

Academic Dissertation

The dry-line method in bast fibre production

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Abstract

This thesis introduces a new harvesting and processing method for bast fibre plants such as flax fibre, linseed flax (*Linum usitatissimum* L.) and hemp fibre (*Cannabis sativa* L). The new combination of the autumn harvesting of linseeds and the spring harvesting of fibres is called the dry-line method®. Originally spring harvesting, on which the dry-line method is based, was introduced for harvesting reed canary grass (RCG) (*Phalaris arundinacea*).

Finnish weather conditions are favourable for ideally weathering the plants for the dry-line method of harvesting. Investigations show that Finnish weather conditions cause a succession of autumn moisture, winter freezing and spring drying of the bast fibre plants. These beneficial Nordic growing conditions offered by nature can be economically exploited.

The existing traditional harvesting and processing methods for bast fibre plants normally present two major problems: high moisture content in the harvested plants and the problem of detaching the bast fibres from the stems. These problems joined with the traditional processing technology used are not responding at the moment to the demands introduced by new industrial products and uses.

Economically the most important aspects of the new dry-line method are the autumn harvesting of the linseed from the bast fibre plants and the low moisture content of the fibre yield in the spring. The autumn conditions are normally dry enough for the harvesting of mature seeds from the tops of the bast fibre plants. For a farmer this guarantees their income in the form of the linseed yield.

In Finnish latitudes (60–63°N) harvesting is possible for both fibre and linseed flax. The advantage of using hemp fibre is based on its photoperiodic properties; hemp fibre does not produce mature seeds in Finland, instead the photoperiodic properties of hemp fibre in the long daylight conditions results in a high biomass yield.

In the dry-line method the linseed and hemp stems have been harvested in the spring after the moist autumn and frosty winter. The relative humidity (RH) of the air is low during the harvesting period, between March and May. This produces an important economical advantage, the equilibrium moisture content (EMC) of the harvested material is low (normally 10% wet basis) the material therefore needs no extra indoor drying. In autumn harvesting, the drying of the biomass is normally a crucial factor because the industry desires bast fibre material with moisture content between 10–20% wet basis. In existing harvesting methods it is not possible to detach the bast fibres before drying the plants.

The winter freezing process on the bast fibre plants results in the easy detachment of the bast fibres. It is now possible to produce new industrial raw materials using existing light farm machinery integrated with simple milling and separation equipment. The new harvesting method enables the use of these materials in applications such as pulp, moulded fibre packages, composites and oil adsorption products.

On the microscopic level the structure of the fibre's surface becomes more open when harvested in the spring. The autumn moisture and repeated winter freezing opens the fibre bundles and pore structures of the bast fibre plants. During the springtime the standing plants are dried under low relative humidity air conditions. This produces much larger surfaces in the bast fibre plant material when compared to the material that is harvested and processed using the traditional methods.

Using the dry-line method (as expected) results in a decrease in the traditional textile fibre quality parameters that is in the fibre bundle strength, while the bast fibres are highly retted. However the detachment of the bast fibres can be carried out easily. These properties can be utilized in bast fibre harvesting, processing and manufacturing. The dry-line method is more economical due to the lower drying costs, easy detachment of bast fibres and higher bast fibre yields during processing when compared to the traditional methods of harvesting and processing.

The properties of the autumn and spring-harvested plant materials were compared in this thesis. Some key investigations into potential new dry-line based product lines such as: adsorption materials, pulp products, and composites were carried out. The focus of the research presented in this thesis has been new economical production lines and products for bast fibre plants.

1. Introduction

1.1 Bast fibre plants in integrated food and raw material production

European agriculture is currently facing new worldwide challenges. Agriculture must be able to respond to the world's food demand but also to demands for raw materials. The use of raw materials will increase in the near future (e.g. Kessler et al. 1998, Hepworth et al. 2000a, Papadopoulos et al. 2003, Ramaswamy et al. 2003). It is obvious that food and raw material production will become more integrated in future production lines (Carruthers et al. 1994, Nemli et al. 2003). In Europe surplus agricultural production has been a problem and for that reason part of Europe's arable land has been kept fallow or in non-food production (Euroabstracts 2002).

1.2 Bast fibre plant production lines

1.2.1 Cultivation areas of bast fibre plants

Interest in using bast fibres in new industrial applications is increasing (e.g. Smeder and Liljedahl 1996, Sankari 2000a, Struik et al 2000, Hughes et al. 2000). Statistically the area used for flax production in Europe is almost 40% of the total area that is used throughout the world (see Table 1). The world's major growers of linseed are Canada and India (Euroflax 2002). The main centres for hemp fibre growing are in China and India (Laue 1995, Corrigan 1996).

Table 1. The growing areas of bast fibre plants in the world.

1000 ha	Growing area yield, 1000 t	Potential fibre 1000 t	Oilseed yield,
Linseed			
Europe	280 ⁴	100 ⁵	340 ⁵
World	3500 ⁴	1400 ⁵	4200 ⁵
Fibre flax			
Europe	210 ³	250 ³	170 ⁵
World	550 ⁴	660 ³	440 ⁵
Fibre hemp			
Europe	50 ¹	50–100	–
World	260 ²	260–520	–

¹(Sankari 2000a), ²(FAO 1994), ³(EU 1999), ⁴(Euroflax 2002), ⁵(Yield levels: linseed fibre 400kg/ha, hemp fibre 1000kg/ha, linseeds 1200kg/ha, flax seeds 800kg/ha)

1.2.2 Traditional pulling methods used for harvesting bast fibre plants

Historically bast fibres have been first pulled and then separated from the stems by hand after retting in water. The surface fibres are “peeled off” from the stems one by one Fig 1. (Corrigan 1996). These methods are still in use when small quantities are needed e.g. when produced for handicraft use. In Europe so-called dew retting (that is retting on the field) has replaced water retting (Sultana 1992). One drawback of water retting is the high nutrient effluents produced, which causes biological oxygen depletion (BOD) in water (Pasila 2001). There has been some development in processing equipment but still these methods require a great deal of human labour and are therefore less economical if the price of labour is high.



Figure 1. Hand produced hemp fibre harvesting, processing, transportation and storage in China (Laue 1995). Photos: Robert C. Clarke, IHA. (permission for reprint applied for)

1.2.3 Harvesting of flax and hemp using pulling

In traditional long fibre production technology, flax and hemp stems are pulled using special machinery so that the flax stalks remain as parallel mats throughout the harvesting and fibre detaching processes. In hemp fibre processing the hemp is collected in bundles, dried on the field and then transported to a storehouse. The drawback with this technology is the large amount of human labour required in the harvesting and processing of the fibre Fig. 1.

Flax plants have short slender tap -roots (Durrant 1976). This makes the flax plants easy to pull from the soil as shown with hemp in Fig. 1. In Europe, until the 1940s, the flax stems were pulled from the soil by hand. Later a mechanized pulling head was developed; one is described in Fig. 2 (e.g. Dambroth and Seehuber 1988). After pulling the pulled flax stems are dew retted by leaving them lying on the surface of the soil for approximately two weeks (Sultana 1992). Retting has an important effect when modifying the fibre surface properties (Zafeiropoulos 2002a).

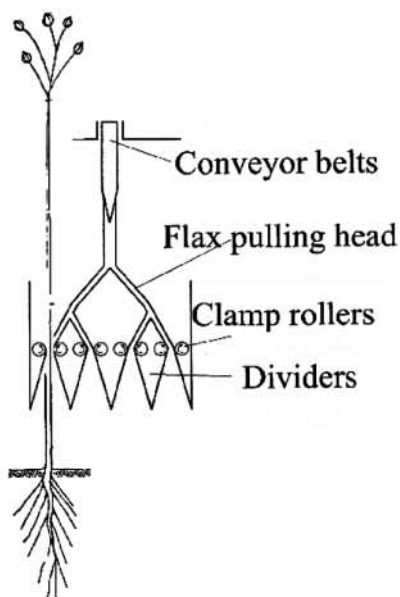


Figure 2. A flax-pulling head. The flax stems are pulled out of the soil using two conveyor belts pressed closely together. Both trailers and self-propelled pullers are used (Dambroth and Seehuber 1988).

1.2.4 Loosening the bast fibres from the stems using existing methods

Retting is a process that dissolves the pectin glue between the bast fibre bundles. Retting can be carried out using dew retting, soaking the stems in water or ageing the plant stems microbiologically in controlled conditions (e.g. Sultana 1992). Retting facilitates the separation of bast fibres from the woody parts of the bast fibre plant stems. In hemp fibre processing controlled retting has always been a problem (Ranalli 1999, Hobson, et al. 2001). Dew retting especially is difficult to control. In addition after retting the indoor drying of the retted stems down to 15 % wet basis is always required (Sultana 1992). The traditional technology however has been used widely to separate fibres and fibre bundles from the woody core (Rowell et al. 1997).

The new uses that bast fibres are put to (e.g. in automotive composites) set new demands on the production of the fibre raw material. To produce randomly orientated short fibres new methods, such as steam explosion, have been presented (Kessler 1998). Using the steam explosion method the fibre bundles and cells are detached by using released and expanding steam. A problem with the steam explosion method is one of economy. Industry requires the moisture content of the bast fibres in the total biomass to be relatively low (10–20%). The total biomass has to be treated with high-pressure steam in special containers.

One logistical problem is the yearly imbalance of raw materials supplied by agriculture and the industrial demand for raw materials to be used in the pulp and paper industry. The pulp and paper industry is running all year long, however the harvesting period of the agricultural raw material is short, at most some weeks (Hemming et al. 1996). Therefore the raw material has to be stored for up to one year.

In the pulp and paper industry one method used to detach the bast fibre cells is the alkali pulping process. Before storage the bast fibre plant raw material has to be dried to a level of 15% wet base to maintain its quality during storage (Sultana 1992). Low moisture and microbe levels are essential for long storage periods to guarantee reasonable fibre quality for the pulping processes. Pre-treatment of dried raw material before pulping is essential to decrease the amount of dust and core fibres amongst the pulped fibres (McCloskey 1995).

1.2.5 Harvesting and processing of pulled and retted bast fibre plant stems

After dew retting the pulled stems are dried and baled using a special baler. The stems are picked from the soil surface in the bale in a uniformly orientated direction Fig. 3.

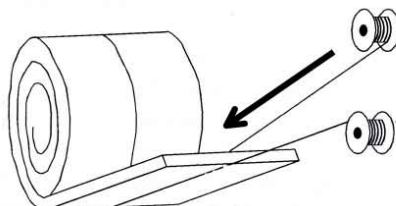


Figure 3. Stems are baled in the form of a uniformly orientated mat. The rolled flax layers in the bale are separated using yarn (Dambroth and Seehuber 1988).

The flax bale is opened on the feeding table of the core remover. On the decortication line the bast fibre stems are transported through the line pressed in-between two conveyor belts. The parallel-orientated direction of the detached and scutched bast fibres is kept unchanged throughout the process. The tows and shives are dropped onto the conveyor under the process line. The capacity of a decortication/scutching line (Fig. 4) is between 300–500 kg stems per hour (Sultana 1992). At a level of approximately 10% bast fibre yield the productivity of this type of machinery is between 25–45 kg of scutched industrial bast fibres per hour. 6–8 people are needed to operate the processing line. For the manufacture of industrial slivers or needle-punched mats (which are used in for example composites) additional hackling or carding processing is required (e.g. Ringleb 1996).

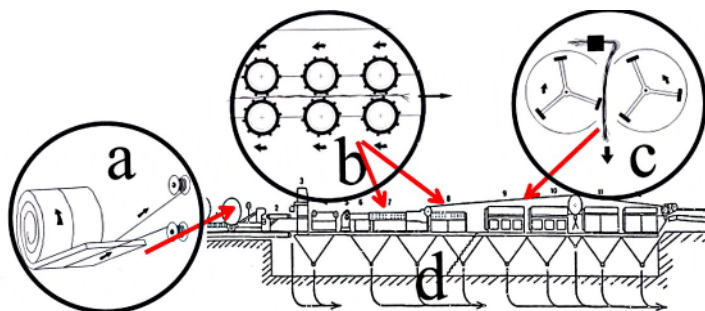


Figure 4. Processing of orientated flax stems to manufacture scutched bast fibre. Parts: a = opening the mat-form bale, b= decortication of the flax stems, c= scutching of the bast fibres, d= flax decortication and scutching line. (modified from photos in: Dambroth and Seehuber 1988, Sultana 1992).

