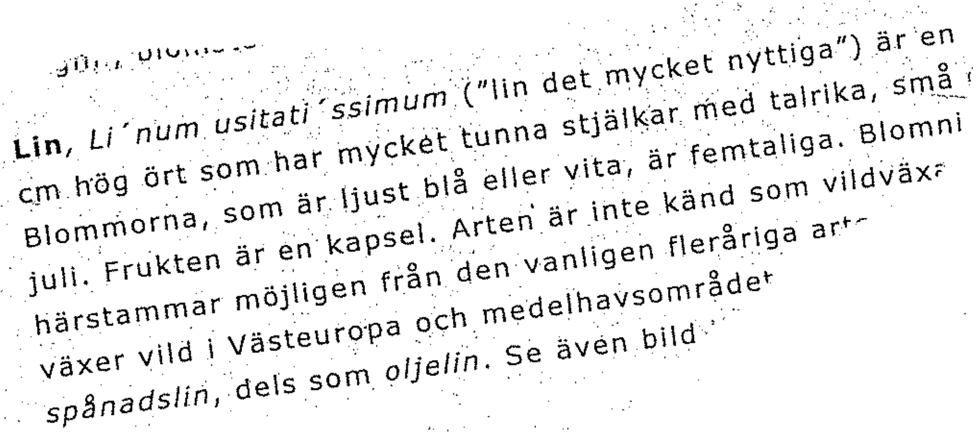
Harvesting and handling of flax for the production of short fibres under Swedish conditions

A literature review

Daniel Nilsson



Lin, *Li´num usitati´ssimum* ("lin det mycket nyttiga") är en
cm hög ört som har mycket tunna stjälkar med talrika, små
Blommorna, som är ljust blå eller vita, är femtaliga. Blomni
juli. Frukten är en kapsel. Arten är inte känd som vildväx
härstammar möjligen från den vanligen fleråriga art
växer vild i Västeuropa och medelhavsområdet
spånadslin, dels som *oljelin*. Se även bild

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ABSTRACT

The increased awareness of sustainable production in our society in recent decades has led to the search for new environmentally-friendly products. Natural fibres from flax (*Linum usitatissimum* L.), which are renewable and can be degraded biologically after their use, are an alternative that has been considered as a replacement for synthetic fibres in many industrial applications, for example, as reinforcement in composites, rubber and concrete.

The objective of this work was to carry out a thorough literature review on the production and use of flax for non-textile applications in general, and on aspects related to harvest and handling in particular. The report starts with a review of earlier Swedish research and development projects and then focuses on harvest and handling methods. Thereafter, quality aspects related to harvest and handling of flax, i.e. straw moisture contents and degree of retting, are reviewed. A summarising discussion and proposals for future research are presented in the last chapter.

After the closure of the last flax long fibre processing plant in 1966, there has been no commercial production of flax fibres in Sweden. However, interest in using flax fibres in non-textile applications was stimulated in the late 1980s, and a number of projects started in the 1990s with the aim of restoring Swedish flax fibre production. Today, there are no flax processing plants in operation, but it is recommended that new research and development projects be directed towards the creation of a demand for biofibres before such plants are established. This would be a first step towards creating a future market for short natural fibres obtained from flax, and also from other fibre crops such as hemp.

The harvest and handling operations constitute an important part of the total production costs. Computer simulation of these operations is recommended in order to find more cost-effective and reliable delivery systems. Such simulations should include quality aspects regarding the straw moisture content and the degree of retting, provided that reliable, quick and inexpensive methods to assess the degree of retting are developed, and that models describing the moisture content changes and the progress of retting are constructed.

SAMMANFATTNING

Den ökade insikten om att vårt samhälle ur resursanvändningssynpunkt inte är långsiktigt hållbart, har lett till att man bl a börjat söka efter nya mer uthålliga och miljövänliga produkter. Naturfiber från spånadslin (*Linum usitatissimum* L.), vilka är förnybara och bryts ned biologiskt efter användningen, är ett alternativ som skulle kunna vara lämpligt för ersättning av syntetiska fibrer i många industriella produkter, t ex som armeringsmaterial i kompositer, gummi och betong.

Syftet med detta arbete var att genomföra en litteraturstudie om produktion och användning av lin för icke-textila applikationer i allmänhet, och om linets skörd och hantering i synnerhet. Studien inleds med en genomgång av några svenska forskningsprojekt, och fokuserar sedan på olika skörde- och hanteringsmetoder. Därefter belyses olika kvalitetsaspekter som är relaterade till skörden och hanteringen, t ex linhalmens vattenhalt och rötningsgrad. I sista kapitlet diskuteras bl a förslag på olika framtida forskningsprojekt.

Det konstateras i rapporten att efter det att den sista svenska linberedningsfabriken upphörde i Laholm 1966, har det inte förekommit någon nämnvärd kommersiell produktion av linfiber i landet. Intresset för att använda linfiber i icke-textila applikationer väcktes dock under slutet på 80-talet, och under 90-talet genomfördes olika forskningsprojekt med syfte att så småningom återuppta linfiberproduktionen igen. Idag finns det inga anläggningar i drift, och det skulle vara av stort värde om framtida forskning fokuserade på att skapa en inhemsk efterfrågan på biofiber. Detta skulle vara ett första steg på vägen för att skapa en framtida marknad för linfiber, men också för fiber utvunna ur andra grödor, t ex hampa.

Skörden och den efterföljande hanteringen fram till beredningsanläggningen utgör en betydande del av de totala produktionskostnaderna. Därför rekommenderas datorsimuleringar av dessa arbetsoperationer i syfte att finna mer kostnadseffektiva och tillförlitliga försörjningsystem. Sådana simuleringar bör inkludera olika kvalitetsaspekter vad gäller halmens vattenhalt och rötningsgrad, förutsatt att man utvecklar modeller som beskriver vattenhaltsförändringar och rötningsförloppet. För att kunna modellera rötningsförloppet måste man först utveckla tillförlitliga och effektiva metoder för att mäta rötningsgraden.

