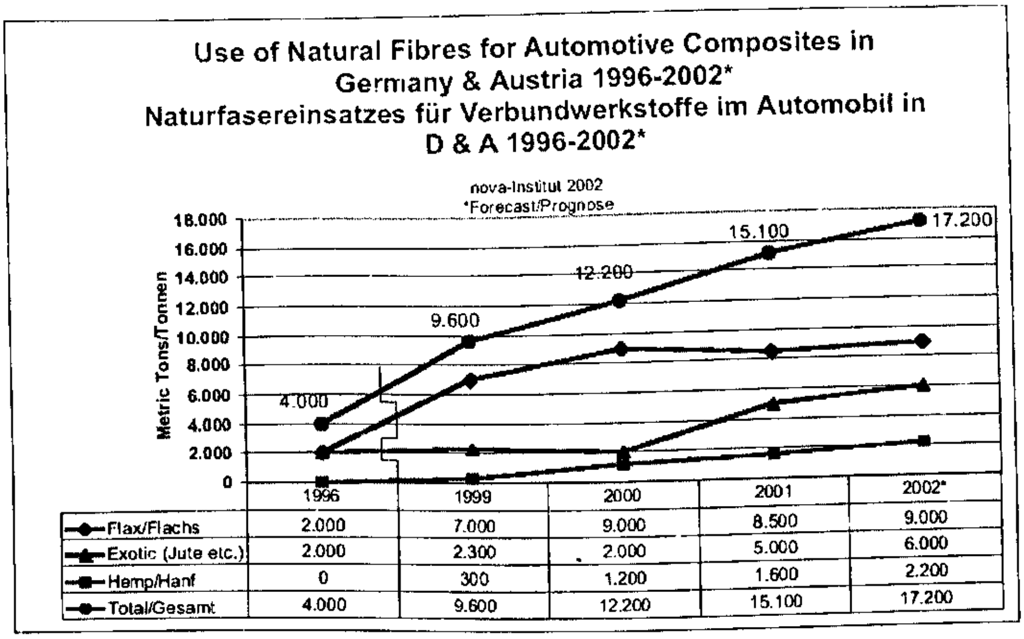

Figure 5: The use of natural fibres for automotives in Germany and Austria [11]

The fibres that are used in this industry are cleaned bast fibres, that are not long enough for textile purposes. The price that the automotive industry paid in 2002 varied between euro 550 and euro 620 per ton. As can be seen in table 3 the price level in the Nova report is comparable with the price levels for flax short bast fibres as presented at the 54th CELC (Confédération Européenne du Lin et du Chanvre) congress [12].

	1998/1999	1999/2000	2000/2001	2001/2002	2002/2003
Long fibre (for textiles)					
Sold (tons)	72100	98100	87700	58284	95688
Price (euro/ton)	**1300**	**1810**	**2360**	**2350**	**1950**
Stock (tons)	20500	6500	13300	6800	10700
Cleaned short fibre(for paper, automotives)					
Sold (tons)	22900	35500	33500	23900	27100
Price (euro/ton)	**290**	**310**	**520**	**570**	**440**
Stock (tons)	25300	18000	13700	12100	9500
Uncleaned short fibre					
Price (euro/ton)	**80**	**180**	**210**	**260**	**160**

Table 3: Prices and amounts of flax bast fibres

Due to the high flax prices of the last years, the use of flax fibres in the automotive industry did not grow. Because of a shortage of hemp fibre production capacity in Europe the extended use of natural fibres in this application was almost totally filled with jute, kenaf and sisal fibres. This means that at the present price level European fibres have to compete strongly with fibres from Asia.

Kenaf fibres are suitable and already used for this application for a price of about euro 500 per ton of cleaned short bast fibres.

As can be seen in table 3, the price of this type of fibre can easily drop to euro 300 per ton, whereas production costs vary between euro 210 and euro 480 per ton. This makes an additional outlet for the core fibre necessary to ensure the possibility of growing and selling kenaf over a longer period.

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

5.3 Description of market possibilities for kenaf fibre compounded granules

Kenaf fibre reinforced granules can be used in the following market segments:

1 *automotive industry:* is interested in agrofibres as a substitute for glass fibres as a reinforcing fibre in thermoplastic and thermoset composite parts, like door panels, but also construction materials like hoods, roofing's, dash board panels.
2 *packaging:* both for inland transport and export of agricultural products like: mango's, fish, tea, etc.; the packaging materials can consist of crates, inlays for crates, pallets, boxes, cases.
3 *engineering packaging:* protection during the transport of consumer-electronics, refrigerators, etc.

In all these aforementioned products the competing product range mainly consists of glass fibre reinforced thermoplastic, thermoset materials or wood. The potential of kenaf based materials is based on its price/performance ratio, where the performance can reach that of glass fibres, but its price range is substantially lower, and its low weight is of large importance in packaging and transportation. In comparison with West European fibre materials, kenaf reinforced thermoplastic materials have comparable mechanical properties.
Most important, *only if* kenaf fibres are cheaper than flax or hemp fibres (for instance 0.5 euro/kg for decorticated kenaf bast fibres, compared to 0.65 euro/kg for decorticated flax or hemp bast fibres), *then* there is an industrial potential for kenaf as a reinforcing fibre material.

5.3.1 Techno-Economical Evaluation

Investments are inevitable for the production of new materials like kenaf/polypropylene granules. The aim is to regain (a contribution of) the cash flow. The material market price based on investments and company costs cannot be calculated. The 'cost + return' price, i.e. the material price the producer prefers, however can be calculated on the basis of a Techno-Economical Evaluation (TEE).

Estimates of investments, costs and returns are the main elements of any TEE. This evaluation present its results based on the production of kenaf/polypropylene granules (see appendix A and B).

A specific example is given for the production of these granules, concerning the European situation; a production of 5 ktpa requires

⇒ a total investment of **euro 3,914,767**, and
⇒ yields a cost+ return of **euro 1,384/ton** (at 30% ROI)

5.3.2 Investment estimates

Calculation of the Total Investment for the production of kenaf/polypropylene granules by compounding on a twin-screw extruder is given in Summary I. A few assumptions are made:

- the plant availability follows the Overnight Construction End of Year Zero
- ground is available in an industrialised area
- subsidies, investments reduction, inflation correction, etc., are not taken into account
- In the example (Dutch situation, 2004) the machine capacity is supposed to be at least 5 kiloton per year; granules produces in this order of magnitude have been suggested as the minimum size for a successful compounding venture [13].
- The (machine) operational hours are 6000, as suggested by the compounding industry.
- It is recommended to depreciate direct investments in 10 years and allocated investments in 20 years [14].
- A compounding set-up consists of a twin screw extruder, two feeders, an underwaterpelletizer and a (granules) dryer; the cost of this set-up - with the item unforeseen (25% of the onsite investment is a common used first estimate) is the 'onsite investment'.
- The 'total allocated investment' consists of the items' instrumentation, storage&transport, utilities, offsites and environmental facilities. The surcharges are based on the development of this extension on an actual location

- One-off investments: these costs are preferred to be depreciated at once. Examples are Engineering&Drafting and Start Up costs.
- Working capital: additional investments are needed for supplies (both starting materials and endproduct), spare parts, deptors, salaries, etc.