1.2.6 Short fibre processing technology

Flax and hemp fibre bast fibre cell lengths are in the range of 5–70 mm. (Ilvessalo-Pfäffli 1995). In bast fibre plants the fibre cells are joined together forming up to stem-long fibre bundles which are utilized in yarn and textile manufacturing. The fibre length of coniferous fibre cells is 1–10 mm (Ilvessalo-Pfäffli 1995).

In a research project “Hemp fibre as a raw material for pulp” (financed by the Finnish Ministry of Agriculture and Forestry) hemp fibre was utilized as a raw material for pulp (Pasila et al. 2001b). Experiences from this investigation showed that during normal pulp processing using wood as a raw material it could be troublesome when bast fibres more than 10 mm long were used and could cause problems in for example; mixers, screens and pumps. Because of these experiences a 10 mm length was used as a classification limit for both short and long bast fibres in this thesis. In bast fibre processing this has in practice meant the cutting of bast fibre plant stems, fibre bundles and cells into 10 mm or shorter fragments.

The capacity of a short bast fibre processing line is 2000 kg of stems per hour (Temafa 1997) (Fig. 5). Depending on the quality of the raw material the tow type bast fibre yield is 200–600 kg per hour (Pasila et al. 1999). The processed bast fibre is randomly orientated in industrial fibre raw material. The length of the bast fibres depends on the pre-treatment (cutting) of the stems.

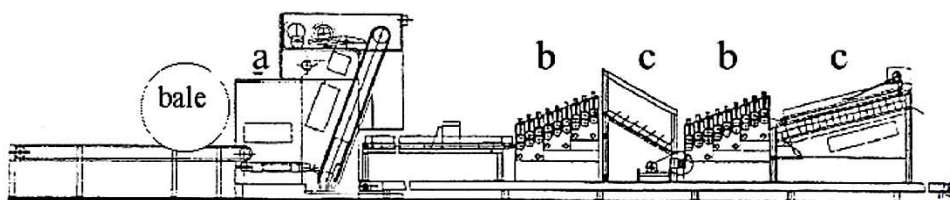


Figure 5. A short fibre processing line “Lin Linie” by Charle/Temafa. In short fibre processing the raw material is in round bales. The stems are packed randomly in the bales. Parts: a= bale opener + pre-treatment, b =decortication, c= shaking sieve (Temafa 1997).

1.3 Bast fibre production and processing at high latitudes: weather conditions

The average daily temperature peaks and relative humidity (RH) in southern Finland are described in Fig. 6. It is remarkable that the highest temperatures are reached in July but the lowest RH is in May (Paper V).

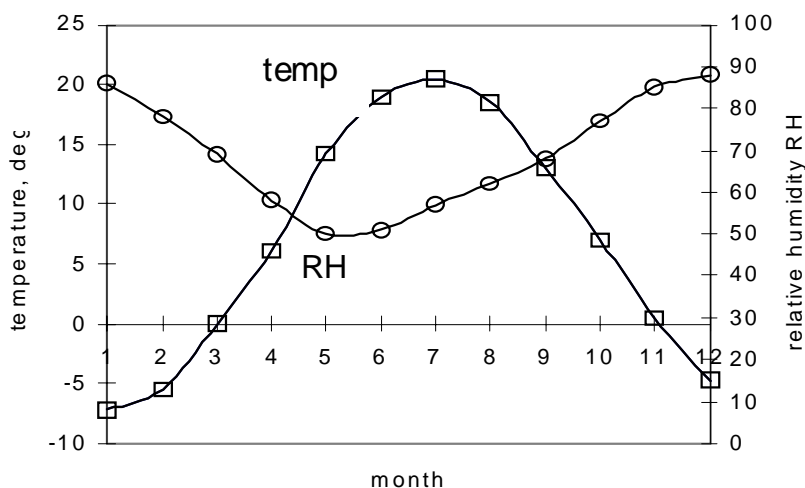


Figure 6. The average monthly temperatures and RH in southern Finland (Paper V).

The main problems with bast fibre plant harvesting and processing in Europe, especially in Nordic areas, are economical and technical. The moisture content of autumn harvested stems is; flax 35 % and hemp fibre 50–70% wet basis.

The drying cost especially of hemp fibre in autumn is intolerable (Pasila et al.1999). Technically the main problem is the separation of bast fibres from the overall biomass. The time available to detach fibres is insufficient during the harvesting period (e.g. Sultana 1992, Temafa 1997). For that reason the storage of harvested stems is essential. Fibre production seems to be a struggle throughout Europe with the same problems as in Finland (Ranalli 1998). However with short summers and moist autumns these problems are emphasized in Finland. The equilibrium moisture content (EMC) of flax was measured during thermal insulation material investigations (Rissanen and Viljanen 1998). The EMC curve is described in Fig. 7.

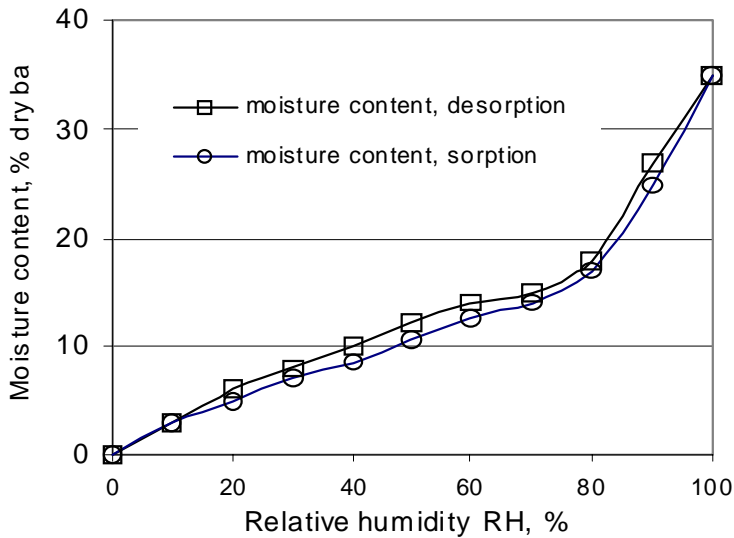


Figure 7. Equilibrium moisture content of flax bast fibres (Rissanen and Viljanen 1998).

The air humidity in autumn during September-October often exceeds 80% relative humidity (RH) (Fig. 6), which means that the equilibrium moisture content (EMC) of flax fibres rises above the critical figure of 18% moisture content dry basis (15 % wet basis¹) (Fig. 7). This is when the destruction of the fibre begins (Sultana 1992). In these conditions both indoor drying and storing of the yield is needed. On the other hand in spring at 50% RH the moisture content of the fibre material is approximately 10% dry basis. The information in Figs. 6 and 7 clearly shows that in spring the moisture content of bast fibre plants on the field is low and that no extra drying is needed.

¹ In fibre and wood technology the moisture content is described in dry basis (d.b.) where water content is compared to the dry weight of the matter. The values of moisture contents may exceed 100%. Instead in agriculture moisture content is widely described in wet basis (w.b.) where the water content is compared to the weight of the moist material the maximum value of moisture content is 100%.

2. Objectives

The use of the dry-line method in adsorption filter applications was introduced in 1998 in FIN Patent 101608 and for pulp and paper applications were introduced in 2001 in FIN Patent 108302. In these patents are described the method of using weathering to facilitate the easy production and processing of bast fibre materials. In addition the background of the dry-line method has been investigated in numerous research reports, which are cited in the references.

The background for the objectives of this thesis has been an attempt to solve the problems of the supply of high quality agricultural raw materials that that meets the demands of industry and to fuse the different viewpoints in the economic feasibility, quality parameters needed and logistical practices used to create appropriate production lines.

The objectives of this research are:

- A. To investigate the new dry-line method for bast fibre plant harvesting in Northern latitudes with respect to the qualities and properties which are required by new industrial products and processes.
- B. To compare any benefits or drawbacks of the dry-line production method on the structure of the bast fibre plants.
- C. To evaluate the validity and economic viability of the dry-line method in the introduction of new bast fibre based products.

3. Introduction of the dry-line method and its physical background

Originally the spring harvesting method was introduced in Sweden for reed canary grass (RCG) to product raw material at as low a cost as possible (Hadders 1993). In Finland Hemming et al. 1996 investigated the spring harvesting of reed canary grass for pulping. In the harvesting of RCG movers and round balers were used. Reed canary grass is normally beaten down under the weight of snow during the winter, whereas hemp fibre remains standing due to its thick and firm stem. For this reason the harvesting period for hemp fibre is longer than for that of RCG.

The dry-line method is a system of combining; bast fibre plants, oilseed harvesting and new processing methods into a single process. The results of this process have been to introduce products with new properties. In this thesis the basic idea of the dry-line method of the harvesting of bast fibre plants is described in paper V.

The feasibility of the dry-line method in different applications has been investigated between 1996–2003 (Pasila et al. 1998, Pasila et al. 1999). The properties of the new dry-line method have been studied in industrial applications such as: thermal insulation materials (Kauriinvaaha et al. 2001), the pulp and paper industry (Pasila et al. 2001b), moulded fibre products (Tavisto et al. 2001), adsorption materials (Pasila 2001) and composites (paper II). The results of these studies were used and the scientific backgrounds reported in papers I–VII.

3.1 The dry-line method

The dry-line method in bast fibre plant harvesting means a combination of autumn harvesting of oilseeds and spring harvesting of fibres. The raw material in the investigations was produced using the dry-line method (Fig. 8). The properties of the dry-line yields are compared to traditionally produced raw materials.

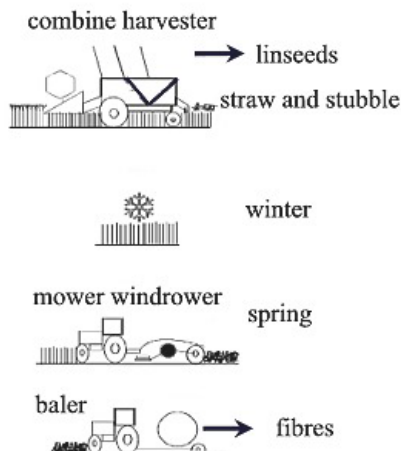


Figure 8. The dry-line method in flax and linseed harvesting (paper V).

3.2 Ice formation during late autumn and winter in bast fibre plants

The daily temperatures and RH are presented in Fig. 9. The repeated temperature changes above and below zero degrees C are important because freezing and ice formation occur in the stems during these temperature falls.

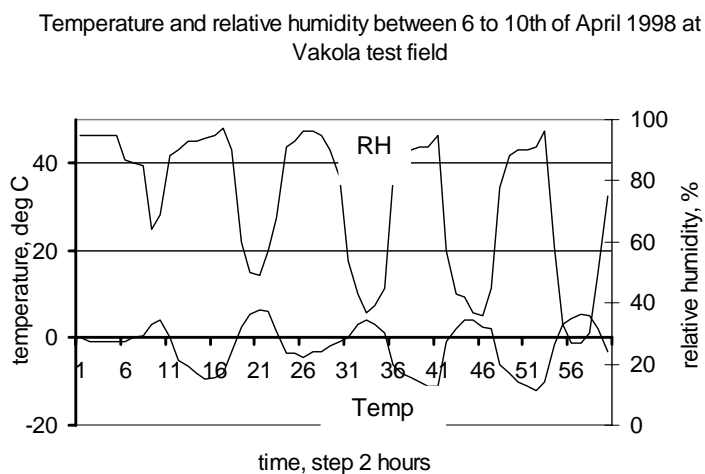


Figure 9. The daily temperatures and RH in spring 1998 in MTT Vakola (at 60°30'N) test fields. (paper V)

In the later studies (paper II) the experiments showed that the temperature and RH changes already appear in the autumn Fig 10.