FOREWORD

This literature study was carried out within the research programme "Technology for Improved Utilisation of Biofibre from Agriculture for Industrial Purposes", which is financed by The Swedish University of Agricultural Sciences (SLU). This four-year research programme includes projects concerning the use of reed canary grass fibres in paper products and the use of flax and hemp fibres as a reinforcement material in concrete.

My project in that research programme concerns harvest and handling of the fibre crops from field to processing plant. Earlier studies have shown that these operations constitute an important part of the total raw material costs, and the main objective is to find cost-effective and reliable harvest and logistics systems. The main tool for the analysis is dynamic computer simulation. The quality of the fibres obtained is dependent on the quality of the raw material, which in turn is dependent on the harvest and handling system chosen. Thus, quality parameters such as moisture content and degree of retting are also included.

This literature review focuses on flax intended for the production of short fibres for non-textile applications. I hope that it will contribute to the knowledge about harvest and handling of flax under Swedish conditions, and also that it will pose new questions to tackle in future projects. I am grateful to my financer SLU, and also to my colleagues in the research programme for helpful discussions.

Daniel Nilsson

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1. INTRODUCTION

1.1. Background

The increased awareness of sustainable production in our society in recent decades has led to the search for new environmentally-friendly products. Natural fibres from flax (*Linum usitatissimum* L.), which are renewable and can be degraded biologically after their use, are an alternative that has been considered as a replacement of synthetic fibres in many industrial applications, for example as reinforcement in composites, rubber and concrete, and for use as an insulation material (Smeder & Liljedahl, 1996). Fibres from flax have, for example, higher strength than fibres made of polyester, whereas their weight is lower than that of glass and carbon fibres (Smeder, 1993a).

The environmental impact from the whole life cycle of a certain product can be assessed by the LCA (Life Cycle Assessment) methodology. LCA studies have shown that insulation materials made of flax fibres lead to lower greenhouse gas emissions in comparison with materials made of mineral wool. The energy demand is also lower for insulation materials based on flax fibres, whereas the effects on eutrophication and ozone depletion are less for materials based on mineral wool (Gärtner et al., 2002).

In a life cycle assessment by Corbière-Nicollier et al. (2001), it is shown that replacement of glass fibres with natural fibres as a reinforcement material in plastic transport pallets reduces the environmental impact considerably, especially when the lifetime of the pallets is above three years. Furthermore, due to lower environmental impacts, lower weight and improved passenger protection in the event of accidents, many car manufacturers now use interior fitting materials based on biofibres, for example in fascia panels, chairs, roof stuffing and hat-racks (IENICA, 2000; Forskning och Framsteg, 2003). These examples show that the use of flax fibres is an attractive alternative from an environmental point of view. The flax crop may also be suitable for organic cultivation (Salminen, 1999).

There is no large-scale production of short fibres from flax in Sweden today. One important reason is the higher costs than for competing synthetic fibres. The costs for insulation mats made of flax are, for instance, about 30% higher than for mats made of mineral wool (Nilsson, 2003). Of the total costs for production of flax fibres, about 37% arise from cultivation and payment to farmers, 36% from harvest, transport and storage, and 27% from the decortication process (with a simplified process line, according to Rosenqvist (1993)). Thus, the harvest and handling costs constitute an important part of the total costs. One reason is the low bulk density of the straw, which means that space rather than weight is often the limiting factor when transporting and storing straw.

The properties of synthetic fibres can be tailored for specific applications, and specified quality criteria (standardization) are defined and available, as Kessler and Kohler (1996) point out. However, the quality of flax fibre (e.g. fineness, strength and cleanness) may vary considerably between different years, and is dependent on the maturity at harvest and the degree of retting, as well as the plant variety and cultivation practices (Kessler et al., 1993; Pallesen, 1996; Sharma and Faughey, 1999). The weather has a crucial impact on the quality, both during the cultivation season and during the harvest season. Poor weather conditions during harvest may, for example, lead to over-retted straw and difficulties in baling the straw with sufficiently low moisture contents. Thus, the processing plants cannot guarantee the industry sufficient quantities of fibres of consistently high quality. A high and uniform quality of the raw material is crucial if flax is to be a successful industrial crop in Sweden.

The choice of techniques for harvesting and handling is of major importance for reliable delivery of flax straw with high and homogeneous quality. The harvest season, i.e. late summer and autumn, are often rainy in Sweden and the machines must have sufficient capacity to harvest the material even in years with poor weather conditions. However, too high machinery capacity results in higher costs. Therefore, a well thought-out harvesting and handling system is required to provide a raw material that is both competitive and has a high quality (Leutscher, 1989).

1.2. Purpose and structure of the work

The purpose of this work was to carry out a thorough literature review on the production and use of flax for non-textile applications in general, and on aspects related to harvest and handling in particular. The study was directed towards Swedish conditions, but with an international perspective in order to benefit from experiences from other countries.

The structure of the work is shown in Figure 1. The literature study starts with a review of earlier Swedish research and development projects in Chapter 2 and focuses on harvest and handling methods in Chapter 3. In Chapter 4, quality aspects related to harvest and handling of flax are discussed. A summarising and concluding discussion is presented in Chapter 5.