5.3.3 Production cost and profit estimates

Calculation of the Cost+ Return price for the production of *50/50 wt%* kenaf/polypropylene granules by compounding on a twin-screw extruder is given in the appendix B. A few assumptions are made:

- raw materials are sufficiently available
- financing of the project fully occurs with company capital

5.4 Conclusions

- Clean kenaf bast fibres are already used in composites made from nonwoven fibre mats and plastics. No extra research is needed for this type of application.

- The production of compounded granules from natural fibres and plastics is in its commercialisation stage. Weakened fibre bundles can be used in this process without affecting the quality of the granules.

- Extra experiments with microbiological affected fibre bundles can determine if this degradation is harmful to the quality of the compound. If the quality is not decreased, drying of the kenaf plants in the field during winter will be possible for application in compounded granules.

6 Kenaf application in building materials

Kenaf stems can be separated into bast fibre and woody core, which both can be converted into building materials. On the market of wood based building panels various types of fibreboards can be distinguished. Generally, soft fibre boards, particleboards, medium and hard fibreboard materials are produced from wood chips, or fibres with different amounts and types of chemical adhesives. Consequently different processing conditions (pressure and temperature, curing time) are applied yielding board materials of varying qualities. Each board type finds other end-markets depending on its performance and price. These may be ranging from exterior decoration panels, constructive boards to insulation panels and interior parts.

6.1 Bast fibre boards

Kenaf bast fibre bundles are relatively long and can be processed into yarns and fabrics that are comparable to well known jute products. For this purpose they have to be cleaned thoroughly from adhering shive and cortex tissues. Generally, for fibreboard production the fibres do not require such cleaning. From own experiments and informal discussions with board manufacturers it is clear that, unless a refining step has been performed, these type of fibres – like also flax, hemp, and jute bast fibres – are less suited for MDF production. They are too long and form entangled clusters that will give problems in spreading and even mat formation. For the use as wood substitute products in fibre boards the kenaf bast fibre has another disadvantage of being a relatively fine fibre that is absorbing high amounts of (expensive) glue to form a consistent board product. Therefore, kenaf bast fibre as such is considered less suitable for fibreboard production.

6.2 Particleboards

Particleboards are primarily made of wood residues from lumber planing operations [15]. As with flax and hemp, lightweight particleboards can be produced of separated shives or woody core of kenaf. In the Fair project it was shown that, the internal bond strength (IBS) of 100% kenaf core board is lower than with wood, but addition of up to 50% kenaf core to woodchips did not affect the IBS. The reduction in measured properties was most significant for smaller particle fractions.

Thickness swelling was increased above 30% wood substitution level. The smaller kenaf particles did not have significantly different swelling. The bending properties were generally unaffected at all levels of substitution. Boards made from the smaller kenaf particles were not significantly different [5]. Technically satisfying building boards for interior applications can only be produced from kenaf core if the amount of resin is increased. It is generally accepted that the adhesive is the most expensive raw material in the manufacture of particleboard and hardboard [16]. Removing the pith rich inner parts

of the core might be another way to raise the IBS and reduce swelling because that par. of the plant absorbs much glue and does not contribute to strength, but of course this will raise the costs of the kenaf core raw material.
Disadvantages are mentioned by particle board industries to be the size distribution of the relatively large particles, with lack of fines (like present in chipped wood and saw dust) that will make sanding difficult and consequently leads to a rough surface of the board product.
As commonly is complicated with particleboards, screwing and drilling is even more difficult with the weak woody kenaf particles. Screw holding capacity of kenaf panels was about 8% of medium-density wood and wood-based panels and about 50% of low-density particleboard [17].
So using kenaf core in particleboards that have to fulfil strength requirements will not be competitive with boards entirely made of wood. Kenaf core might be competitive in boards that do not require strength, but only a basic stiffness to be able to handle them, for instance application in sound and thermal insulation panels.
Like flax core, the kenaf core has to compete with wood residues in this application field. The price will be a little bit higher than for use in energy applications and is estimated to be around euro 40 per ton dry matter.

6.3 Medium density fibreboard (MDF)

MDF are used in applications that require higher strength properties than particleboards. So good strength properties are essential in MDF boards. In the Fair project, substitutions of wood by refined kenaf core material in the production of medium density fibreboard (MDF) were tested. No significant differences in properties were measured up until a level of addition of 10% kenaf core. At higher content de-lamination problems of panels occurred [5]. There were uncertainties on the controlling of moisture and wax content. (In the last period this would be investigated again, but reports on that period are not available).
So application of kenaf core is possible in small amounts, but then it has to be cheaper than wood to make it profitable for the manufacturer to deal with the different properties and logistics of this extra raw material.

Kenaf whole stem was also tested as a substitution for wood in MDF. The IBS was progressively reduced at increasing substitution level. The thickness swelling increased with increasing kenaf stem content. Bending properties did not change up to 50% substitution, but at 100% the bending properties were reduced [5]. Increasing substitution resulted in progressively darker colour of the boards. In a later consolidated report, it was found that using a catalyst with the resin wood could be successfully substituted with kenaf whole stem up to 30%. The panels have properties that 'fit for use' in many of the key applications for the product [18]. No report is available of test that would take place at substitution levels higher than 30%. No advantages over wood has been found, so whole stem kenaf has to compete with wood on price. Again it has to be cheaper than wood to make it profitable for the manufacturer to deal with the different properties and logistics of this extra raw material.

6.4 Hardboards.

By themo-mechanical refining (TMP) of the whole kenaf stem a suitable feedstock for hardboard production is obtained [19]. To facilitate feeding and to avoid bast fibre clustering in the refiner, hammer milling of the stems should be performed. The pulped kenaf needs to be dried below 10% moisture content before resination (7% phenol resin) and mat formation takes place. By hot pressing panels with satisfactory mechanical performance can be produced. In spite of the technically satisfying performance of boards made of kenaf, production kenaf will not be economically feasible. Kenaf will have to compete with rest wood fraction and woodcuttings, which are even cheaper than wood chips, so the whole kenaf will bring a price, lower than woodcuttings. It is not likely that production, harvesting and transportation costs will ever become lower.