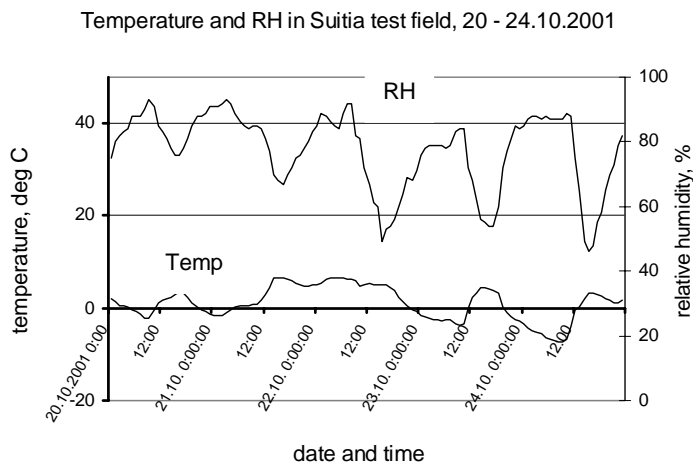


Figure 10. Daily temperature and RH changes during the first frosts in autumn 2001. The readings were taken on the Helsinki University experimental farm in Suitia (60°15' N).



During the autumn experiments the detachment of the bast fibres were already observed after the first autumn frosts, see Figs. 11 and 12. In the field the ice detachment of the hemp bast fibres can be seen in the shape of a bow. Fig 11.

The frost has a crucial effect on bast fibre plants with high moisture content. The frost detaches the bast fibres from the plant stems. Therefore from the point of view of the plant processing, freezing is an important economical consideration when the production of bast fibre in Nordic conditions is considered.

The reason behind this phenomenon was discovered by chance: After one frosty October night (about -5°C), some hemp fibres had changed into a bow shape in the field. The weather data for those days is given in Fig. 10.

Figure 11. Detached hemp fibres after an autumn frost night.

Already after only one frosty night in autumn an ice layer can be seen in the hemp fibre stems Fig. 11. A close inspection of the hemp fibre stems reveals the consequences of the frost: In Fig. 12 it can be seen how a thick layer of ice has developed between the core and the outer bast fibre layer and broken the firm bonds that anchor the bast fibre bundles to the core. The pressure or tension caused by the ice is sufficient to break the bonds and detach the fibres.

The ice mantles surrounding the core of the stems reach up to 1.5 m and the approximate thickness of the ice is 2 mm. The diameter of the stems studied was about 2 cm, which results in the volume of ice being about 200 cm³ which corresponds to up to 200 ml of water on a single plant. The ice forms in the green living stems.



Figure 12. Ice forming on a living hemp fibre stem (paper II).

3.3 Plant freezing under a microscope

The more detailed information was obtained using an electron microscope to investigate both autumn and spring-harvested reed canary grass and bast fibre samples. The reed canary grass (RCG) was the first plant used in the microscope experiments; the structure of the plant leaves was investigated to localize the SiO₂ concentrations.

Reed canary grass is a perennial grass not an annual herb as is flax and hemp. The structures of stems and leaves are different in these plants. One major difference is the high concentration of silica in the form of opaline SiO₂ in grasses (Marschner 1993). In Fig. 13 the underside of reed canary grass leaves are shown. The nearby silica shields of

evaporating cell openings are clearly seen in the photographs. Some of the silica shields are partly detached. In the photograph the heavier particles in the cell structures are lighter in colour.

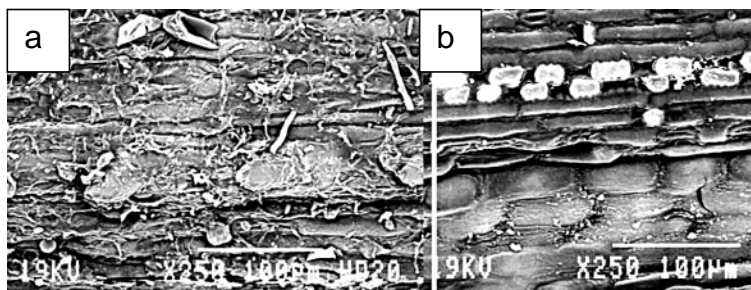


Figure 13. The reed canary grass leaves in a SEM microscope. To the left “a” is an autumn leaf which is covered with wax and moulds. To the right “b” is a spring-harvested leaf. The light areas in b are silica shields.

The observations of the silica shield detachment while investigating reed canary grass for oil adsorption led us to use the microscope when investigating the bast fibre plant (paper VI, Tavisto et al. 2001).

Autumn and spring-harvested flax fibre bundles were photographed from the side using an electron microscope (Fig. 14). In the autumn harvested samples the fibre cells were “welded” together. In the case of the spring harvested samples the fibre cells were completely detached and none of the fibre cell’s jointing “glue” was visible.

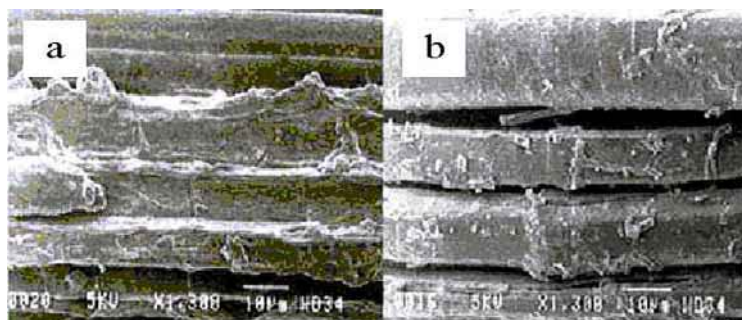


Figure 14. Flax fibres photographed from the side. To the left “a” an autumn harvested flax fibre bundle. To the right “b” a spring-harvested fibre bundle (paper V).

Hemp fibre bundles were studied using wax impregnation. The samples were cross-sectioned, coloured and photographed under a light microscope to see the effect of the frost (Tavisto et al. 2002). Fig 15. In the autumn harvested stem cross-section the fibre bundles are clearly seen. The fibre cell lumens (the empty spaces in the cores of the fibre cells) are clear and open. In the spring harvested fibre stem cross-section the fibre bundles are separated and even individual fibre cells can be seen.

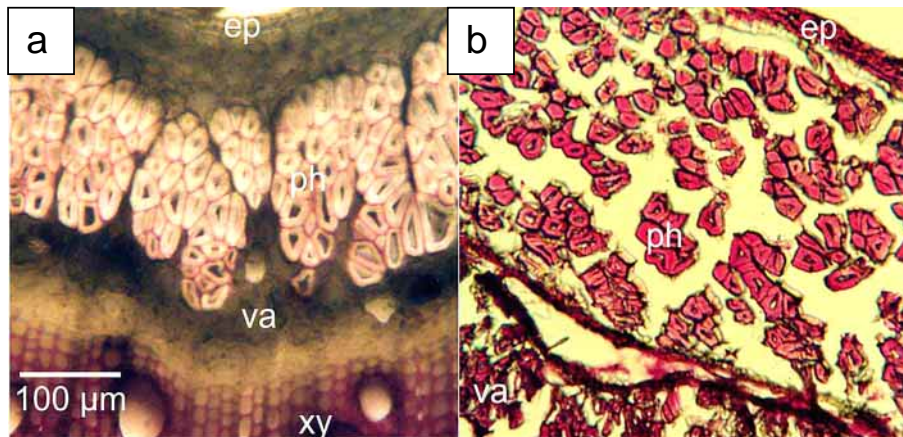


Figure 15. Cross-section of hemp fibre bundles. To the left “a” autumn harvested hemp fibre bundles. To the right “b” spring harvested hemp bast fibres. Terms: ep=epidermis, ph=bast, va=vascular cambium, xy=xylem (Tavisto et al.2002).

4. Materials and methods used in testing the dry-line method

The harvesting experiments were carried out using traditional field experiment methods. New separation methods were introduced during processing. Existing methods were applied for wetting and capillary measurements. In composite testing both the measurements of reinforcing fibres and the testing of produced composites were used.

4.1 Dry-line method of harvesting bast fibre plants

The major difference with the earlier spring harvesting of reed canary grass (RCG) and the new dry-line method is the harvesting of the bast fibre plant's seeds. Harvesting of oilseeds economically covers the raw material production costs. Autumn harvesting of oilseeds was integrated into the spring harvesting of the fibres. Under Finnish weather conditions the oilseed yield was mature when harvesting the linseed varieties (Fig 16). During the experiments none of the hemp fibre varieties produced mature seeds.

The seed yield for the linseed varieties "Norlin" and "Helmi" were harvested using a combine harvester. The yields for the test areas and/or the total yield of experimental field were weighed. The dry weight of the stems was measured using 5 different samples, each from a 1 square meter area.



Figure 16. Harvesting linseeds using a self-propelled combine harvester.

In the spring the flax stems were cut using a prototype “Junkkari” 2.6 m rotary mower. Hemp fibres were cut with an “Aros” 1.8 m cutter bar mower whose stroke speed was increased up to 1000 strokes/min. The cutter bar blades were sharpened and the bar set.

The cut flax and hemp fibre stems were baled with a changing chamber “New Holland 654” round baler (Fig. 18). The bale size is (1.2m by 1–1.5m diameter) and the average weight was 300–450 kg. The capacity of a trailer truck is approximately 50 bales of this size (Hemming et al. 1996). This means in the case of spring-harvested flax and hemp fibre 15 and 23 tonnes respectively per load/trailer truck.

The cutting of the hemp fibre was troublesome in the spring due to the detached and dropping down of the bast fibre strips (Kautto et al. 2001). The method used for hemp cutting in the field experiments was to use a traditional cutter bar mower Fig. 17 with increased cutter bar speed from 540 up to it’s maximum of 1000 strokes/min.



Figure 17. Cutter bar mower used in the spring cutting of hemp fibre on Suitia experimental farm in May 2001.

The density of bales produced by the baler was high, approximately 200 kg/m³ (Fig. 18). The bales were tied with a net and some were wrapped in plastic. During baling the bast fibres easily twisted around the picker reel. Great harvesting losses were recorded when the shives first met the bale compressor rubber belts, after the picker reel.



Figure 18. Harvesting hemp fibre with a round baler on the Suitia experimental farm in May 2001.

4.2 Processing of dry-line harvested bast fibre plants

The opening and partly cutting of flax and fibre hemp bales was carried out using a “Tomahawk” bale chopper which was originally designed for straw chopping Fig. 19. The outlet of the bale chopper was connected to feed the pre-processed fibre stems into the hammer mill. The head of the bale was pressed against a plate rotating at 1000 rpm. The robust steel plate is equipped with sharpened triangular blades that cut the bale.



Fig 19. The “Tomahawk” straw chopper (right) combined with a hammer mill (left) as a round bale opener is tested in Viikki in the autumn of 1999.

A hammer milling system (Kamas 30 kW, with sieves 8–20 mm) was built for processing the spring-harvested dry stalks Figs 19 and 20. After milling the raw material was first blown through a cyclone to remove the dust which was measured (n=5). Through

the lower outlet of the cyclone the milled fibres were fed into a rotary screen with opening sizes of 2.5 and 3.7 mm or 1 and 5 mm. The chopper/hammer mill combination in Fig 19 is the first prototype with no optimum finishing and was only for researching raw material production.

The milled material was fragmented using a rotary screen into bulky cotton-like fibres and chip-like shives Fig. 20. The distribution of the fragments was measured ($n = 5$). In adsorption material processing a modified rotary screen with 1 mm and 5 mm sized sieves were used.

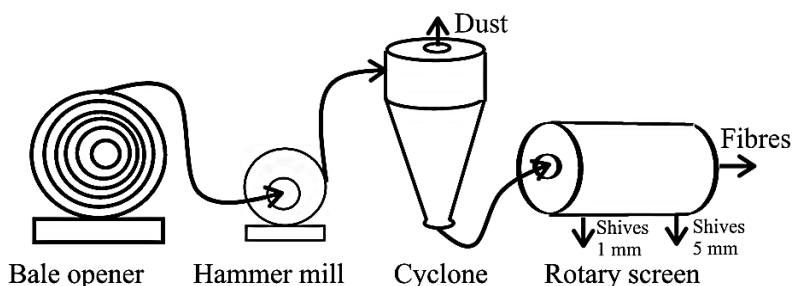


Figure 20. The diagram of a simple milling and screening system for flax and hemp fibres.

The dry weight was measured using five samples in each case. A bulk distribution diagram using the measured weights was drawn. The moisture content of the harvested material was approximately 10 % w.b.

4.3 Adsorption properties of processed materials

4.3.1 Adsorption measurements (paper I)

Oil spill adsorption studies were carried out using reed canary grass (RCG), flax and hemp fibre fragments. RCG has a different fibre structure having shorter fibre cells in the stems than bast fibre plants such as flax and hemp fibre. RCG has also a high silica concentration.