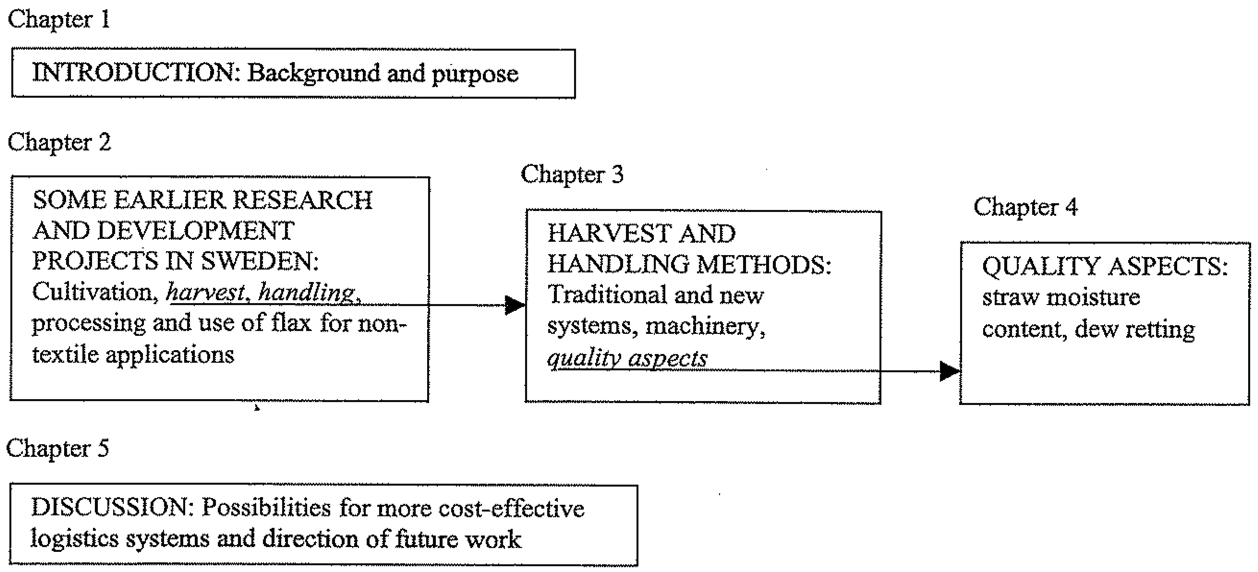

Figure 1. Structure of the report.

2. SOME EARLIER RESEARCH AND DEVELOPMENT PROJECTS IN SWEDEN

2.1 "Linutredningen 1987"

The newly-awakened interest in Sweden for production of flax fibres originated in 1985, when the Swedish Parliament commissioned the Swedish Government (mot. 1984/85:1395, JoU 36, rskr 404) to investigate the possibility of increasing the cultivation, processing and use of flax products in Sweden (Industridepartementet, 1987). This decision was taken in light of the fact that the cultivation of flax had ceased since the last Swedish flax fibre factory in Laholm closed down in 1966. A main reason for this closure was that flax had been driven out of the market by less expensive synthetic or imported fibres. The investigation was commissioned to consider flax in general, and the objectives were to survey the domestic need of flax fibres and linseed, and to analyse the prerequisites for a resumption of commercial cultivation and processing of flax in Sweden.

In general, the report had a fairly positive view of flax as a future raw material for fibre and linseed oil production in Sweden (Industridepartementet, 1987). This was due to the unique characteristics of flax, both from environmental and technical perspectives. The most important drawback, in comparison with other raw materials for fibre production, was the high processing cost from field to intermediate fibre product or to the final thread. However, the report pointed out new application areas for flax fibres, such as a material for replacing asbestos or reinforcing building materials, which both are non-traditional niches in which the flax may have a higher competitiveness. The report also had proposals on how to support and stimulate the production of flax fibres and linseed in Sweden. In addition to stimulating the production and processing of flax for traditional textile use and to increasing the yield by plant breeding, there were proposals to further investigate how flax can be used in non-textile industrial applications (Industridepartementet, 1987).

As a result of this report, STU (Styrelsen för teknisk utveckling) further investigated the possibilities for using flax fibres, linseed and linseed oil in industrial non-textile applications (Karth, 1989). STU had a more moderate view and considered that flax fibres for non-textile use would not be able to become a competitive alternative in the foreseeable future. They also noted that neither fibre consumers nor fibre producers had sufficient interest for a large-scale introduction of flax fibres on the market at that time.

2.2. Market-orientated studies on the non-textile use of flax fibres

A market survey on potential non-textile use of flax fibres in Sweden was carried out by the ALA-group at the Swedish University of Agricultural Sciences in 1992 (Liljedahl & Smeder, 1992). The aim of the study was to investigate potential markets, as well as to identify research and development efforts necessary. The results were based on about 120 interviews with persons representing different research and development institutions, business associations, small and large companies involved in producing intermediate fibre products and consumer fibre products, etc. In a first screening of possible flax fibre applications, the following products were considered to be interesting:

- Building materials (insulation material for bulk insulation, reinforcement of concrete, particle board, fibre board, gypsum wallboard, vinyl floor carpet, acoustic damping materials)

- Polymer compounds (thermoplastic composites, thermoset composites, rubber composites, construction composites)
- Geotextiles (ground protection during construction, weed control, gardening, road construction, erosion control mats).
- Pulp and paper (newsprint, printing and writing paper, sack paper, folding boxboard, recycled paper, liner and top-liner, tissue and fluff pulp, fluting and middle of board)
- Cellulose (carboxymethylcellulose, viscose fibres, microcrystalline cellulose)
- Absorbent materials (diapers, sanitary towels, industrial wipes, napkins)
- Others (friction lining, gaskets, nonwovens, filters, drain-pipes)

In their evaluations of the above-mentioned applications, Liljedahl and Smeder (1992) considered the following aspects: industrial interest, industrial capacity (i.e. knowledge, entrepreneurship and financial situation), market value, market volume and development efforts necessary with respect to costs and time. Taking these aspects into account, they concluded that the most promising applications for Sweden were: insulation material for bulk insulation, concrete cement finish and rendering concrete, particle board including moulded products, reinforcement of plastics and rubber, gasket, pulp and paper including paper filters, microcrystalline cellulose, drying cloths, wet laid nonwoven, and geotextiles for weed control. The authors found a general industrial interest for using flax fibres, mainly due to the environmental advantages of flax fibres, as well as the length and strength of the fibre. More research and development were also proposed, in particular concerning the absorption, insulation and fire properties of flax fibres.