6.5 Binderless boards

A few articles from research in Japan show that binderless boards can be produced with finely ground powders of kenaf core. The mechanical properties met the requirements for grade 15 MDF by JIS A 5905-1994, but thickness swelling and water absorption exceeded the maximum permitted level [16].
So these boards can only be used in dry conditions as indoor panels, or in applications like disposable trays. Xu found a good internal bond, but a poor durability [20]
Low density binderless particleboards from kenaf core that was reduced to 0.5 mm showed thermal conductivity values similar to rock wool. These boards show potential as panels for thermal and sound insulation [21].
In thermal and sound insulation binderless panels kenaf core fibres might be competitive to wood. The core particles are small and light compared to wood. Extra research on this topic is needed.

6.6 Insulation mats

The long kenaf fibres bast fibres can be processed into non-woven dry laid (needle punched) or resinated mats by conventional technologies. The bast fibres should be cleaned and cut to suitable length for processing. The performance of the mat as insulation material in building application should be examined (thermal and acoustic insulation, moisture absorption, sensitivity towards moulds and insects). The properties can be expected to be comparable to products based on flax and hemp, that find increasing market as thermal insulation in building applications within the EU. Like insulation boards these products only require a minimum strength and stiffness, which is

normally brought by the glue that is used. Because of these low strength requirements, the strength of the fibre bundles is allowed to be low too, this would make it possible to use fibre bundles that are weakened. This weakening can happen if the cheap separation method as tested in the Fair project is applied or by weathering when the kenaf is dried in the fields during winter before harvesting takes place.
Because of the low demands the performance of such kenaf mats as insulation material in building application should be examined (thermal and acoustic insulation, moisture absorption, sensitivity towards moulds and insects). In the Netherlands this type of insulation mats are made with short flax fibres, that are not long enough for textile applications. These quality guaranteed fibres cost around euro 500 per ton. In Spain kenaf fibres probably have to compete with imported jute fibres that cost around euro 350 per ton.

6.7 Conclusions

With respect to the application of kenaf in building materials, it can be concluded that;

- Kenaf bast fibre as such is considered less suitable for fibreboard production.

- In particle boards kenaf core will not fulfil strength requirements and will not be competitive with boards entirely made from wood.

- In MDF boards, substitution of wood by kenaf core is possible in small amounts (up to 10%), but it has to be cheaper than wood to make it profitable for the manufacturer to deal with the different properties and logistics of this extra raw material.

- In MDF boards, substitution of wood by whole stem kenaf is possible up to 30 %. Again this whole stem kenaf has to be cheaper than wood, which will not be likely.

- In particle- and MDF board applications kenaf will have to compete on price with wood, so at this moment a maximum of euro70 per ton will be paid.

- Application of kenaf core fibre in binderless thermal and sound insulation panels seems technically feasible and on price it will have to compete with woodchips. Extra research is needed.

- Application in thermal and sound insulation mats of kenaf bast fibre will be possible if kenaf gives comparable mat properties as flax fibres. If technically feasible, the kenaf fibres will have to compete with the almost similar jute fibres. The import price of jute fibres in Spain is around euro 350 per ton..

- The application of kenaf bast fibres in insulation mats still has to be investigated.

7 Pulp and paper application

7.1 Pulping processes

To be able to use wood or plant fibres for papermaking purposes, these fibres have to be released from their embedded structure in woods or plants. This process is called pulping.

There are different types of pulping processes:

a) Chemical pulping
b) Mechanical pulping
c) Intermediate processes

(a) In chemical pulping processes, lignin is dissolved and removed from the plant tissue by cooking in alkaline, sulphide or sulphite solutions. The highest amount of lignin can be found in the S2 layer of the cell walls and the highest concentration of lignin in the plant tissue is in the middle lamellae between the adjacent fibres. Once this lignin is removed, it is easy to separate the fibres from each other and the small amount of remaining lignin can be removed by bleaching. After bleaching fibres consists of cellulose and hemi-cellulose. As the yellowing component lignin is almost completely removed this pulp can be used for printing and writing papers. If the bleaching step is omitted, the fibres can be used as wrapping paper. There are several different types of chemical pulping processes like kraft, sulphite and soda pulping. The choice of pulping process, temperature, duration and chemical concentration determines the yield, pureness and paper properties. The chemical processes have yields of around 50% and the produced paper has a high brightness (if bleached) and is strong.

(b) In mechanical pulping processes, fibres are liberated from their plant or wood structure by mechanical forces. The oldest process is the ground wood process in which wood was pressed against a grindstone. With this process the fibres are damaged heavily, fibre shortening takes place and besides some agglomerates a lot of fine fibre particles are created. In the early 1950s the refiner mechanical pulping process (RMP) was developed, followed by processes as chemi-mechanical pulping (CMP), thermal mechanical process (TMP) and chemi-thermo-mechanical pulping process (CTMP). These processes are developed to create less fibre damage than the ground wood process does. The chemicals that are applied in the CMP and CTMP process are not used to dissolve the lignine, but to lower the softening temperature of the lignin and to obtain a better separation between the fibres and less damage of the fibres. Nevertheless all these pulps have a high amount of fine particles and the average fibre length is low compared to chemical pulps. All these pulps have high yields ranging from 85 to 95% and the pulps are also called high yield pulps. These pulps are used in newsprint where yellowing is not a problem or in light weighed coated paper were the coating prevents the yellowing. The fines in the pulp create a smooth printable surface. A disadvantage of this process is the high amount of electrical energy that is needed. The CTMP abbreviation is somewhat confusing, because some people exclusively use this name for the original process in which sulphite was the softening chemical. Others use it for all type of chemicals that are used. In the eighties a mechanical pulp process was developed on the basis of alkaline and peroxide treatment combined with mechanical pulping in a refiner. This process is named Alkaline Peroxide Mechanical Pulping (APMP), but especially during the development stage of this process some authors were still referring to it as a CTMP process.

(c) Between chemical and mechanical pulping all kind of intermediate processes are possible. In general the rule is that the energy requirement is decreasing with increasing chemical action.

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

7.2 Kenaf as a raw material for pulp and paper applications

Extended research has been carried out on the application of kenaf in pulp and paper applications.
In 1957 the United States Department of Agriculture started a research program called "A search for new fibre crops" In this program it was the objective to find the most suitable new fibre crop for the expanding pulp and paper industry. A large number of monocotyledoneae as well as dicotyledoneae were screened and rated for their chemical composition, cell dimensions and maceration yields [22, 23]. The most promising raw materials were subjected to kraft pulping experiments in which yield and paper properties were established [24]. On the bases of these studies, kenaf was chosen for further detailed study [25]. These USDA studies boosted the number of studies on kenaf all over the world.
In response to a shortage of vegetable fibres already in the early 1950's trials were conducted in growing kenaf in northern Queensland in Australia, but this work was discontinued when adequate supplies of fibre came available. In the late 1960's the pulping studies in the USA lead to a renewed interest in kenaf in Australia and agronomic and pulping studies were undertaken by the CSIRO [26].