The remarkable swelling of the adsorption materials, however, changed the size of capillaries during the test and caused a delay in the capillary rise in the test equipment described in Fig. 22. This led us to use a different method for the adsorption measurements. The adsorption material was packed into a cone shaped tube. The test was also carried out passing the liquid (oil+water) through the adsorption material. Fig. 21.



Figure 21. Oil adsorption filter and test equipment.

4.3.2 Capillary rise (paper IV)

The measurements were carried out using a capillarity tube that was filled with equal weights and densities (4.8 g , 0.17 g/cm^3) of adsorption material (Nevander and Elmars-son 1994). Fig. 22. The water level was raised until the first fibres in the tube were in contact to the liquid. Five samples were made to test material variations.

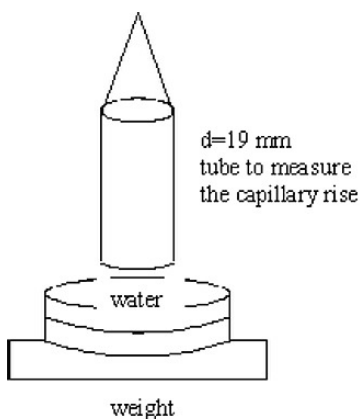


Figure 22. A method to measure the capillary rise.

4.3.3 Adsorption times and contact angles of bast fibre fragments (paper III)

Both words adsorption and absorption are used in this thesis. *Adsorption* means after the Latin word “ad” = “on surface” and “sorption” = penetration of liquid or gas in a solid material“. *Adsorption* appears when liquids are spread on surfaces. The word absorption means “ab” = “inside“. In physics the word *absorption* is widely used to describe the behavior of radiation. However in applications such as textile science or in filtration the word *absorption* is used to describe the water or oil *absorption* capacity of a *filter* or a *fabric*, i.e. the macroscopic sample (e.g. Bertrand 1992, Warner 1993).

The contact angles of liquids on solid surfaces were measured by photographing the drops on solid surfaces. Figs 23–24. Five samples were recorded in each case. The adsorption materials had typically rough surfaces. To increase the reliability of the measurements the adsorption materials were milled with a laboratory hammer mill equipped with 0.5 mm sieve and pressed into a tablet form in a 30 mm diameter cylinder with 75 MPa pressure. The idea was to retain the surface of the fibres and shives as natural as possible. So on the tablet’s surface measurements this meant more transverse and less cross-sectional stalk sections.

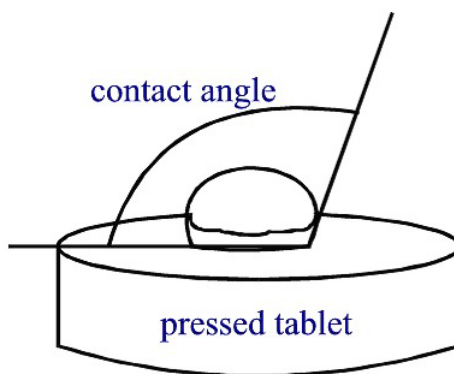


Figure 23. Measurement of the contact angle

A 0.02ml (oil) or 0.04ml (water) droplet of liquid was placed onto a tablet with an injection needle. The droplet was illuminated with a 2mm ”Maglite®” fibre optic cable. The ending of the reflected light showed the moment when all of the liquid was adsorbed. The wetting time of the drops in different fibre materials were measured.

The contact angle measurements were carried out using a digital camera with macro zoom and a fast shutter Fig 24. The shortest adsorption time of the drop that was recorded reliably was 3 seconds. The digital photos were edited with “Photo Draw 2” software to define the exact values of the contact angles.



Figure 24. Large contact angle of a water drop on a pressed tablet.

4.3.4 Adsorption under pressure

Another method used to evaluate the adsorption properties and the structure of the adsorption materials was the membrane press (paper VI). Fig. 25. The samples under investigation were first tested to find out the maximum adsorption capacity. Afterwards the samples were pressed to find out the mechanical structure of the materials.

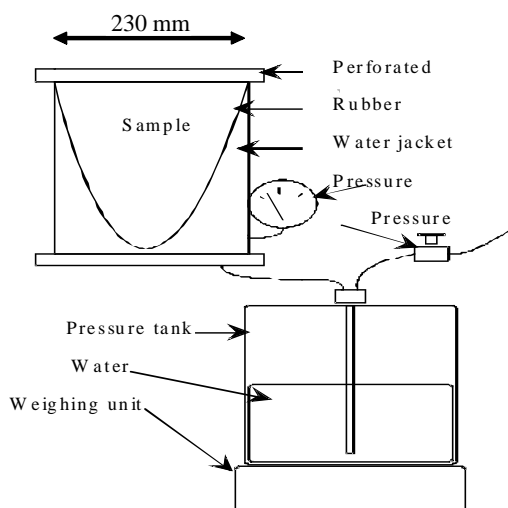


Figure 25. The membrane press used to measure the adsorption of biomaterial samples under pressure.

Using the membrane press for plant material measurements it is possible to compare the adsorption of liquids. When measured at pressures between 0-100 kPa the liquid drainage curve is of a non-linear logarithmic form while the free liquid flows out from pores. With pressures above 100 kPa on the jacket of the membrane press the liquid drainage curve of the samples is linear while the adsorbed water from the surfaces is pressed out (Pasila 1995).

4.4 Testing of composites from autumn and spring harvested bast fibres (Paper II)

Measuring the composite strengths tests the adhesion of the resins. The effects of the dry-line method on the adsorption properties are measured using capillarity, adsorption filter, contact angle and wetting time.

Bast fibre strips were used in composite beams in a somewhat similar way as to those described by Hepworth et al. (2000a and 2000b). This enabled the development of plywood type structures for testing. In the present study fibre bundles were separated from the shives, but fibres were not separated from each other. Pectin and other natural resins, which are bonds between cellulose fibres in plants, were not removed using retting. The process requires a new decortication method, which is gentle enough not to break down the un-retted fibres in the fibre bundles.

A simple decortication method, partly the same idea as described in Fig 4 (b) in chapter 2 was developed to decorticate, that is, to remove the central woody shive material from the hemp fibre strips. Some of the strips were removed by hand and some by pushing the stems between two wheels in a way similar to that described by Keller et al. (2001) who processed dried stems and needed five steps in the process to obtain bast fibres that were sufficiently free of shives to be used in composites. In our study we used fresh, dried and icy hemp stems to make fibre strips. The “Fedora 19” variety hemp plants were grown according to common Finnish farming practices (Sankari and Mela 1998).

In the case of the frozen stems the shives and fibre strips were totally detached from each other in one stage, because of the contrast between the brittleness of the shives and the toughness of the fibres (Niklas 1992). After detachment the fibre strips were dried for several days. This is much cheaper than drying the whole stem. Furthermore, the drying process turns the fibre bundles into thin strips 10-20mm wide and approximately 1 m long. The use of these fibre strips leads to a very economical method of obtaining an orientated long fibre structure of even quality. The strips are easy to process into a plywood form.

Another fabrication method was to use already existing industrial needle-punched fibre mats, which were originally made for thermal insulation purposes. The mats were manufactured from dew retted flax or spring-harvested hemp fibres. The question was if it is possible to obtain strong enough recyclable structures at a competitive price.

The mats were industrially manufactured with a non-woven needle-punch carding unit that produces a randomised three-dimensional fibre distribution in the mat. The raw materials were autumn harvested dew retted flax (variety Viking) and spring-harvested hemp (variety “Beniko”). The flax mat was 6 mm thick. A total of 48 layers of 110mm by 150mm mat pieces were used (Fig 26). Between each layer 4ml of adhesive was spread. The pile was compressed in a steel mould with 6–8 MPa pressure. About 10g of the adhesive leaked out from the mould. The final density of the composite was 1.3g/cm^3 with a fibre fragmentation mass of 61%. The hemp mats used were 12mm thick and the final fibre fragments mass in the composites was 51%.

The bending and tensile properties were measured with a LLOYD Instruments universal testing machine. The testing speed was 0.1 mm/s in all cases. In the three-point bending test the size of the beam was 20 by 20 by 150mm. A length of 100mm was used in the tension tests. Five samples were tested in each case.

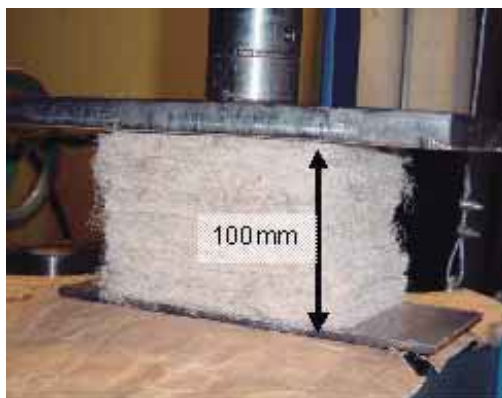


Figure 26. Mat layers with intermediate adhesive layers before compressing the hemp fibre composite test beams.

5. Results

5.1 Results in yield, harvesting and processing

5.1.1 Stem yields of bast fibre plants

The linseed harvesting tests were carried out during 1996–97. 200m² test fields (n=3) were harvested in the autumn of 1996 and the spring of 1997 and the yields were compared. The results are presented in Tables 2 and 4.

Table 2. The dry mass yields in the first harvesting experiments 1996–97 for flax, linseed and hemp fibre.

Plant+ Variety	Autumn total yield, kg/ha	Autumn seed yield, kg/ha	Autumn yield stems kg/ha	Spring total yield, kg/ha	Winter- loss, %	Spring- harvested yield, kg/ha	Harvesting loss, %
Flax, Viking	5 700	1 200	4 900	3 900	32	3 050	22
Linseed, Helmi	4 400	1 000	3 400	3 000	32	2 200	27
Hemp fibre, Felina 34	7 100	–	7 100	5 950	16	5 100	14

Typical moisture contents of the harvested yields are described in table 3. In table 3 all the harvested yield fragments, except the spring-harvested stems, need indoor drying to reach the 15% moisture level for adequate storage.

Table 3. Typical moisture content of fragments measured during the investigations.

Fragment yield	Moisture content in % w.b.
Autumn harvested oilseeds	20–25
Autumn harvested flax stems	30–35
Autumn harvested hemp fibre	50–70
Spring-harvested flax and hemp	10

The first experiments in 1996–97 were carried out partly using hand tools for harvesting. For that reason the hemp fibre yields especially are not comparable to the yields described in Figs. 29–30. Harvesting using production size machinery causes more harvesting losses than described here. The later hemp variety in Figs 29-30 is “Fedora 19” instead of “Felina 34” in Table 2.

The dry line method was investigated for hemp fibre harvesting. The later harvesting tests were carried out between 1998–2001 using a pilot scale cutter bar mower and round baler. The hemp variety was “Fedora 19”. The capacity of the pilot harvesting machinery during the experiments was about 0.5ha per hour.

5.1.2 Oilseed yields of bast fibre plants

The oilseed yield of linseed is of crucial importance for the economical viability of linseed growing. In table 4 the yields are compared to earlier official Finnish variety tests in the years 1985–92 (Vilka 1993). On the bottom line there is the approximate yield and value of barley grown in Finland

Table 4. Oilseed yields and approximate values of linseed varieties.

Linseed variety	Yield, kg/ha	Approximate value of the yield, technical use 0,24€/kg food 0,35€/kg ¹
Norlin 1996	2000	480–700
Helmi 2002	2200	530–770
Laser 2002	2700	650–950
Official variety tests linseed 1985–92, Helmi	1700	430–600
Barley (comparison)	4500	400 (appr. 90€/t)

¹ Price level in 2002 from Elixo oil ltd

As shown in table 4 the value of the linseed yield is compatible with the value of grain yields in Finnish conditions.

5.1.3 Processing of bast fibre plant stems

The first milling tests were carried out milling spring-harvested hemp fibre. The decoction using the hammer mill and rotary screen produced bast fibre fragments using the hammer mill sieve sizes 8–20 mm. Fig 27.