Some marketing and technological barriers to non-textile applications of flax fibres were identified by Liljedahl and Smeder (1994). Three main marketing barriers were: lack of knowledge about the flax fibre in the processing industry; the gap between agricultural production and the process industry, i.e. non-existing semi-manufacturing industry; and the fact that many industries do not trust agriculture as a reliable supplier. Technological barriers were: lack of knowledge concerning the properties of flax fibres; lack of knowledge of how flax fibres can be used in reinforcement; and the focus on end products instead of on processing and flexibility in choice of technology.

The most important properties for flax fibres in technical uses were identified by Smeder and Liljedahl (1996). The results were based on market opinions on the most interesting applications identified in their earlier study (Liljedahl and Smeder, 1992). The choice of raw material was assumed to be dependent on price, performance, fundamental properties and other factors (terms of delivery, existence of acceptable suppliers, etc.), see Figure 2. The authors also assumed that the fibre properties determine the functional properties of the material, i.e. the main reason for using the fibre. The fibre properties also affect the secondary effects, which include the influence on the production process and other product properties. The performance describes the overall quality of the product. It should be noted that the fundamental properties and the fibre properties are only dependent on the material itself, whereas the other factors are also dependent on the application.

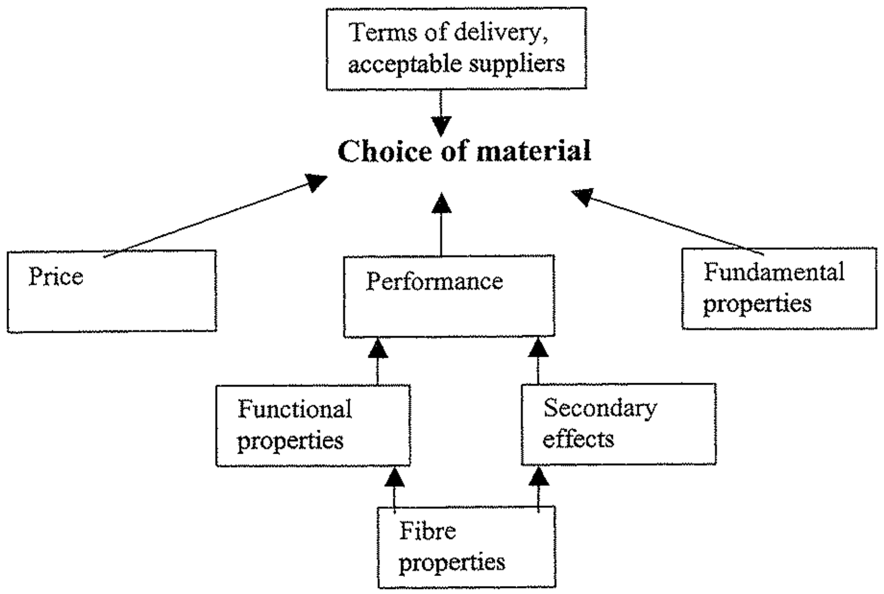

Figure 2. The interrelation between various levels of fibre properties and their relevance for the choice of raw materials (Smeder and Liljedahl, 1996).

The results for the most interesting applications are presented in Tables 1-4. One of the most important fibre properties of flax is the fibre length. The original fibre length is in most cases longer than the length demanded by the industry. Thus, it has to be adjusted during the processing. The diameter, strength and chemical composition of the fibres are also significant properties, which indicate that purity from shives is of importance.

Table 1. Fibre properties of primary interest for the relevant function of flax fibres (X) in different applications. Brackets indicate a weaker interest. For strength, special interest in tensile strength (X^T) or stiffness (X^S) is indicated (Smeder and Liljedahl, 1996)

Application	Dimensions: Density	Length	Diameter	Strength	Chemistry: Composition	Surface
Bulk insulation				X^S		
Concrete cement finish and rendering concrete		X		X	(X)	
Particle and fibre board		X	(X)	(X^T)		
Reinforcement of plastics and rubber	(X)			X		
Paper products:						
Reinforcement pulp		X	(X)	X^T		
Speciality pulp		(X)	(X)	X^T	(X)	
Paper filters		X	(X)	(X^T)		
Fluff pulp		X	(X)	X		(X)
Wet laid nonwoven		X	(X)	X		
Industrial wipes		(X)	X	X^S		(X)
Geotextiles for weed control		X		(X)		

As expected, the most important functional property in most applications is reinforcement (Table 2). The suspected negative secondary effects are mainly associated with mixing and the problems with distributing the fibres uniformly in the material (Table 3). The reason is that flax fibres have a tendency to form knots during the processing. The environmental benefits are important regarding fundamental properties (Table 4). Some examples are health benefits of using flax fibres instead of mineral wool for insulation, biodegradability in geotextile applications, recyclability and the fact that flax fibre is a renewable resource in reinforcement of plastics and rubber, etc. (Smeder and Liljedahl, 1996).

Table 2. Functional properties of interest among industries (X) for use of flax fibres in different applications. Brackets indicate a weaker interest. Structure means structure of fibre network or matrix-fibre network (Smeder and Liljedahl, 1996)

Application	Absorption	Insulation	Fire resistance	Reinforcement	Structure
Bulk insulation		(X)	(X)		X
Concrete cement finish and rendering concrete				X	(X)
Particle and fibre board				X	(X)
Reinforcement of plastics and rubber				X	
Paper products:					
Reinforcement pulp				X	
Speciality pulp				X	(X)
Paper filters	(X)			X	
Fluff pulp	(X)			X	(X)
Wet laid nonwoven				(X)	X
Industrial wipes	(X)				X
Geotextiles for weed control				X	

Table 3. Suspected negative secondary effects (X) for use of flax fibres in different applications. Difficulties in adjusting existing processes for new material are not included. Brackets indicate minor problems or problems that depend on the specific product within the application (Smeder and Liljedahl, 1996)

Application	Chemical resistance	Biological resistance	Water swelling	Mixing	Adhesion
Bulk insulation		(X)	(X)	X	
Concrete cement finish and rendering concrete	(X)		(X)	X	X
Particle and fibre board			(X)	X	
Reinforcement of plastics and rubber		X	X	X	X
Paper products:					
Reinforcement pulp				X	
Speciality pulp				X	
Paper filters	(X)			X	
Fluff pulp				X	
Wet laid nonwoven	(X)			(X)	(X)
Industrial wipes	X			(X)	(X)
Geotextiles for weed control		(X)		X	