7.2.1 *Research on chemical pulping*

USDA

With different types of chemical pulping processes it was shown that whole stem kenaf could be transformed to pulps and bleached papers with physical characteristics comparable to those of many woods. At the same dewatering rate on the paper machine (freeness levels), the strength characteristics were superior to hardwoods. With the exception of tear strength the kenaf pulps were in strength properties comparable with softwood kraft pulps and superior to hardwood pulps [27]. More detailed sulphate pulping experiments showed that yields varied between 45 and 48% for unbleached pulps and 41 to 43 % for bleached pulps, which is about 5% lower than the yields of wood pulps [28]. In 1970 the U.S. government laboratory demonstrated in a pilot run on a paper machine with a furnish of 60% mixture of softwood and hardwood fibres and 40% of kenaf kraft pulp [29]. These experiments showed that chemical pulping of whole kenaf stems results in pulps that are not better than wood pulps, but the yield of these pulps is about 5% lower. This means that for this application kenaf must have a lower price than wood. If that is possible than a stand-alone pulping mill for kenaf must have a size of five hundred thousand to one million tons of kenaf a year to be able to compete with pulping mills that use wood. Continuous delivery of such an amount of kenaf will be very difficult. Contracts with a lot of farmers and storage of the voluminous kenaf during the year are necessary and high transport costs are involved. So in the bulk applications for printing and writing kenaf is not likely to be able to compete with wood.

CSIRO

Bast fibres give good strength properties with very high tearing strengths. The strength of the core pulps was low and could only be improved at unacceptable high drainage times.

Kraft and soda pulping of bast fibre gave similar yields and similar pulp and papermaking properties, confirming the work of the USDA.

It appeared to be more economical to produce neutral sulphite semi-chemical (NSSC) pulps. The bark pulps had excellent tearing strength and good bonding strength, comparable with those of chemical pulps, which makes these NSSC pulps suitable for linerboard [30]. NSSC pulps from core had lower tearing strengths but higher bonding strengths than chemical pulps. These pulps can only be applied in corrugating papers unless blended with higher strength pulps. It is unlikely that separated fibres of kenaf will ever be used in these paper segments in Europe, because both type of papers are made of much cheaper recycled paper.

7.2.2 *Research on mechanical pulping*

USDA

Besides chemical pulping, the USDA also studied the possibilities of mechanical pulping.

The advantage over a chemical process is that production scale can be much smaller. Because of the limited size of the refiners that are used in this process large scales do not bring as much profit as with chemical pulping. Capacities of 70.000 tons/year are economic. Mechanical pulps have a high yield, but a lot of electrical energy is needed to produce them. Due to this high energy requirement, mechanical pulp mills are normally integrated with a paper mill. The surplus of steam generated in the refining process is used in the paper mill. So there is only a very small market for mechanical pulps. In 2003 only 3.2 million tons (8%) of the total world production of 41 million tons of mechanical pulp was available for the market [31]. From economical point of view a mechanical pulp plant based on kenaf fibres can better be integrated with a paper mill.
The strength properties of kenaf Thermo Mechanical Pulp (TMP) were very poor, but peroxide bleaching of the TMP pulp greatly improved the strength properties [32]. This bleaching raised the brightness to newsprint level [33].
Handsheets made of a mixture of bleached kenaf TMP and 10 to 15% of kenaf soda chemical pulp showed strength properties comparable with commercial newsprint. However on a laboratory paper machine trial in 1977, this ratio of pulps formed a mat that tended to pick to the press and only sheets of high basis weights could be formed. With 30 to 40% of this kenaf chemical pulp, a paper web with low basis weight and desired strength could be made [34].

CSIRO
With kenaf bark satisfactory RMP pulps could be produced for use in furnishes for newsprint. A sulphite pre-treatment resulted in a small increase of the strength properties.
Alkaline sulphite CTMP pulping of kenaf core resulted in much poorer pulps than bast fibre pulps. Alkaline sulphite CTMP pulping of the whole kenaf stem gave satisfactory pulps with a reasonable balance between tearing strength, bonding properties and drainage rate [35].

Others
As already written in the chapter on pulping processes, sometimes alkaline peroxide mechanical processes (APMP) are referred to as CTMP processes. Some of the articles mentioned below use the name CTMP. Myers found that the chemical load reduced the needed specific energy down to a factor 1/2 compared to TMP pulping. The amount of energy needed with 3% NaOH and 3.8% H2O2 to reach CSF 100 ml was 1750 kWh/ton. These chemicals were injected into the pressurised refiner. Most paper strength properties were between newsprint and printing and writing papers. Brightness was to low for printing and writing papers. Post bleaching of kenaf TMP is not a viable alternative [36]. Lawford found that in applying alkaline peroxide energy needed was 2/3 of that of kenaf TMP and 1/2 of that of southern pine TMP [37].
Akthar found that biomechanical pulping of kenaf could reduce the energy needs with 38% compared while at the same time the strength properties of the paper was improved for RMP pulps [38]. The brightness was reduced, resulting in a higher hydrogen peroxide

demand during bleaching. This biological pre-treatment before mechanical pulping is still in a developing stage and it is not clear yet if the energy reduction is enough to compensate for the costs of this processing step and the extra chemical demand
Xu found that alkaline peroxide mechanical pulps from whole kenaf stems had higher tensile strength at the same density, or the same strength at a higher bulk than aspen APMP pulp [39]. Xu did not present any information on the energy that was needed. In recent A&F experiments with APMP pulps (2003) made from jute, it was shown that jute needs less than 50% of the energy that is needed to produce Aspen APMP pulp. As kenaf is quite similar to jute, kenaf might have this advantage too. The energy costs form a major part of the production costs, so the use of kenaf can result in lower production costs. A similar experiment as the jute experiment at A&F can is needed to determine if kenaf has this technological advantage too. Such an advantage in energy consumption may result in a higher kenaf price than for woodchips is paid.