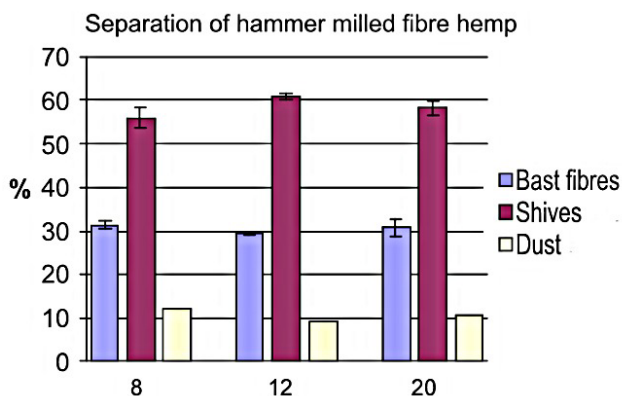


Figure 27. The separation of hemp fibre fragments using 8, 12 and 20 mm sieves. The fragment yield is compared with the weight of milled samples. (n=3).

The separation of bast fibres was carried out in this part of the research to produce loose fill thermal insulation materials (Pasila et al. 1999). The different raw materials are compared in Fig. 28. The results clearly show the effect of the dry-line method. The bast fibre yield in all the hammer mill sieve sizes is the highest when spring-harvested material is used.

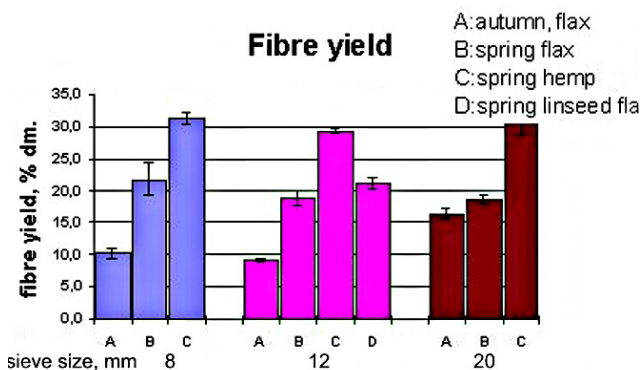


Figure 28. Autumn and spring harvested hemp and flax bast fibre and shive fragments. The weight of the fragments is compared with the milled weight. (n=3).(paper V)

5.1.4 The bulk flow of bast fibre plant fragments

In the dry-line method there exists losses before processing the harvested bales. Fig. 29 shows the production line and how the average losses of hemp bast fibre occur. Even though the results are not totally comparable with the results in Tables 2 and 4 it can be seen that the final bast fibre yield is at a competitive level when the dry-line method is applied.

The reasons for the losses in the production line can be seen in Fig. 30. They are: winter (20 units) and harvesting (30 units) when compared to the autumn yield. When comparing Tables 2 and 4 it seems possible to decrease the harvesting losses easily. The winter losses are at the same level in Figs. 29 and 30 as in Table 4.

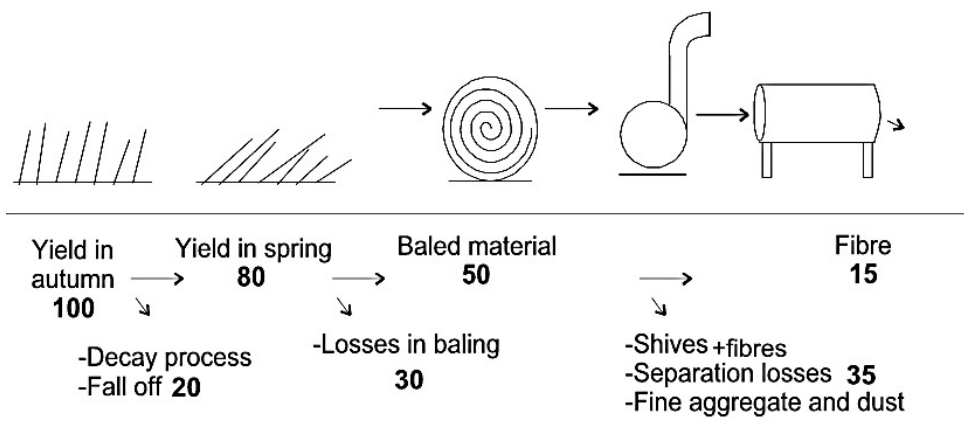


Figure 29. The bast fibre bulk flow of hemp fibre during harvesting and processing. The total processing line results are described in a more simplified flow chart in Fig. 30.

The harvesting was carried out using a cutter bar mower and round baler. The processing of the hemp fibre samples was carried out using a bale chopper, a hammer mill, a cyclone and a rotary screen as described in chapter 4.1 and 4.2.

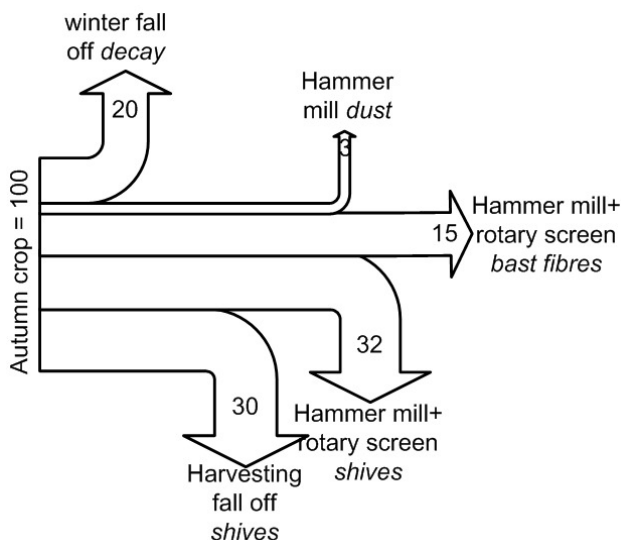


Figure 30. A simplified flow chart describing the processing of spring-harvested hemp fibre. The distribution of the bulk is based on dry mass weight.

In Fig. 30 the relative yield in each part of the process is compared to the autumn crop, which is set to 100. The numbers of the figure are based partly on the results shown in Figs 27 and 28. The amount of dust is based on the filtered amounts measured from the out-going cyclone air.

5.2 Results of adsorption properties

5.2.1 Results of bast fibre fragment filters in water and oil adsorption

The adsorption tests with low concentrations of oil (0,4–0,45 g oil per 1000g water) were carried out. The purification of oil-polluted water was investigated using gas chromatography. Reed canary grass (RCG) samples purified the dissolved fuel effectively: the RCG adsorption filter adsorbed 99 % of the dissolved fuel oil (paper I).

Three different oils mixed with de-ionised water were used in the maximum oil adsorption capacity tests. The maximum oil capacity and the ratio between oil and water adsorption were measured. The oil/water mixture was passed through an adsorption filter

(AF). The tests were continued for 1000 min and all the free oil and water had been passed through the filter. The maximum 10W–30 oil and water capacity results are presented in Fig 31.

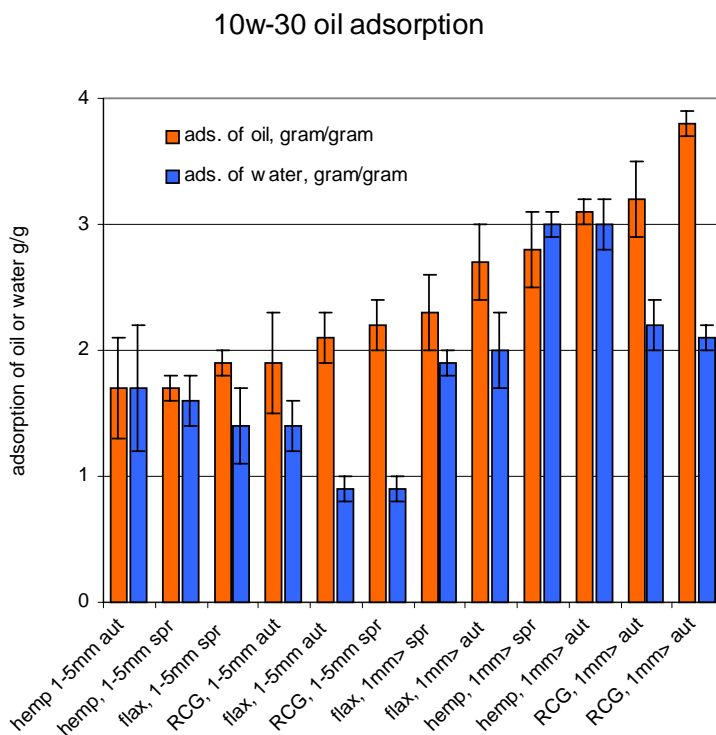


Figure 31. The adsorption of 10W–30 oil and water after 1 000 min of drainage. The results are in grams of oil or water per gram of sample material. Deviations ($n=3$) are given by error bars. The samples are arranged in increasing order based on oil adsorption capacity.

The size less than 1mm samples have the highest adsorption capacity. In the 1 to 5mm sized samples the oil and water capacity are following each other in decreasing order. In the case of the less than 1mm samples adsorption of oil and water seem to follow each other in increasing order. In most of the cases the spring-harvested sample seems to have the higher oil adsorption capacity.

In Fig. 32 is described the same experiments which were carried out using domestic fuel oil no. 2. Fuel oil no. 2 has a lower viscosity than lubricating oil 10W–30. In Fig. 32 the oil adsorption level is approximately at the same level as the adsorption of 10W–30 oil in Fig. 31.

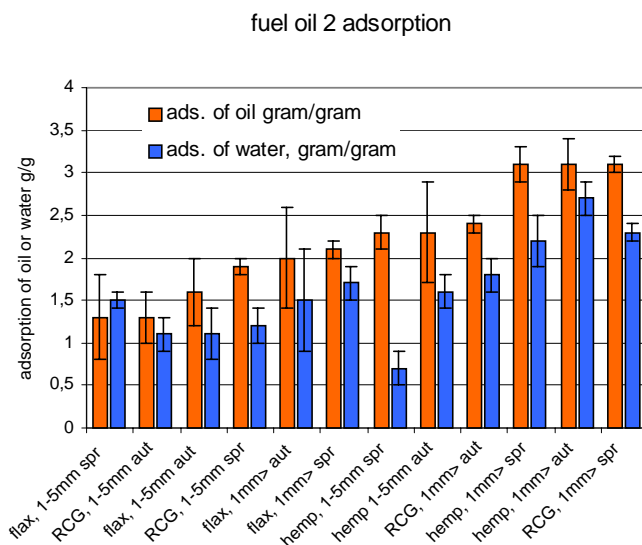


Figure 32. The adsorption of fuel oil no. 2 and water after 1000 min. The results are in grams of oil per gram of AF. The standard deviations ($n=3$) are given by error bars. The samples are arranged in increasing order based on oil adsorption capacity.

The results of fuel oil adsorption are arranged in increasing order on the basis of the ratio between oil and water adsorption in Fig. 33. The spring-harvested hemp and RCG samples have the highest oil/water adsorption ratios.

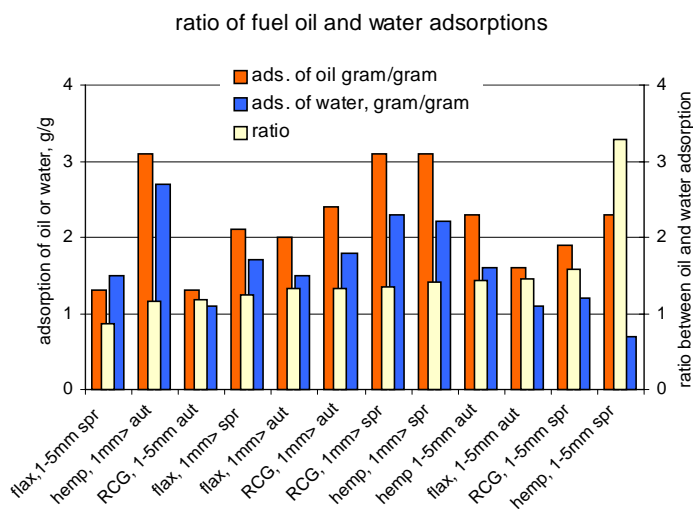


Figure 33. The ratio between fuel oil no. 2 and water adsorption capacity. Samples are grouped in increasing order on the bases of their fuel oil/water adsorption ratio capacity.

In order to determine the ratio of the adsorption material properties and adsorption capacity a correlation matrix was first calculated. The correlations of 10W–30 lubrication oil adsorption, the chemical properties and water adsorption are compared in Table 5.

Table 5. Correlation matrix of the adsorption of oil and water with the properties of the adsorption materials, n= 39. The strongest correlations are in bold. The 1 % risk level with 35 df is the value of critical correlation coefficient is $r=0.42$. So the observed correlation level of 0.82 is strong.