Table 4. Fundamental properties of interest among industries (X) for use of flax in different applications. Brackets indicate a weaker interest (Smeder and Liljedahl, 1996)

Application	Environmental benefits	Domestic raw material	General product image
Bulk insulation	X		(X)
Concrete cement finish and rendering concrete			
Particle and fibre board	(X)		
Reinforcement of plastics and rubber	X		(X)
Paper products:			
Reinforcement pulp	(X)		(X)
Speciality pulp		(X)	
Paper filters			
Fluff pulp			
Wet laid nonwoven	X	(X)	
Industrial wipes	X		(X)
Geotextiles for weed control	X		

2.3. "Projekt Linindustri"

The interest for using flax in non-textile applications resulted in a flax research project between the Swedish Institute of Agricultural Engineering in Uppsala, the University of Karlstad and "Hushållningssällskapet" in the county of Örebro. The project, which was entitled "Projekt Linindustri" ("Project Flax Industry"), started in 1989 and ran for three years.

It was directed towards the following aspects:

- Cultivation, harvest and handling of flax straw
- Decortication
- Possible non-textile use of flax fibres and possible use of seeds.

From that project, Schölin (1991) reports on trials with a prototype machine for decortication of unretted non-parallel flax straw. The machine consisted of a section with rollers for braking the material, followed by a scutching section with flat bars radially placed on two rollers (Figure 3). The advantage of using non-parallel straw is that conventional farm machines can be used for mowing and handling of the straw. Unless further chemically processed, unretted straw has a higher content of shives and is, therefore, not suitable for making textile products. It can instead be used as a reinforcement material in concrete, plastics or rubber, or for making geotextiles, paper, etc.

The results showed that the moisture content in the straw should be 11-15% (wet basis) in order to attain the highest outcome of the machine (Schölin, 1991). A too wet material resulted in a higher content of shives in the processed material, and a too dry material resulted in a high content of (short) fibres in the shive fraction. The trials also showed that the distance between the braking rollers should be carefully adjusted to avoid stoppages (small distances) or too high contents of shives in the processed material (long distances). The content of shives in the processed material was, on average, 45% when the material had passed through the machine 12 times, and 21% when it had passed through the machine 24 times (Schölin, 1991).

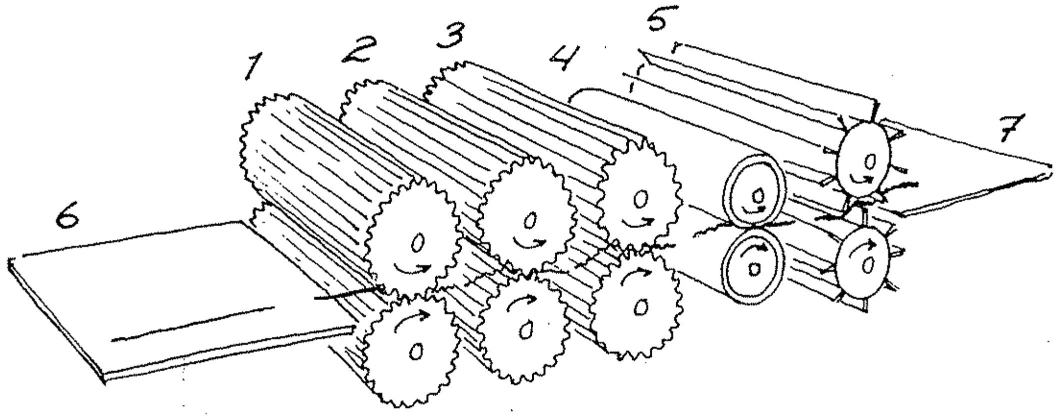

Figure 3. Prototype of the flax decortication machine tested by Schölin (1991). 1-3 braking rollers, 4 rollers covered by rubber, 5 scutching rollers, 6 feeding table, 7 outlet table.

The use of different technologies from hay and grain production for harvesting and drying of fibre flax was also investigated in the "Linindustri" project (Ihrsén, 1993). The intention was to find out low-cost and less weather dependent harvesting systems for production of short fibres. More specifically, the objective of the project was to study the performance of suitable harvesting machines, and to study the drying rate of the straw in the fields and in artificial drying indoors.

In comparison with harvest of hay and cereals, the following problems were identified when harvesting flax: suitable harvesting times for straw and seeds do not coincide (of interest if the seeds also are to be used), the strength of the straw requires sharp and well-adjusted mowing equipment, the straw has a tendency to tangle with rotating parts, and it may be difficult to pick up the straw from the ground or ted/windrow it. Various machines were tested, for example, single and double knife mowers, rotary mowers, rotary tedders, side-delivery rakes, rotary windrowers, combine harvesters, self-loading trailers, round balers, big balers, etc. The results showed that it is possible to use common farm machines for harvesting and handling of flax for production of short fibres, even though some machines are not suitable. However, most machines should, more or less, be adjusted to the special properties of flax straw, and it should be noted that more maintenance is necessary (Ihrsén, 1993).

The most serious problems were associated with the difference in suitable harvest time for straw and seeds, which made the harvest system more complicated (Ihrsén, 1993). If the seeds are not to be used, or are seen as a by-product separated in the processing plant, the harvest system becomes less complex, because combine harvesters are not necessary. The straw can also be harvested earlier in the harvest season in such cases, which may result in a higher fibre quality and better weather conditions for drying the straw.

The trials with in-field drying demonstrated that the crushing degree of the straw strongly affects the drying rate (Ihrsén, 1993). The author showed that flax straw can be dried to a moisture content suitable for storing (about 18%, wet basis) within 3 days, provided that the weather conditions are good. Under similar weather conditions, the straw was dried to 30-35% m.c. (wet basis), which was considered as suitable for drying in an artificial drier, within 1-2 days. Bearing the results from the artificial drying trials in mind, the author recommends the standard dimensioning used for drying of hay when flax straw is to be dried.