7.3 Commercialisation

7.3.1 Commercial scale paper machine trials

Kugler [40, 41] presented two papers with an overview of the commercialisation activities of kenaf in newsprint application. In 1978 CTMP pulp (probably sulphite) of kenaf was produced at C.E. Bauer Springfield Ohio. Due to all kind of mechanical problems the production capacity dropped from around 10 metric tons to 2.2 tons/day. Instead of the planned 50-70 metric tons only 22 tons were produced. Severe erosion by metal, stones and sand required replacement of refiner parts like blow valves and plates already after 12 production hours. In spite of all the efforts to remove this contamination, plate damage and wear continued and it was decided to terminate the run to avoid costly damage to the refiner [42].
The produced pulp was sent to International Paper's Pine Bluff mill in Arkansas for a paper machine trial. The paper machine ran without problems on a mixture of the kenaf pulp and 8 to 25% of kraft pulp. The strength of the produced kenaf paper was higher than that of the control. Smoothness was comparable and porosity was generally lower. The brightness of the sheet was considerably higher, with a corresponding lower opacity. In general the newsprint sheet was strong and bright. Printing of the newsprint paper was tested with different type of printing machines at different newspapers. The pressroom runnabililty was good, but the opacity and print through were identified as a problem in all six pressrooms [42].
So in spite of all the problems in the pulping stage, the paper and printing machine runs went well. This illustrates the importance of a clean raw material. It is obvious that the amount of dirt in a crop like kenaf will exceed the amount of dirt in logged trees from which the bark is removed anyhow. So in harvesting and handling of the kenaf, one has to choose for operating procedures that give a clean quality product. For instance,

increasing the cutting height of the stem can reduce the amount of soil. A paper mill that uses kenaf will probably need a facility to wash the chopped kenaf. Lawford showed that washing and cleaning reduces the amount of metals that disturb the peroxide bleaching [37]. Cubing of the chopped kenaf to reduce transport costs will make the removal of contaminant in a later stage almost impossible. The ash content of clean kenaf varies between 2 and 6% [43, 44], whereas the ash content of wood is only a few tenths of a percent. This higher ash content may result in extra plate wearing, but that can only become clear if refiners can run for a long period on kenaf and that has never been done yet.

In 1981 a second commercial-scale newsprint trial was conducted at International Paper in Mobile - Alabama. It was the first time that kenaf fibre handling, pulping and newsprint manufacture took place in continuous steps. It demonstrated the feasibility of design and operation of a newsprint system based on kenaf [40]. This time, eight newspapers tested the product successfully [45].

In 1981 Kenaf International was formed, a company with the sole purpose of pursuing the commercial potential of kenaf. It was a joint venture company composed of Agrifuture Inc., The Bakersfield Californian and Dr. Charles S.Taylor.
USDA and Kenaf International initiated "The kenaf Demonstration Project" within a public-private partnership. To answer a broad range of questions posed by the paper industry, the project team joint with the manufacturer of pulping equipment C-E Sprout Bauer and with the Canadian paper company CIP inc. to form the Joint Kenaf Task Force (JKTF). The efforts of this task force resulted in a new commercial scale trial in 1987 at total cost of approximately $650,000 [40].
For this kenaf newsprint trial 80 tons of chopped and baled kenaf at 15 to 25 % moisture content was transported to Sprout Bauer facility for CTMP pulping. Due to all kind of unforeseen and unexpected problems about 27 tons of wet-lap pulp was produced, only half of the desired quantity. Pulping was done with a two-stage CTMP process and once the material was washed, it could be pulped in conventional TMP or CTMP equipment. The energy needed to produce the pulp was estimated at 80% of the energy required for wood pulps. Conversely, much more chemicals were used in the kenaf CTMP process. The CIP Inc.'s Trois Rivieres mill was selected to manufacture the kenaf newsprint. After a 4-hour run on the paper machine approximately 15 tons of saleable newsprint were manufactured at a speed of 600 metres per minute. Roughly half of the kenaf pulp was lost to broke or unrecoverable from pipes and chest bottoms. The paper was produced on the basis of 82% whole kenaf stem CTMP and 18% kraft pulp from balsam and spruce and had a higher brightness than the conventional newsprint furnish. The paper had superior strength to southern pine newsprint and the opacity equal to or better than western newsprint
Thirteen finished rolls were shipped to four newspapers for pressroom runs. Printing of the paper went smoothly and the kenaf prints were brighter and had more contrast [40].

The Kenaf Demonstration Project showed economical and technological feasibility for a kenaf newsprint system, it supported CIP's business plans for the Kenaf Rio Grande newsprint mill [40]. One of the major problems still remaining is to get the bulky kenaf to the mill and the space needed to store it for 6 to 8 months [46].
In the planning phase of the 90-ton-per-day newsprint mill, the paper industry entered a cyclic down turn resulting in overproduction and low prices. Financing the planned mill became untenable and private entrepreneurs and USDA start searching for less capital intensive, smaller scale markets for the core and bast fibres from kenaf. For this purpose efficient and clean separation of the two fibre types is necessary.
In 1990-1991 three mills started mechanically separating the core and bast fibres and sell it for use in different products. Products range from high quality printing and writing paper from bast fibre to adsorbents and horticultural mixes from core fibre [41]. Starting in 1992 Vision Paper still produces tree-free printing and writing paper from kenaf bast fibres [47]. The small scale and batch pulping make the kenaf paper more expensive than traditional printing and writing paper [41].

Kenaf International did new efforts to build a kenaf newsprint mill in the Rio Grande, the project was brought into a partnership with Kafus Industries [48]. In 1997 Kafus planned another 80.000 metric tons per year mill in Southern Carolina [49]. In 1998 the planned capacity was increased to 110,000 tons/yr mill and Kafus announced the plan to built an equal sized mill in Spain [50]. In 2000 Kafus got in financial troubles. The company founder and the company president were removed from the board of directors, but Kafus could not be saved and went bankrupt.
So in spite of all the efforts to build a newsprint mill based on kenaf, it could not be realised. This shows how difficult it is to realise large-scale application of agricultural fibres in this branch of industry. Investments are high and the traditional companies often own large areas of forest and their processes are highly tuned on wood as a raw material.

Representatives of the Australian pulp and paper industry gave a very pessimistic assessment of the prospects for kenaf pulp in Australia at the 1990 ASRRC workshop [51]. Although acknowledging that markets were available for the various kenaf pulps, their view was that the entrenched conservatism of the Australian pulp and paper industry would make it very difficult for a new product to penetrate the Australian market unless it had significant advantages in either price or quality.
One of the conclusions of the workshop was that it was most unlikely that kenaf could be used in existing pulp mills in Australia. This conclusion was based on the following aspects.

- Transport costs from potential sites to the mills will be too high.
- Kenaf is not seen by the existing Australian pulp and paper industry as producing a pulp with specific properties that give significant advantages over wood pulps in blending or for the production of special products.

- Kenaf displayed some disadvantages in processing. These include a low density, which adversely affects digester throughput.

In addition, the equipment that is required for kenaf processing is not entirely the same as that of wood fibres. Modification of existing mills would be needed for storage, handling, separation, washing, digesting and refining.