	Bulk Density, kg/m ³	Waxes,%	Ash content,%	Water adsorption, gram/gram	10W–30 oil adsorption, gram/gram
Bulk density, kg/m ³	1.00				
Waxes, %	0.47	1.00			
Ash content, %	0.21	0.53	1.00		
Water adsorption, gram/gram	0.26	0.61	0.44	1.00	
10W–30 oil adsorption, gram/gram	0.36	0.70	0.82	0.55	1.00

In Table 5 the two highest correlations exist between oil adsorption and the chemical properties of the filter materials. Ash and wax concentrations have a strong correlation with oil adsorption. Wax content of AFs correlates with both oil and water adsorption.

The ash contents of AFs and 10W–30 oil adsorptions were compared using linear chart Fig. 34. A variation of 10 % change in ash content changes the oil adsorption by 1,7 grams per gram. On the chart there can be seen three concentrations of observations. The separate group of observations includes reed canary grass samples.

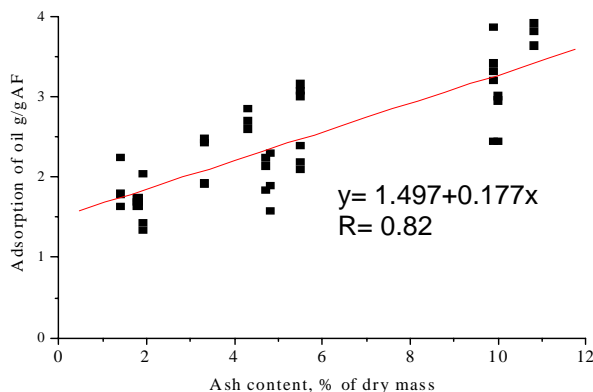


Figure 34. The regression between ash content and 10W–30 oil adsorption, n= 39.

The relationship between oil adsorption and the natural wax content of the adsorption filter materials in Fig. 35 is also shown. However the observations are less concentrated compared to the results in Fig. 34.

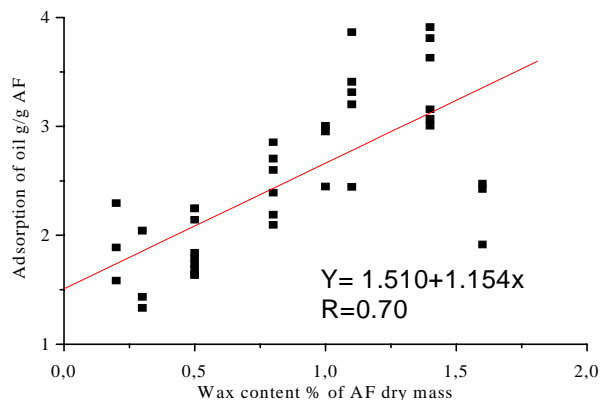


Figure 35. The regression between the wax content and 10W-30 oil adsorption.

5.2.2 Results of capillary rise of water and oil

Oil and water capillary rise in reed canary grass was compared using a tube that was filled with plant material. The capillary rise in the tube was slow (Fig. 36). One reason for this was the swelling of the plant material, which clearly throttled the capillaries and water flow on the bottom of the tube. In some extreme cases the tubes broke due to the swelling.

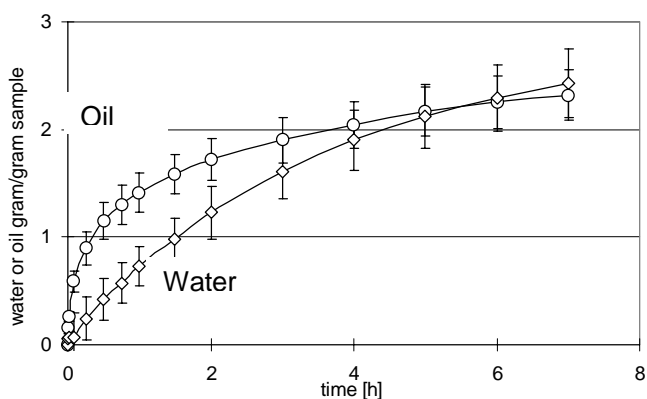


Figure 36. Water and 10W-30 oil capillary action were compared using autumn harvested reed canary grass samples. Standard deviations ($n=5$) are given by error bars.

The difference between oil and water capillary flow can be seen in the beginning of the capillary curve. Oil starts to rise in the tube immediately after contact. The rise of water starts instead with a lower slope. However the adsorption time of oil seems to be longer.

5.2.3 Results of adsorption tests for the dry-line method

The wetting of the bast fibre samples was measured using contact angle and wetting time. Fig. 37 shows the measured contact angles and the adsorption times of water.

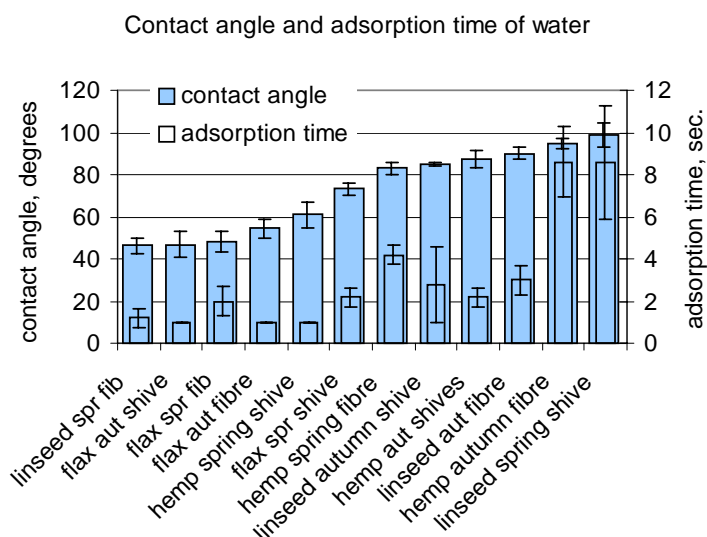


Figure 37. Contact angles and adsorption times of water on bast fibre fragments. (n=60). The samples are in increasing order based on contact angle (Paper III).

The adsorption time of a water drop is shorter in Fig 37 compared to the saturated adsorption showed in Fig 36. The sudden rise of adsorption after first water contact can however be seen in Fig 36. The spring-harvested samples are concentrated in the area where the contact angle (in degrees) is smallest (to the left in Fig 37). In Fig. 38 are shown the contact angles of oil on bast fibre fragments, which have clearly smaller values when compared to the contact angles of water in Fig 37.

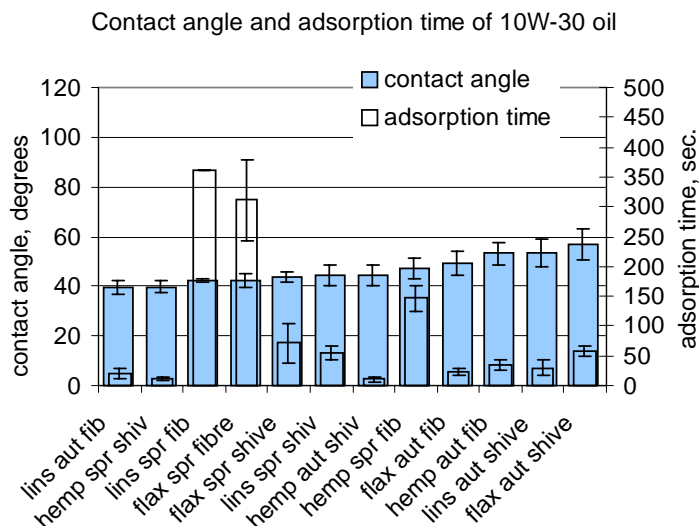


Figure 38. Contact angles and adsorption times of oil on bast fibre fragments (n=60).

The total adsorption time of oil drops is at an equal level here in Fig. 38 compared to the results of oil shown in Fig. 36. The adsorption times of oil here in Fig 38 are however longer than the adsorption times of water in Fig. 37.

In order to determine the ratio between contact angle and adsorption times of water and oil against the samples a correlation matrix was calculated. The correlations of water contact angles and adsorption times were the strongest Table 6.

Table 6. Correlation matrix comparing the contact angles of oil and water with the adsorption times, n= 60. The strongest correlations are bolded. The 1 % risk level with 60 degrees of freedom is =0.33. So the highest observed correlation level 0.69 is strong.

	Contact angle of oil, °	Contact angle of water, °	Adsorption time of water, sec.	Adsorption time of oil, sec.
Contact angle of oil, °	1.00	–	–	–
Contact angle of water, °	0.09	1.00	–	–
Adsorption time of water, sec	0.14	0.69	1.00	–
Adsorption time of oil, sec	–0.23	–0.35	–0.23	1.00

The adsorption time and contact angle of water were compared using linear regression Fig. 39. The concentration of 60 measured contact angles is situated between 40 and 60 degrees and the concentration of adsorption times at less than 5 seconds.

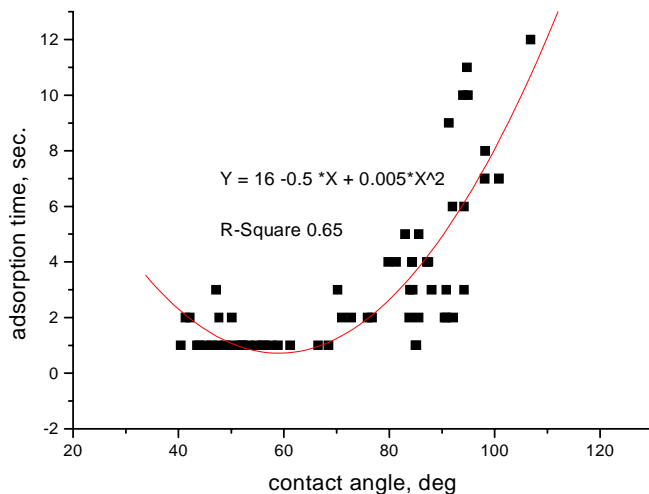


Figure 39. The non-linear regression between contact angles of water and adsorption time of adsorption material samples, n=60.

Between the contact angle values of 50 to 100 degrees the adsorption time follows an exponential curve (x^2). The contact angle of 90 degrees seems to cause a sudden rise of adsorption times of water. The concentration of most recorded contact angle values between 40 and 60 and the adsorption times less than 5 seconds may have effect on the slope of the curve. The slope of the curve seems exponential between contact angles 50-100 degrees however the phenomenon does not follow a form of a parabola out of these limits.

5.2.4 Results of water adsorption under pressure

The water capacities of reed canary samples (RCG) were tested under pressure Fig 40. Basic information of the difference between the water capacities of autumn and spring-harvested reed canary grass was obtained by pressure measurements. The samples were first saturated in water and then drained. After draining the pressure was raised up to 500 kPa. The drainage curve is logarithmic in the intervals between 0–100 kPa and nearly linear above 100 kPa.

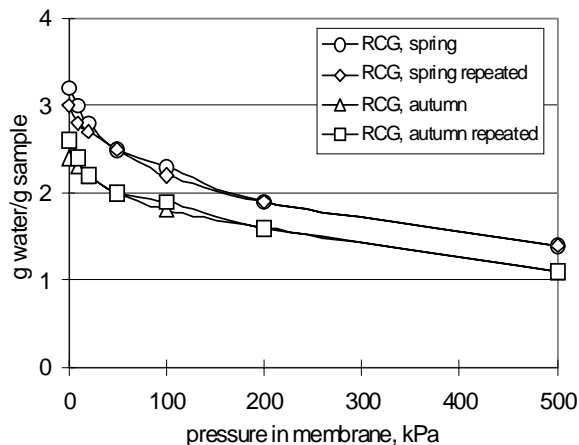


Figure 40. Water capacity of autumn and spring-harvested reed canary grass samples, when the samples are tested under pressure (n=3, highest deviations 0,1 grams per gram of sample material).

Results in Fig 40 clearly show the difference in water adsorption between the spring and autumn-harvested materials. The difference stays unchanged under rising pressure. The linear part of the curve in Fig. 40 shows the compression of solid material. The decreasing difference between the curves shows that the extra water in spring-harvested material is distributed in both new pores and surface areas.