Cost calculations for the production of short fibres from flax are presented in another report from the "Linindustri" project (Rosenqvist, 1993). The calculations included all costs for cultivation (by rights, the payment to the farmers), harvest, handling, drying, storing and processing of flax straw, as well the income from selling the shives as a fuel. Different alternatives were analysed, for example, with various straw yields, in-field drying or artificial drying, harvest with self-loading trailers, balers or the self-propelled flax processor manufactured by Claas (Figure 4), processing in small-scale plants (800 tonnes of straw processed per year) or medium-scale plants (5 600 tonnes of straw processed per year), and making bales or pellets of the shives for use in furnaces. It should be noted that the costs for the processing plants were based on a fictitious and rather simple production line with a shredder, chopper, a mill for decortication, and equipment for pneumatic separation of shives and fibres.

Some results of the study are presented in Table 5. The costs in the table varies from 3 500 SEK per tonne of short flax fibres free at the factory, to 7 700 SEK/tonne. For a comparison, the cost for imported cotton fibres was about 10 SEK/kg, but note that the costs in Table 5 refer to unboiled and unbleached flax fibres.

Figure 4. The Claas field processor machine (Ihrsén, 1993).

The cost of processing was a relatively small part of the total cost for most alternatives analysed. For the alternative with indoor drying shown in Table 5, the costs were distributed as follows: cropping costs 24%, handling costs to the drier 21%, drying, storage and transport

38% and factory costs 17%. Rosenqvist (1993) concluded that artificial drying of the straw, with the extra handling operations required, was one of the most expensive parts in the fibre production chain. The advantage of artificial drying is, however, that the quality of the fibres can be guaranteed also in years with poor harvest conditions. The alternative with the Claas processor machine was less expensive than the alternative with indoor drying, but had higher costs in comparison with the field drying and baling alternative. The advantage with the Claas machine was that the quantity of material handled was reduced considerably, because about 70% of the straw was left in the field (the bales from the machine were assumed to have a content of 90% fibres and 10% shives). The cost estimation for the Claas machine was uncertain, however, because the machine was not commercial.

Table 5. Costs for production of short flax fibres with a yield of 6,0 tonnes/ha, and a processing plant with an annual capacity of 5 600 tonnes of flax straw (SEK per tonne of short fibres) (Rosenqvist, 1993)

	Cost of short-fibre, excl. fuel income	Income of shives sold as bales for fuel purposes	Cost of short-fibre, incl. fuel income
Field and indoor drying	7 700	1 400	6 300
Field drying only	4 900	1 400	3 500
Claas flax processor	4 300	200	4 100

Rosenqvist (1993) also showed that the income from selling the shives for use as fuel is of great importance for the profitability in short fibre production. He recommended that new short fibre plants should be located as close as possible to heating plants in order to reduce transport costs.

The costs for small-scale production of fibres were somewhat higher than for the medium-size plant presented in Table 5. This was due to higher processing costs, which did not counterbalance the lower transport and handling costs (Rosenqvist, 1993).

The University of Karlstad was responsible for the part concerning decortication, and also, to some extent, fibre properties and system studies, in the project "Projekt Linindustri". Their work was directed towards comparative studies of different decortication methods, and a comprehensive information collection was carried out by means of literature studies, interviews and study visits. The aim was to identify and evaluate interesting decortication methods (Smeder, 1993b). The results are described by Smeder (1993a; 1993b). The author presents various methods for retting (dew retting, anaerobic water retting, aerobic water retting, retting with microbial additives, and enzymatic retting) and chemical decortication processes (long fibre processes, elementary fibre processes and pulp processes). He also presents the costs and environmental *pros* and *cons* for some of these methods. Regarding future research, his recommendations include further investigations on the fibre properties for the use in non-textile applications (Smeder, 1993b).

2.4. "Fiberfriläggningssystem och kvalitetsvärdering av kortfiber"

A fibre research project was carried out during 1991-94 at the Swedish Institute of Agricultural Engineering and the University of Karlstad. The project was entitled "Fiberfriläggningssystem och kvalitetsvärdering av kortfiber" ("Methods for decortication and quality evaluation of short fibres"). In that project, Ihrsén and Sundberg (1995) report on trials with mechanical decortication of flax straw for production of short fibres. They tested existing agricultural equipment for small-scale decortication of flax in order to produce a crude fibre material at low cost. Equipment possible for use in the following three processing stages were tested: comminution of flax straw before grinding; decortication and fibre-shortening in mills; and separation of shives and fibres.

The function tests showed that the strength and slenderness of the flax straw caused many problems with several of the machines and equipment tested. For example, the straw was difficult to cut and had a tendency to wind around rotating parts. From the test results, the authors built an experimental installation of the most promising machines (Figure 5). The installation had a hammer mill for decortication and fibre-shortening of the straw, which was first shortened with a precision-chop harvester. After air separation in a cyclone, the material was fed into a rotating cylinder screen for separation of shives and fibres. The cylinder screen was developed in the project. Both linseed and flax straw were tested in the experiments, and the straw moisture content was either 10% or 15% (wet basis).

The results showed that the fibre content in the cleaned fibre fraction varied between 70-90%, where the lower values were valid for linseed and the higher values for flax. It was also shown that larger holes in the screen resulted in lower values. The recovery of fibres, i.e. the quantity of fibres in the fibre fraction in comparison with the total quantity of fibres in the straw, varied between 33-59%. "Wet" straw (15% m.c.) had higher recovery values than dry straw (10% m.c.).