7.3.2 Commercial Applications

As already written before, kenaf is not likely to be able to compete with wood in bulk applications for printing and writing paper if wood is available. It will be different if kenaf pulp can be sold as a specialty or when (soft)wood has to be imported and transported over longer distances. Two companies are known to produce kenaf chemical pulps.

7.3.2.1 Use of chemical bast fibre pulp

In the USA Vision paper produces 100% kenaf paper and paper made from a mixture of recycled paper and kenaf bast fibre chemical pulp on a small-scale. The price of the kenaf bast fibre pulp that is used is more than three times as high as the price of wood pulp. Separation of the bast fibre is not complete, it still contains 20% of core fibre. According to Rymsza , the small scale of this process together with the infant status of the kenaf industry are the major reasons for this price difference [52]. In the future it is expected that the price of kenaf pulp will drop due to yield improvements in the field and adapted pulping technology. If the production scale could be increased, price would drop further. Vision paper does not have an own pulp mill yet, but makes arrangements with existing pulp mills to manufacture their kenaf pulps.

Vision paper sells its paper products as tree-free total chlorine free printing and writing paper that has environmental benefits. Rymsza writes "There are plenty of potential customers that agree on that, but only a small part is willing to pay the extra costs. High prices bring low volumes, but volumes must increase to lower the prices, a classical chicken and egg problem" [53].

In Japan a great number of the Japanese paper mills use kenaf in at least one of their products [54]. Nevertheless only 15000 tons of kenaf pulp is used in the total production of 30 million tons of paper [55].

7.3.2.2 Use of chemical pulp from whole kenaf stem

Another pulp mill that uses kenaf fibres as a raw material is the Phoenix pulp mill in Thailand. This mill started in 1981 with whole stem kraft pulping and had a capacity of 200 ton/day [45]. It was situated in an agricultural area and due to a lack of forests thought to be competitive with wood. Nowadays this mill converts plantation-based eucalypt, bamboo and kenaf to chemical pulps with the kraft process on a much larger scale then Vision Paper does. The mill has two pulp lines of each a 100,000 tons/year [56]. The whole kenaf stem is used which makes the raw material much cheaper than using separated bast fibre. The larger scale and low wages are other factors that make this pulp cheaper than the pulp produced by Vision Paper. The costs of raw material delivered to the mill are 20% lower than in the U.S.A [57]. Phoenix is producing for local market and export market. There is no indication given how much kenaf pulp is produced at this moment.

7.3.3 *Specialty papers*

Specialty papers are produced in small quantities with very special requirements. Examples of specially papers are cigarette paper, Bible paper, filter paper, banknote and security papers. The usual fibres used in those types of papers are cotton, flax, hemp and abaca.
No actual use of kenaf in this type paper today is known.

A paper mill in Yugoslavia used kenaf bast fibre pulp pure or in blends with flax and hemp pulp to produce cigarette paper. Because of pollution problems they had to close down. The German firm Schöller and Hoesch conducted trials with kenaf and concluded that kenaf can substitute the normal fibres for specialty cigarette and filter papers. They improved the cooking process, which permitted kenaf pulp to be produced cheaper than pulp from flax, abaca and sisal [58].
Preferably high quality retted fibres have to be used instead of the cheaper bast ribbon, as extra chemical costs will exceed the difference in raw material costs.
For cigarette paper flax and hemp are the premium materials. The elementary fibres of these raw materials are split longitudinal in the paper making process which give a fine and uniform paper without becoming impermeable like grease proof paper. The microfibrils in flax and hemp elementary fibres have an angle to the longitudinal axes of the fibre of almost zero. This makes this longitudinal splitting of the elementary fibres possible.
Jute and kenaf have an equal microfibril angle [59], these fibril angle varies between 7 -12 ° [60].

Fike describes that Kenaf has been evaluated in North Carolina as a fibre source. Due to the enormous forest areas and number of tree farms, it was concluded that kenaf would never be grown as a fibre-crop to substitute wood fibres. Instead, application of kenaf bast fibres in specialty products seemed an option. A North Carolina paper company that was producing cigarette paper was interested in contracting kenaf production. Unfortunately this company stopped their research and continued to use flax as a raw material. Their motives to stop the research are not described by Fike [61].

Due to a lack in regularity of supply of kenaf fibres, the Spanish producer of specialty papers CELESA which produces pulp from flax, hemp, jute, sisal and abaca does not use kenaf as a raw material [62].

In specialty papers kenaf fibres have to compete with flax, hemp, abaca and jute fibres. The shorter fibre bundles of flax that cannot be used for textile find their application in this market. The producers of flax fibres always have the advantage that the textile fibres bring in most of their income. It will be very hard to compete with them on the basis of only one application of the kenaf bast fibre
Because jute and kenaf fibres are technically very similar, kenaf will compete mostly with jute. The average import quantities and values in 2002 of jute fibres in the southern European countries according to the FAO database [63] are given in table 4. No indication is given of the quality of the fibres. From these data it can be concluded that separated kenaf fibres can compete with jute fibres at a price of around euro 350 per ton.

Table 4: import quantities and price of jute fibres

	Quantity in metric tons	Value in $	Appr. price in $/ton
Greece	88	25	280
Italy	598	208	350
Spain	4444	1582	360
Portugal	39	25	640

7.4 Bottlenecks for use of kenaf bulk paper applications:

- Storage is expensive and has to be optimal to ensure kenaf of good quality.
- Other process equipment than for wood is necessary
- Installed investments are high. A trial on a production machine is very costly and the risk of cleaning and readjusting of the machinery discourage producers to run full-scale experiments.
- A continuos supply of kenaf of a constant quality has to be guaranteed. Weather conditions can influence the amount and quality of the kenaf fibres

7.5 Bottlenecks for use of kenaf in specialty papers

- Regularity in supply
- Storage has to be optimal to ensure kenaf of good quality

7.6 Conclusions

Technically it is possible to use kenaf raw material for different types of pulp and paper, however the economics of using kenaf compared to wood are mostly in favour of wood. In spite of good prospects in applying kenaf as a raw material for high yield pulps a pulp mill has never been realised. High investment costs and the need for reliable delivery of kenaf, result in high risks. Large-scale applications of kenaf in the western paper industry are not likely to happen in the coming decades

Kenaf cannot compete with wood in large-scale chemical pulping if sufficient wood is available, but small-scale chemical pulping for niche markets is possible and is actually done.

Because of their similarity, separated bast fibres will have to compete with jute fibres in chemical pulping for specialty papers. Jute fibres are imported in Spain at a price of euro 350 per ton.

Small separation mills that produce separated bast and core fibre fractions have a good chance to survive due to the possibilities of using these fractions in different type of industrial applications.