5.3 Results of tests on fibre bundles and composite strengths

The strength of the fibre strips and bundles were measured using a LLOYD'S universal testing equipment Fig 41. The strengths of different sample lengths were measured. In all cases spring-harvested fibre was clearly the weakest.

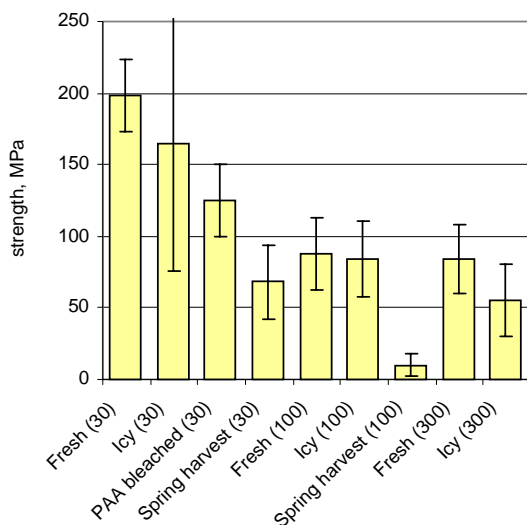


Figure 41. The strength of hemp strips (*Cannabis sativa*) and their gauge length (in brackets). The deviations (n= 4-5) are given by error bars.

However the results were different when composites were manufactured out of these fibres Fig. 42. The composites which were manufactured out of spring-harvested fibre strips had the same strength compared to the composites which were manufactured out of autumn-harvested and dew retted fibres.

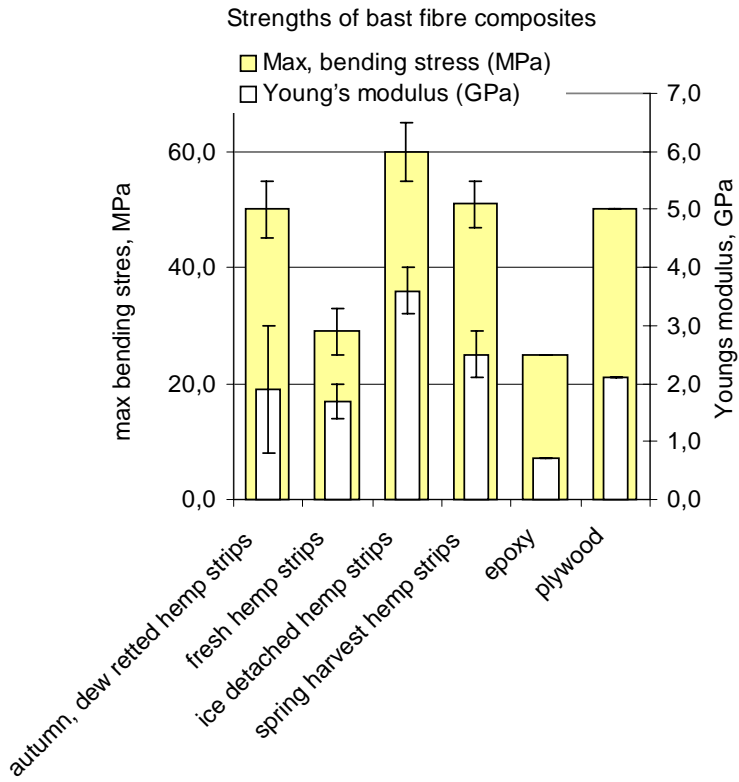


Figure 42. The strength of composites which are manufactured out of autumn and spring-harvested fibres. The deviations ($n=5$) are given by error bars.

6. Discussion on the benefits and drawbacks of the dry-line method

In the present study, new research-based processes and applications for bast fibre harvesting and processing were introduced. The background in all publications and studies was spring harvesting of bast fibre plants by the so-called dry-line method. Major challenges throughout the work have been the new quality demands, which differ partly from the yarn and textile quality definitions. Robust quality criteria and means to control the criteria are needed at the beginning of the raw material production line. The further the process progresses, the more are needed; precise criteria and quality control.

The development of new harvesting methods at high latitudes is especially important because of the high moisture content of the harvested yield. Growing bast fibre plants in northern areas however is reasonable because of the long daylight conditions. Hemp fibre especially is a photoperiodic plant and because of this it gives no seed yield at high latitudes but instead produces a high biomass yield (Werf et al.1994). The disadvantage in hemp harvesting at northern latitudes is the delayed maturing of the seeds. None of the varieties, which were used in the investigations, produced a mature seed yield.

6.1 The freezing of bast fibre plants

Evidently, herbs such as flax and hemp fibre are not accustomed to the northern climate and therefore, they have no mechanism to prevent freezing. On the other hand they are annual plants and the obvious reason for a winter standing stem is to spread the seeds in the spring. During the frosts the outermost layer of the plant freezes first. Consequently, small cavities are formed between the outermost layer and the xylem. The cavities suck water from the xylem cells by the capillary phenomenon in much the same way as water is normally transported in plants.

The water freezes in the plant stem and more ice mantle develops. The water in the xylems does not have time to freeze since the water coming up from the ground is warm and the forming ice produces heat. The heat peak can be measured during freezing (Pasila et al 2003). The already formed ice layer also functions as a point of freezing for the newly forming ice. The outer ice layer is subjected to tension and breaks. Micro cracks in ice are formed in the direction of the stem. In fact, they were dimly visible in the morning. The osmotic pressure in the roots helps the capillary phenomenon to pump more water, and icing may continue. As more ice is formed, the tension increases and the detachment begins. The top part of the stem either freezes completely or there is not enough water coming from the ground to enable ice forming above 1.5 m. In accordance with the observations, the mechanism only operates in living stems.

Where does the ice-forming water in the stem come from? There are three possible sources; the plant itself, the air around the plant or the ground. The total amount of water in a hemp plant with a height of 1.5 m and a stem diameter of 2 cm is necessarily less than the entire volume of the plant, 450 cm^3 . The dry volume weight of the porous hemp core is 0.15 g/cm^3 so the weight of a single 1.5 m stem is 70 g dry mass. The water content is typically 50–75 % w.b. of the weight and the water volume therefore is $70 \text{ g} = 70 \text{ ml}$ that is less than the observed ice volume.

The day before the ice formation was quite warm ($+8 \text{ }^\circ\text{C}$ with a RH of more than 90%, see Fig. 10 in chapter 3.2) thus making it possible for a noticeable water concentration to form on the plants surface during the frosty night. In the morning the plant stems were covered with frost. However there is no evidence of why the water penetrated through the bast fibres instead of accumulating on the plant's surfaces and forming an ice mantle there.

Thus the freezing phenomenon in bast fibre plants is very similar to the one occurring when, for example, late in the autumn an ice lens is formed in soil under a stone that conducts heat well. The temperature of the soil under the stone diminishes more rapidly than in its surroundings. The soil freezes and the developing ice dries the soil. This makes the capillary rise of water from the ground possible in fine sandy soil. An ice lens dozens of centimetres thick may form under the stone. The outcome of this in frozen areas of ground is that stones rise and roads break.

The expanding power of ice is clearly seen in Figs. 11 and 12 in chapter 3.2 where the ice has detached the bast fibre strips. The thick ice mantle mechanically breaks the bast fibre layer that is surrounding the xylem, the core part of the stem. More detailed photographs in chapter 3.3 (Figs. 13 and 14) reveal the changes in the structure of the fibre bundles in spring-harvested stems. The repeated freezing during autumn and winter opens the structure of the fibre bundles and large surface areas are uncovered.

As shown in Fig. 36 in chapter 5.2.2 and Fig 40 in chapter 5.2.4 there are differences in the adsorption slope of oil and water at the beginning of adsorption. These phenomena show the potential applications of the dry-line method in different uses where hydrocarbons such as oil are to be adsorbed.

On the other hand in Fig. 40 in chapter 5.2.4 the water capacity under pressure is clearly divided in free water and absorbed surface water. The increase of surface area as seen in Figs. 14 and 15 in chapter 3.3 also increases the water capacity both in the large intermediate pores and on the newly created surfaces.

6.2 Discussion about harvesting methods

The yield losses during the winter when dry-line method is used were 16-32% compared to the autumn yield. The losses during flax retting have been approximately 20% (Sultana 1992). The advantage of the dry-line method is the harvesting of seed yield. This covers the growing costs of the linseed or flax. When linseed or flax is used in short fibre production the integrated oilseed harvesting is essential to increase the farmer's interest in this method.

Figure 29 in chapter 5.1.4 shows that the bast fibre yield is at a level of 15 % of the weighed dry mass. The harvesting method was however in no way optimised in this research. There is a clear need to improve the harvesting technology when the results are compared to Table 2. There is also a clear need for a more detailed analysis of the concentrations and cleanliness of the separated fragments.

The increasing use of bast fibres requires at the moment the use of traditional harvesting methods, which are used for example in Asia (Laue 1995, see Fig. 1). However the logistic problems of low price and low-density fibre raw materials result in a need to develop new harvesting methods (Hemming et al. 1996). This is essential in Europe where the demand of bast fibres is expected to increase (Hepworth 2000a and 2000b). The cost of human labour is at a higher level in Europe than it is in Asia. New technological development is needed because the population in Europe is already involved in existing industries. There are no free workers for a production line as described in Fig. 1.

Harvesting on frozen land in early spring is a clear advantage because it avoids the soil compaction that normally occurs when harvesting on wet soils in the autumn (Alakukku and Elonen 1995). The harvesting period for hemp fibre is the longest due to its high winter-standing stem.

6.3 Discussion about the dry-line method in adsorbent applications

The effect of freezing on fibre detaching is visible in bast fibre structures (paper V). The effect on equilibrium moisture content, wicking and adsorption depends however on the surface properties of elementary fibre surfaces which have opened after the frost retting (paper IV). In the case of hemp fibre the water adsorption increased but in the case of linseed and flax fibre the water adsorption decreased when the adsorption properties of autumn harvested un-retted and spring harvested frost-retted bast fibre samples were studied.

The freezing which causes detachment of fibre cells from the bast fibre bundles seems to have a "power effect" on the specific properties of the selected bast fibre fragments.

This is understandable due to the growth of the surface/volume ratio during the frost-detachment of small-diameter elementary bast fibres (Adamson and Gast 1997). In these studies the adsorbed liquids are water and oil and the corresponding properties of the bast fibre plants are the hydrophilic capillaries and oil-attracting waxy surfaces.

When wetting, wicking and adsorption of plant stem fragments are measured the water drops have large contact angles on the stem surfaces because the surfaces are wax covered (Esau 1977). By contrast, oil drops easily stick and spread on the waxy bast fibre surfaces (paper I). The situation changes when the stem is cross-sectioned into smaller fragments. The fragmented bast fibre plant material is a randomised mixture of waxy surfaces, intermediate pores and cross-sectional capillary openings (paper III). The randomised structure of a bast fibre-based adsorption filter (paper I) works like a flytrap with the oil drops. The oil drops are first captured by the waxy surfaces of the bast fibre stems and afterwards the drops are adsorbed in the capillaries.

The filtration method described in this thesis bears some similarity to deep bed filtration (Dickenson 1992). The method is also partly similar to that of Choi et al. (1993) who measured the absorption properties of cotton and polypropylene mats. The difference in this investigation was the flow of the oil-polluted water through the filter material, whereas Choi et al. (1992) soaked the absorption mats on oily water surfaces. Compared to the results of Choi et al. (1993) the adsorption capacities in this investigation were lower. The results of this study are comparable to the oil adsorption capabilities that Rankin et al. (1989) measured when investigating the adsorption capacity of crushed corncobs. The capacities of industrial polyester oil adsorption mats were higher (approximately 10 gram oil/gram of mat) compared to the bast fibre fragments (Pasi-la 2001).

The chemical properties of the surface of the adsorbing material may affect oil adsorption. In Table 5 the chemical contents of the adsorption materials were compared to the oil adsorption capacities. Ash content seems to explain oil adsorption. One reason for this was presumably the easily detaching silica in the adsorption material, which increase the viscosity of the oil penetrating through the adsorption material. Oil with a higher viscosity has sufficient time to become adsorbed during the slow flow through the filter. When oil spills are collected in practice, qualitative tests are necessary to select the optimum adsorption material. Using the method described in this study the test could easily be accomplished.