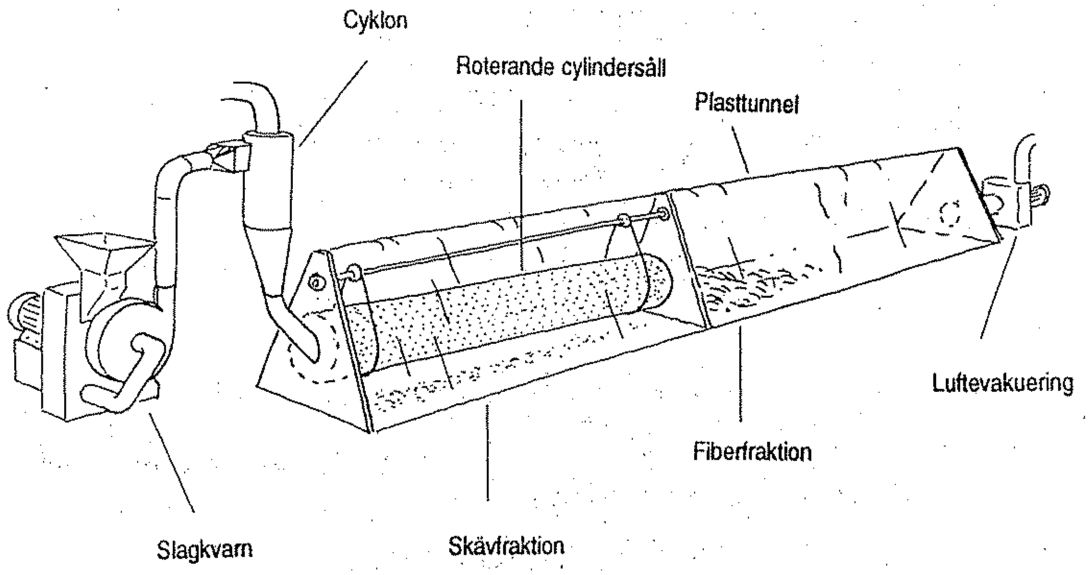

Figure 5. The experimental installation tested for production of short flax fibres (Ihrsén & Sundberg, 1995). Slagkvarn – hammer mill, cyklon – cyclone, skävfraktion – shive fraction, roterande cylindersåll – rotating cylinder sieve, fiberfraktion – fibre fraction, plasttunnel – plastic tunnel, luftevakuering – air evacuation.

The results from the studies with the experimental installation demonstrated that fibres can be produced at low cost with existing farm equipment (Ihrsén & Sundberg, 1995). The decorticated fibres were not fully cleaned of shives, and the fibres had in some cases large variations in length, but the authors consider that these properties may be acceptable for certain applications. If higher fibre qualities are required, the fibres must be further processed mechanically or chemically.

2.5. Possible non-textile applications of flax fibres

After the projects "Linindustri" and "Fiberfriläggningssystem och kvalitetsvärdering av kortfiber", a report about possible non-textile applications of flax fibres was published by Berggren (1995). The purpose of the study was to identify new research and development projects to further promote the production and use of flax fibres in Sweden. Berggren (1995) pointed out that flax fibres can be produced for two different areas of application: production of fibre bundles (with a diameter of 0.05-0.5 mm, and often denoted "short fibres") or production of elementary fibres (with a diameter of 0.012-0.035 mm). The fibre bundles can be used for insulation, reinforcement of concrete, or for production of fibre boards or geotextiles for weed control. The elementary fibres can be used for reinforcement of plastics and rubber, or for production of nonwoven materials, wipes, fluff pulp or paper. Fibre bundles are produced via a mechanical decortication process, whereas production of elementary fibres also requires chemical treatments. The results from an evaluation of different applications are presented in Table 6.

Table 6. Evaluation of the most interesting non-textile applications for flax fibres. + means that there is a high probability that the evaluation criteria can be fulfilled, 0 a medium probability and – a low probability (Berggren, 1995)

Application	Possibility to use the unique properties of flax fibres	Interested develop-ment partners available	Possibility to become commercial in Sweden	Development costs vs expected market value
Insulation	0	+	+	+
Reinforcement of concrete	-	0	0	0
Particle and fibre (incl. moulded) boards	-	-	0	0
Reinforcement of plastics and rubber	+	+	+	0
Replacing asbestos in gaskets, etc.	+	-	+	0
Paper products (incl. filters)	0	0	0	-
Microcrystalline cellulose	-	-	0	0
Nonwoven incl. industrial wipes	+	+	+	0
Fluff pulp	+	+	+	0
Geotextiles for weed control	-	-	-	-

Berggren (1995) concluded that the most interesting future application for short flax fibre bundles would be insulation, whereas the most interesting elementary fibre applications would be to use the flax fibres for reinforcement of plastics and rubber, and for production of nonwoven (incl. industrial wipes) and fluff pulp. He recommended that future research and development be directed towards these two areas of application. He also proposed more basic research about the formation of fibres in the flax plant and more research to clarify how plant breeding, cultivation conditions, harvest and handling technologies, etc. affect the quality of flax fibres.

2.6. Cultivation trials and other studies

Some orientating cultivation and retting trials were carried out in the county of Örebro during 1985-86 (Wilén, 1987). Following those, forty-five field trials with cultivation of linseed and fibre flax were conducted during 1986-89 at various locations in Sweden (Bengtsson & Larsson, 1991). Several varieties of both linseed and flax were tested with respect to yield of seed and straw, whereas only flax varieties were tested with respect to different levels of nitrogen fertilisation, seed rates and harvest times.

From these studies, it can be noted that the flax variety Regina had the highest fibre content; 22% on average. The reference variety Natasja began to flower 55 days after the sowing date, with the highest deviations for Nike with +1 day and Regina and Belinka with –1 day, whereas full ripeness occurred after 121 days for Natasja, with the highest deviations for Ariane with +1 day and for Bryta with –3 days. The trials with different harvest times, i.e. at early yellow ripeness (20-25 days after full flowering), late yellow ripeness (30-35 days after full flowering) and at full ripeness (about 40 days after full flowering), showed that harvest at full ripeness resulted in the highest yield of both seed and straw. The fibre content and fibre quality, on the other hand, was best at early yellow ripeness (Bengtsson & Larsson, 1991).