An Alkaline Peroxide Mechanical Pulping experiment is needed to determine if whole stem kenaf has an advantage over wood in power consumption. Whole stem kenaf has to compete with wood on price. In APMP pulping an extra energy advantage may result in a higher kenaf price than for woodchips is paid.

8 Kenaf core absorption particles

If bast fibres are separated an outlet for the kenaf is necessary to prevent that the bast fibre will be too costly. As already described core fibres are not suitable for the production of pulp and paper and the only possible board application is in insulation panels.
Another possible application is the use of core fibres as absorption particles. Kenaf core fibres are actually sold for this application as animal bedding [64] and as oil absorber [65].

8.1 Animal bedding material

Watkins found that kenaf core fibres could be used as bedding material for horses and rodents [66]. One of the criteria of bedding material is that the animals do not eat it. Watkins reports that mice and rats did not eat the bedding material, but he does not mention this aspect in relation to a trial with horses. In the U.S.A. kenaf core is sold as horse bedding material [64]. In Europe kenaf core has to compete with flax and hemp from which the core fibres are also sold as horse bedding material. This bedding material is normally pressed in small bales of 15 kg to 25 kg and packed in plastic, but it can also be delivered as bulk material. On the Internet, discussions can be found on the use of flax, hemp and wood shavings. Horses can get problems with their intestines if they eat their bedding material. People mention these problems for all three bedding materials. The company Hempflax sells bedding material from hemp core and also offers a biospray to prevent horses to eat from it, to hamper bacterial growth and to mask unpleasant smells [67].
Of course transportation costs play a major factor in the actual price and competitiveness of kenaf core. Depending on the transportation distance, the revenues of horse-bedding material in Canada vary from Can$150 to $750 per ton [68], this is equivalent with euro 95 to euro 470 per ton. In the Netherlands a price of around euro 225 per ton is paid for wood shavings delivered at the stables [69].
Animal bedding material must have a low dust content. As with flax and hemp core, the dust in the kenaf core fraction has to be removed. A good comparison of the sorbent characteristics of kenaf, flax and hemp is needed.

8.2 Oil sorbents

Kenaf can also be used as an oil absorber. Goforth found that kenaf plant fines and kenaf milled fines are excellent sorbent materials, both of which are comparable to sorbent materials that are currently used in industrial situations [70]. Ghalambor found that kenaf has the same sorption capacities and a higher retention capacity as polypropylene. Compared with polypropylene and wool kenaf appears to be the most economic sorbent. Calculated at a price of euro 200 per ton kenaf, kenaf absorbs per unit of cost three times the amounts of oil than polypropylene does [71]. Probably due to

different absorption methods, Anthony [72] found quite different absorption ratios than Ghalambor, but he also concluded that kenaf is an efficient absorbent. Choi found that kenaf core performs as well as a polypropylene web does in sorption of high-viscosity oil from seawater [73]. S&S farms offers its absorber at a price of US $ 4.22/lb which equals at this moment euro 780 per metric ton. They claim that their product absorbs 5-gallon of oil per 2.94lbs of kenaf, which equals 13.5 its weight in oil.
With these prices it seems more profitable to use the kenaf core as an absorber than in insulation boards. But due to the bulkiness of the material, profits depend strongly on transportation distances. Again kenaf has to compete with the core of hemp and flax, but the different characteristics measured by different researchers make a comparison difficult. Ghalambor found that the pith within the core absorbs 500% more oil than the woody part (xylem). In contrast with hemp and flax; kenaf contains a lot of pith material in its stem and this might give kenaf better absorption characteristics than flax and hemp. A good comparison of the sorbent characteristics of kenaf, flax and hemp is needed.

8.3 Conclusions

- Technically kenaf core is suitable as bedding material for animals and as oil sorbent and is actually sold for these purposes in the U.S.A..

- The prices of these products are high, but profits will strongly depend on transportation distances.

- Kenaf core has to compete with flax and hemp cores. A good comparison of the sorbent characteristics of kenaf, flax and hemp is needed.

9 Small-scale separation of kenaf

Previous experience shows that large-scale application of a new raw material like kenaf or hemp is hard to implement. In spite of all the positive technical results of commercial scale trials and the commitment of farmers and printers, efforts to build a large-scale newsprint mill based on kenaf in the USA failed up to now. Small-scale mills that separate the fibres and sell them for different applications seem to have more success. Vision paper produces kenaf-based paper on a small scale and appeals on the environmental awareness of the consumers. They sell their more expensive products as tree-free and chlorine-free printing and writing paper.
In the Netherlands an extensive hemp research programme (1989-1993) did not result in large-scale application of hemp fibres in the paper industry, but a private company picked up the challenge and still produces separated hemp fibres for different applications [67]. Similar activities for hemp take place in Germany, UK and France. In Canada several small-scale companies are producing fibres and other products from hemp.

Gradual expansion from a small-scale mill to a larger scale plant must be easier than starting at a large scale for a dedicated application. In large-scale dedicated applications high investment costs and the need for a reliable delivery of kenaf, result in high risks. Small-scale fibre extraction mills have the possibility to sell their fibres on different niche markets, so sales are not totally dependent on one competitive market. Small-scale fibre processing mills, within the agricultural area where kenaf is grown, that are supplying to diversified markets seem to be more viable than large-scale mills. If in a particular market, kenaf has advantages in price or quality over other natural fibres, or if application in for instance in the automotive industry or in specialty pulps is growing, these mills can expand to supply demands. But the kenaf bast fibres always have to compete with other natural fibres like flax, hemp, jute and sisal. This means that to be competitive, also the kenaf core should have its market value higher than for energy applications. For energy application the price of biomass is around euro 30 per ton of air dry biomass, delivered at the power plant. Of course the profits heavily depend on the transportation distances.

The quality of the fibre bundles (strength) depends on the technology of separation of core and bast. If a traditional separation after warm water retting or dew retting can be applied than strong fibre bundles are produced, but this traditional separation is expensive because of labour and high investments in specialised machinery. Fibre extraction can be performed cheaper if green stems are hammer-milled followed by separation of the bast and core fibres. As in the FAIR project has been shown, the strength of the fibre bundles is strongly decreased by the mechanical action in this process.

In the present BIOKENAF project, the first small samples of kenaf are tested at this moment and we have strong indications that the strength of the fibre bundles is seriously affected by microbiological degradation in the field or during storage.
The method of harvesting, storage and separation determines the number of market possibilities. If the fibre bundles are weakened during these processing steps, than only those applications where strength of the fibre bundles is not important are possible. For example the use of bast fibres in insulation mats will not require high fibre bundle strengths. In other applications like compounds for automotives and pulp for paper, where the elementary fibre strength is important rather than the strength of the fibre bundles, the use of weakened kenaf fibre bundles is possible, provided that the elementary fibres are intact.