The selective adsorption of oil appears clearly in Fig 33 chapter 5.2.1. Spring harvested 1 to 5 mm hemp fibre adsorbs 3 times more fuel oil no. 2 than water. Spring harvested 1 to 5 mm RCG and autumn harvested flax adsorbed twofold as much 10W-30 oil than water. Autumn harvested flax and hemp fibre fragments have the highest variations in

adsorption capabilities. An obvious reason for these variations is the spaces between the long fragments of material. The flow is faster through these spaces than through the randomly oriented shorter fragments.

One weakness of the tested adsorption filter in Fig. 21 in chapter 4.3.1 is the gravity sedimentation of oil and water. When soaking the adsorption pillows in or running oily water through the filters the water always passes the material first. Therefore the water always touches the original dry surface of the plant fragments first.

In practice there is a difficult economical problem in being prepared to cleanup an oil spill. Economically it is unprofitable to store large amounts of adsorption materials. A combination of bio fuel and adsorption material production could be one solution to improve this problem and make it more economically viable.

In one possible application during normal situations the biomaterial yield is utilized in a coastal bio power plant. During oil spill the bio fuel is used as adsorption material instead of being burnt. In the case of marine oil spill the adsorption material can be shipped in a small vessel to the coast near the spill. After adsorption the oil-saturated adsorption material can be shipped back to the bio power plant and burnt there. Hemp fibre is suitable for bio fuel purposes due to its low ash content. It could be possible to put this technology into practice at a reasonably low cost, for example in the Baltic Sea coastal areas.

6.4 Discussion about bast fibre composites

In Figs. 41 and 42 is shown a situation where the weakest spring harvested fibres were used in epoxy composites. In spite of the low tensile strength of the spring harvested fibre bundles, the strength of the manufactured spring fibre composites were of a moderate level. The possible reason for this result may be the following: During the composite manufacturing the matrix glues are in the beginning of the process a liquid. The good adsorption and penetration of the liquid glue ensures a good contact between the glue and the reinforcing fibres. The fibre cells have far larger tensile strength than the tested fibre bundles. The large external surface area and highly detached fibres of the spring-harvested material affects the adsorption of the liquid glue and the adherence of the hardened glue to the surfaces.

In composites, the differences due to the varying strengths of the strips mainly disappear. This is direct evidence of the fact that the glue or glue-fibre interface does not necessarily withstand as much shearing stress as it should. The surface adhesion is incomplete, that is surface treatment is crucial in composite materials, as is well known (Hepworth et al. 2000a, Joseph et al. 2002).

With minimal harvesting and decortication costs it is possible to manufacture (even on a farm level) plywood type structures that are at least as strong as plywood but considerably cheaper. This offers farmers new sources of income. One tempting possibility for the application of this new strategy is making furniture. The fibres can be moulded into any shape. Furthermore, with different treatment of the fibres and varying the positions of the strips it is possible to make surfaces with a pleasing appearance. The fresh strips produce green surfaces, the spring-harvested yellow.

6.5 Quality, validity and economic properties of the introduced processes

Because the materials being produced are of natural origin it is possible that for example; different parts of a plant will have different properties. Therefore even the quality of the same plant fragments can change depending on the location and weather. As a result it may be that only a minor part of a plant is suitable for the desired use. It is however important to realize that the by products also are valuable raw materials for other processes (Pehkonen and Mäkinen 1998).

It is necessary to process the bio raw material in even quality fragments (Pehkonen 1996). After this it is usable as an industrial raw material. The fragments are distributed in different value groups as described (Carruthers et al. 1994):

- Speciality products, which have a high value compared to their volume, these are for example; medicines, spices, aromatic substances and additives also some extra strong composites or filter substances can have a high value.
- Food for human beings and feed for animals
- Industrial raw materials like starch, fatty acids and fibres
- Bio fuels

Only a small part of raw material is normally used in high value products. In practice this means that the manufacturer of valuable products must be prepared to make use of the by products.

By-products such as bio fuels are normally uneconomical when produced alone. Unprocessed biomass is uneconomical to transport long distances. According to the calculations in “agro pulp research”(Hemming et al. 1996) the critical distance was 50–100 km. In practice this means that the first fragmentation has to be done locally on the farm or on a village level (Pehkonen 1998). The fragmentation may occur for example, near a local heating plant or pellet mill.

The succession of moist autumn, cold winter and dry spring in the northern areas described in chapter 3.2 can be used in bast fibre harvesting. No indoor drying is needed when the stem yield is harvested in the spring. Also the detachment of the bast fibres is effective by using simple machinery as described in chapters 4.1 and 4.2.

The economic viability of the dry-line method is good in Northern latitudes because the indoor drying of material is not normally needed as described in chapter 1.3. The detachment of the bast fibres can be carried out economically because the bast fibre yields have been reasonable even during the first experiments, as described in chapter 5.1.

The feasibility of the dry-line method has been tested in manufacturing thermal insulation material (Pasila et al. 1998, Kauriinvaha et al. 2001). A simple chopper/hammer mill combination was used in the manufacturing of loose fill thermal insulation material and lightweight structural building elements (Heino et al. 2000).

The dry-line method was used also in pulp and paper production while the yearly pulp yield of hemp fibre was approximately 2.4-fold when compared to the fibre yield of spruce in Southern Finland (Pasila et al. 2001b). The pulping process needed for spring harvested hemp fibres was slight. Flax and hemp fibres were also tested in Moulded Fibre Technology (MFT). Hammer milled fibres were mixed with pulped fibres. The industrial MFT packages were manufactured using this mixture as a raw material (Tavisto et al. 2001).

7. Conclusions

The background to research was the spring harvesting of bast fibre plants using the so-called dry-line method. In the present study these new harvesting methods, processes and applications are introduced. Major challenges throughout the work have been the new properties of the spring-harvested raw material that differs from the properties and definitions required by the traditional yarn and textile industries.

The dry-line method is an integrated harvesting method where the oilseed yield of flax or linseed is harvested in the autumn with a combined harvester. The bast fibre stems of the plants are harvested in the spring when the weather is dry. The equilibrium moisture content of the stems is low and normally no extra drying of the yield is needed. This makes the dry-line method an economical and very competitive alternative to the traditional method.

During the winter moist bast fibre stems are frozen and thawed several times. Due to this mechanical stress and ice expanding movement on the stem surfaces the bast fibres are detached. So in the spring the yield is dry and it is easy to process the bast fibres as desired. This freezing process also affects the raw material properties so that the bast fibre yield in later processing is high. Harvesting in spring on frozen soil creates no risk of soil compaction.

The harvesting and processing used in the dry-line method were investigated in this thesis. The harvesting of hemp fibre was especially troublesome due to the hems robust structure. Harvesting of the flax and linseed oilseed was carried out using a combined harvester in the autumn. In the spring the bast fibre stems were harvested using a mower and a round baler. The bales were processed using a bale chopper, a hammer mill and a rotary screen.

Economically the most important parts of the new dry-line method are the autumn harvesting of oilseeds from the bast fibre plants and the low moisture content of the yield in the spring. The autumn conditions are normally dry enough for the harvesting of the mature seeds from the tops of the bast fibre plants. For a farmer this guarantees income in the form of the oilseed yield and gives an additional economic reason for the feasibility of producing the fibre yield for industry.

The harvesting machinery already exists on the farms and is applicable to bast fibre harvesting with only minor modifications. The processing machinery, including a power hammer mill and a rotary screen are not normally used on farms but this machinery is available at a low level of investment.

The investigation into the adsorption properties of the processed bast fibre plants showed that these materials are suitable for use in oil adsorption. In the case of a major oil spill

it is possible to prepare to prevent the oil slicks from landing ashore, for example by spreading hemp fibre shives on the water to adsorb the oil.

On the microscopic level the structure of the fibre surfaces in the spring harvested material is more slatted. After the autumn moisture and repeated winter freezing the fibre bundles and pore structures open in the bast fibre plants. During the springtime the plants are dried under low RH air conditions. This causes extensive adsorption surfaces in the bast fibre plant fragments compared to the fragments, which are harvested and processed using the traditional methods.

Bast fibres have been used in composite reinforcing materials instead of glass fibre. The investigations in this thesis showed that the strength of tested composites appears to be dependent on the surface properties of the fibres even more than the strength of the fibre bundles. The very weak spring harvested fibres produced the strongest composites.

The manufacturing of strong composites could be applied, for example, in plywood or chipboard manufacturing. The industrial manufacturing of non-woven fibre mats already exists. The good fibre strength properties of these mats could possibly be combined with birch and spruce raw materials and used in plywood manufacturing. The increased strength of this material provides new opportunities, for example in furniture manufacturing.

As described in the cited articles the dry-line method was used in the harvesting and processing of bast fibre plants. Different industrial applications were investigated. First experiments were done using linseed straw as a raw material for loose fill thermal insulation materials.

Experiments were carried out using spring harvested hemp fibre as a raw material for pulp. Hemp fibre was easy to process and produced a good yield: 2.4 tons long fibre marketable pulp per hectare per year.

A major problem with spring harvesting is the risk of uncontrolled decrease in quality during the moist and warm autumns. It is quite clear that the part of the crop that is pressed down against the soil surface will be destroyed during the winter. It is essential that the fibre-containing bast fibre stems remain standing during the autumn and winter. During the winter the frost and later in spring the dryness are climatic factors that preserve the fibre crop.

During the experiments, the dry-line harvesting of the flax and hemp was carried out on frozen soil from the beginning of March. This naturally depended on the existence of snow. The harvesting should be carried out not later than the middle of May, which is before the sowing of new crops in the spring.

8. Summary

The existing traditional harvesting and processing methods of bast fibre plants include normally two major problems: high moisture content of harvested plants and the troublesome detachment of the bast fibres from the stems. These problems joined with the traditional processing technology are not responding to the demands of new industrial products and uses at the moment.

The principle idea in these studies was the development of new production lines for bast fibre plants such as linseed, flax and hemp fibre. As a result of this the dry-line method is introduced, which economically produces short bulky fibre that is suitable, for example, in the production of non-woven mats and pulp.

Finnish weather conditions are favourable for the weathering of bast fibre plants, which is caused by frosts and the following ice growth and expansion work. The results of the investigations show that the Finnish climate causes a succession of autumn moisture, winter freezing and spring drying of bast fibre plants. This natural phenomenon can be economically exploited in Nordic countries.

In the dry-line method the winter standing flax and hemp stems have been harvested in the spring after the moist autumn and frosty winter. The relative humidity (RH) of the air in spring is low during the harvesting period from March until May. This produces an important economical advantage, while the equilibrium moisture content (EMC) of the harvested yield is low (normally 10% wet basis) the yield needs no extra indoor drying. In the spring, harvesting on frozen soil causes no soil compaction.

The drying of the total biomass is normally crucial because the industry requires the moisture content of the bast fibre yield to be between 10–20% w.b. of the total harvested mass. Earlier it was not possible to detach the bast fibres without drying the plants.

The results of composite studies show that the originally low tensile strength of spring-harvested hemp fibres are suitable for composite manufacturing. The results show that the strongest composite beams were manufactured from spring-harvested hemp fibres. The industrial production of needle-punched mats from flax and hemp fibre already takes place.

In Finnish latitudes (60–63°N) oilseed harvesting is possible for flax varieties. Due to the photoperiodic properties of hemp fibre they do not produce mature seeds in Finland. Instead the advantage of hemp fibre has been the high biomass yield that is partly based on the photoperiodic properties of hemp fibre in long daylight conditions.

The third consequence of winter in the processing of bast fibre plants is the easy detachment of the bast fibres. It is to be possible to produce raw materials to different industrial standards using existing farm machinery integrated with simple milling and separation equipment. The new harvesting method enables the use of these materials in applications such as pulp, moulded fibre packages, composites and oil adsorption products.

Using the dry-line method causes an expected decrease in the traditional textile fibre quality parameters that is in fibre bundle strength, while the bast fibres are highly over retted. However the detachment of the bast fibres can be easily carried out. These stages can be utilized in bast fibre harvesting, processing and manufacturing. The dry-line method is more economical due to the lower drying costs, easy detachment of the bast fibres and higher bast fibre yields during processing, when compared to the traditional processing methods.

The properties of autumn and spring-harvested plant fragments were compared in this thesis. Some key investigations into potential new dry-line based product lines such as: adsorption materials, pulp products, and composites were carried out. The focus in the research presented in this thesis has been new economical production lines for bast fibre plants together with new economical products.

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10. Papers I – VII