10 Research topics to be addressed

As already mentioned (chapter 7), large-scale pulp and paper applications are not likely to happen if no substantial process advantages are present. As with whole jute already has been shown on laboratory scale, Alkaline Peroxide Mechanical Pulping for newsprint needs much less energy than pulping of wood. A laboratory scale experiment will have to confirm this with whole kenaf. As energy forms a considerable part of the total production costs, this might give kenaf a chance to be used on larger scale.

A few small-scale kenaf fibre extraction mills are operating in the U.S.A. and in the Netherlands a mill is working with hemp. Those companies are able to sell their products for different markets. In southern Europe similar types of small mills based on kenaf processing have a better chance for success than a large-scale mill which is dedicated to one application. As already mentioned in chapter 9, cheaper separation methods and harvest after winter of the kenaf stems in the field results in weaker fibre bundles. To increase the chances of application of such kenaf crop, special attention has to be addressed to the application of these lower quality fibre bundles.

As already is shown in the FAIR project compounds of plastics with lower quality kenaf fibre bundles performed only slightly less than compounds made with strong fibre bundles. If kenaf has to dry on stem in the fields in winter, microbiological activity on the exterior of the stem is unavoidable. A compounding experiment with these microbiological affected fibre bundles still has to be carried out.

Insulation mats may form another profitable outlet for bast fibres where strength of the bundles is not important. For this application research is still needed. Experiments will have to be carried out on a larger scale and this will require large amounts of bast fibres from the experimental fields.

If the bast fibres are separated, the core fibres preferentially have to yield more than their profit from its energy value of around euro 30 (delivered at the power plant). Otherwise the costs of producing the bast fibres becomes too high to be competitive. Core fibres can be used as absorption particles in animal bedding and oil spill removal. In both applications core fibres can bring a price of euro 200 to euro 250 per ton. Kenaf core has to compete with flax and hemp core fibres. Experiments in which the performance of kenaf core is compared with the performance of flax core and hemp core are needed.

Another application in which kenaf core fibres can be applied is in insulation panels. In this application kenaf has to compete with wood and that will lead to a maximum price of euro 70 per ton. Experiments to produce binderless boards from kenaf core are needed

A&F will focus the experiments on the application of kenaf bast fibres for insulation mats and kenaf core as absorption particles. If time and budget allows it, A&F will also carry out experiments on compounding of microbiological affected fibres, APMP refining of whole kenaf and production of binderless boards from kenaf core.

This results in the following priority list of experiments.

1. **Insulation mats of bast fibres.**
2. **Comparison of kenaf core with flax and hemp core as absorption material in stable bedding and as oil spill absorber.**
3. **Compounding of microbiological partly degraded kenaf bast fibre.**
4. **APMP comparable to already done jute experiment**
5. **Insulation boards of core fibres.**

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Appendix A

Techno-economic evaluation of a PP/agrofibre compounding production plant

I. Investment Estimate

DEFINITION of the process:	**Continuous industrial production of PP/agrofibre granules by compounding on a co-rotating twin-screw extruder**				
Location:		*Start Up Year:* 2003	*Currency:* €		
Machine Capacity [TPA]:	5000				
Operational Hours Per Annum:	8000				
Depreciation Direct Investments [Years, lineair]	10				
Depreciation Allocated Investments [Years, lineair]	20				
ONSITE INVESTMENT					
Process equipment	Type	Amount	Module investment [f.o.b.]		
	Twin Screw Extruder	1	€ 600,000		
	Feeder	2	€ 50,000		
	Vacuum Pump	1	€ 20,000		
	Underwater Pelletizer	1	€ 100,000		
	(granules) Dryer	1	€ 50,000		
	Unforeseen/Contingencies	(10% Onsite Investment)	+ € 91,111		
TOTAL DIRECT INVESTMENT				€ 911,111	
ALLOCATED INVESTMENT					
	Instrumentation	(2% Onsite Investment)	€ 18,222.22		
	Tankage, Storage & Handling	(1% Onsite Investment)	€ 9,111		
	Utilities	(3% Onsite Investment)	€ 27,333		
	Offsites	(1% Onsite Investment)	€ 9,111		
	Environmental Facilities	(1% Onsite Investment)	+ € 9,111		
TOTAL ALLOCATED INVESTMENT				€ 72,889	
LANG FACTOR				€ 1,822,222.22	
ONE-OFF INVESTMENT		(3% Onsite Investment)		€ 27,333	
TOTAL PROCESS INVESTMENT				+	€ 2,833,556
WORKING CAPITAL	Raw Material Supplies End Product Supplies Spare Parts Debtors Creditor Cash + Salaries	(20% production costs)	€ 1,081,212		
				€ 1,081,212	
TOTAL INVESTMENT				+	**€ 3,914,767**

Appendix B

Techno-economic evaluation of a PP/50%agrofibre compounding production plant

II. PRODUCTION COSTS + PROFIT

FLOATING COSTS

		€/#	#/t	€/t compound	€/a compound		
Raw Materials:	Polypropylene	850	0.43	365.5	€ 1,827,500		
	Agrofibres	600	0.5	300	€ 1,500,000		
Additives:	gMA-PP	4000	0.05	200	€ 1,000,000		
	TiO2	1800	0.02	36	€ 180,000		
Utilities:				25	€ 125,000		
TOTAL FLOATING COST			**1**	**926.5**		**€ 4,632,500**	

FIXED COSTS

	Operation		€ 287,500		
	Maintainance	(4% Total Direct Investment)	€ 36,444		
	Laboratory:	(5% Operation)	€ 14,375		
	Staff + Additional	(10% Operation)	€ 28,750		
	Ground Rent	(1% Total Process Investment)	€ 28,336		
	Tax, Insurance	(1% Total Permanent Assets)	€ 3,994		
TOTAL FIXED COST				**€ 399,399**	
TOTAL EXPENDITURE BEFORE PRODUCTION (variable + fixed)			+		**€ 5,031,899**
DEPRECIATION		(10% Total Direct Investment + 5% Total Allocated Investment)		**€ 276,978**	
COST EX WORKS			+		**€ 5,308,877**
Management-, Sales-, and Research Work		(2% Total Production Cost)		**€ 109,461**	
TOTAL PRODUCTION COST			+		**€ 5,473,069**
Intellectual Property Rights				**€ 273,653**	
Profit at 30% RoI (before tax)				**€ 1,174,430**	
			+		
		COST + RETURN			**€ 6,921,152**
		COST + RETURN/ ton compound			**€ 1,384**