In addition to different harvesting times, Lustig (1991) also investigated the influence of different retting methods on yield and quality of flax fibres. Three fibre flax varieties (Bertelin, Regina and Natasja) were harvested at three different stages of maturity (early yellow ripeness, late yellow ripeness, and at full ripeness), and retted in three different ways (dew retting, water retting and enzyme retting). The cultivations were located at Uppsala. The yield of seeds was highest when the crop was harvested at late yellow ripeness for all varieties except Natasja, which had the highest yield at full ripeness.

Lustig (1991) also found that the fibre content, in general, became lower as the maturation process progressed. The highest fibre quality was obtained when Bertelin and Regina were harvested at early yellow ripeness and dew retted, which indicated that high-quality fibres can be produced with dew retting at such locations as Uppsala if harvesting is carried out early in the season. Water retting and enzyme retting resulted in a relatively high fibre quality, but the author pointed out that a homogeneous material is required in water and enzyme retting. A problem in his study was that the flax re-flowered due to a rainy and relatively cold period at the end of July. This may limit the generality of the results in the study (Lustig, 1991).

In connection with the start of the new Swefibre flax processing plant in Laholm in 1999, a cultivation study was carried out by Isaksson (2000). She tested 13 different flax varieties with respect to time for maturity, plant height, technical length, yield and fibre content. She also studied the influence of different seed rates and the effects of various herbicides, and investigated how the farmers followed the cultivation recommendations from the regional farmers' association (HBKL), which owned the Swefibre company.

It was shown that Henryk, Hermes, Marylin, Viola and Viking are early varieties, that Hermes has a high straw yield, that Henryk and Marylin have favourable plant heights, and that Ilona has a high fibre content. Furthermore, it was shown that higher seed rates result in weaker and shorter stems, and that all herbicides tested had a good weed control effect. The farmers followed the recommendations in most cases, except for nitrogen, which was used slightly above the recommendations, and phosphorous and potassium, which were used below the recommended rates (Isaksson, 2000).

A preliminary study on the feasibility and costs for large-scale production of linen sheets in the county of Västernorrland in Northern Sweden was presented by Brangenfeldt and Liljedahl (1990). The idea was to locate as much as possible of the production chain from cultivation of flax to weaving of sheets in this area. It was found that the total costs for a fictitious production line were 50-100% higher than the price for imported sheets. The authors stated that the price of short fibres would have to be much higher than the value used in their calculations (1.40 SEK/kg) if the idea were to become realizable. This price can be compared with the price for long fibres, which is around 25 SEK/kg (Brangenfeldt & Liljedahl, 1990). A similar study on the labour demand and costs for a semi-mechanized production system of textile fibres from flax in Järvsö in Sweden was reported by Fröier and Hamrebjörk (1989).

The Swedish Business Development Agency (NUTEK) financed a three-year project in which the Institute of Fibre and Polymer Technology was involved, as well as other parties (Skogsindustrierna, 1999). Seven companies participated in the project, e.g. SCA, and the results showed that there are no determining technical obstacles to the use of short fibres from flax in many industrial applications. Flax fibres are an interesting alternative as a reinforcement material in paper, and especially for the manufacture of wet-formed products, in which synthetic fibres cannot be used (Skogsindustrierna, 1999).

The Swedish Institute of Composites (SICOMP AB) in Piteå carry out research on the use of flax fibres as reinforcement in composite materials (www.sicomp.se), and similar research is also carried out at other institutes and universities (e.g. at Luleå University of Technology). SICOMP has, for example, investigated the mechanical properties of thermoplastics reinforced by natural fibre mats (Oksman, 2000), the mechanical properties and the morphology of melamine formaldehyde composites reinforced by flax fibres (Hagstrand and Oksman, 2003), and flax fibre composites manufactured by the resin transfer moulding process (Oksman, 2003).

3. HARVESTING AND HANDLING METHODS

3.1. Traditional harvesting and handling systems

Flax can be harvested and handled in a large number of ways. For hundreds of years, manual work was the only alternative, but most of this hard work has now been replaced by more mechanised handling systems. The most common systems for traditional handling of flax fibres are presented in Figure 6.

As can be seen in Figure 6, the flax can be retted in various ways, e.g. via dew retting (ground retting, field retting) and water retting. The objective of retting is to facilitate the decortication process, in which the fibre bundles are separated from the surrounding plant tissues, by loosening the pectic bindings between the bundles and the wood (xylem) in the inner layers and the parenchyma with chlorophyll in the outer layers of the stem.

Dew retting is common in Europe because it can be completely mechanised and is less expensive than water retting. However, dew retting is less easily controlled due to its dependence on the weather, the consistency in fibre characteristics is poorer, and the fields are occupied for several weeks (van Sumere, 1992; Foulk et al., 2002). The dew retting process is described in greater detail in section 4.2. Water retting in tanks is more expensive and the waste products may cause environmental problems, but this method allows control of the retting process. The times required for dew and water retting are shown in Table 7. Note that dew retting during late summer and autumn is most often carried out in connection with the harvest, whereas the other alternatives are carried out after the straw has been harvested and stored from the previous growing season.

Alternatives to dew and water retting are enzymatic retting with addition of enzyme mixtures (e.g. Flaxzyme and Novozyme), and chemical retting with alkali, sodium sulphite, steam, tensids, chelating compounds, etc. (van Sumere, 1992). These methods are much faster and easier to control than dew retting and are not dependent on weather conditions (Smeder, 1993b; Foulk et al., 2002). They are, however, more expensive in comparison with dew retting. In fact, about 95% of the flax in Western Europe is still dew retted (Smeder, 1993b).

Table 7. Retting times for different retting methods in a trial from 1941-42 at Svalöv in Southern Sweden (Fröier and Zienkiewicz, 1979)

Retting method		Start of retting (date)	Retting time (days)
Dew retting	Late summer	20/8	20
	Spring	28/4	34
	Winter	23/12	105
Water retting	Cold water in a brook	30/7	14
	Warm water in a basin		4-5

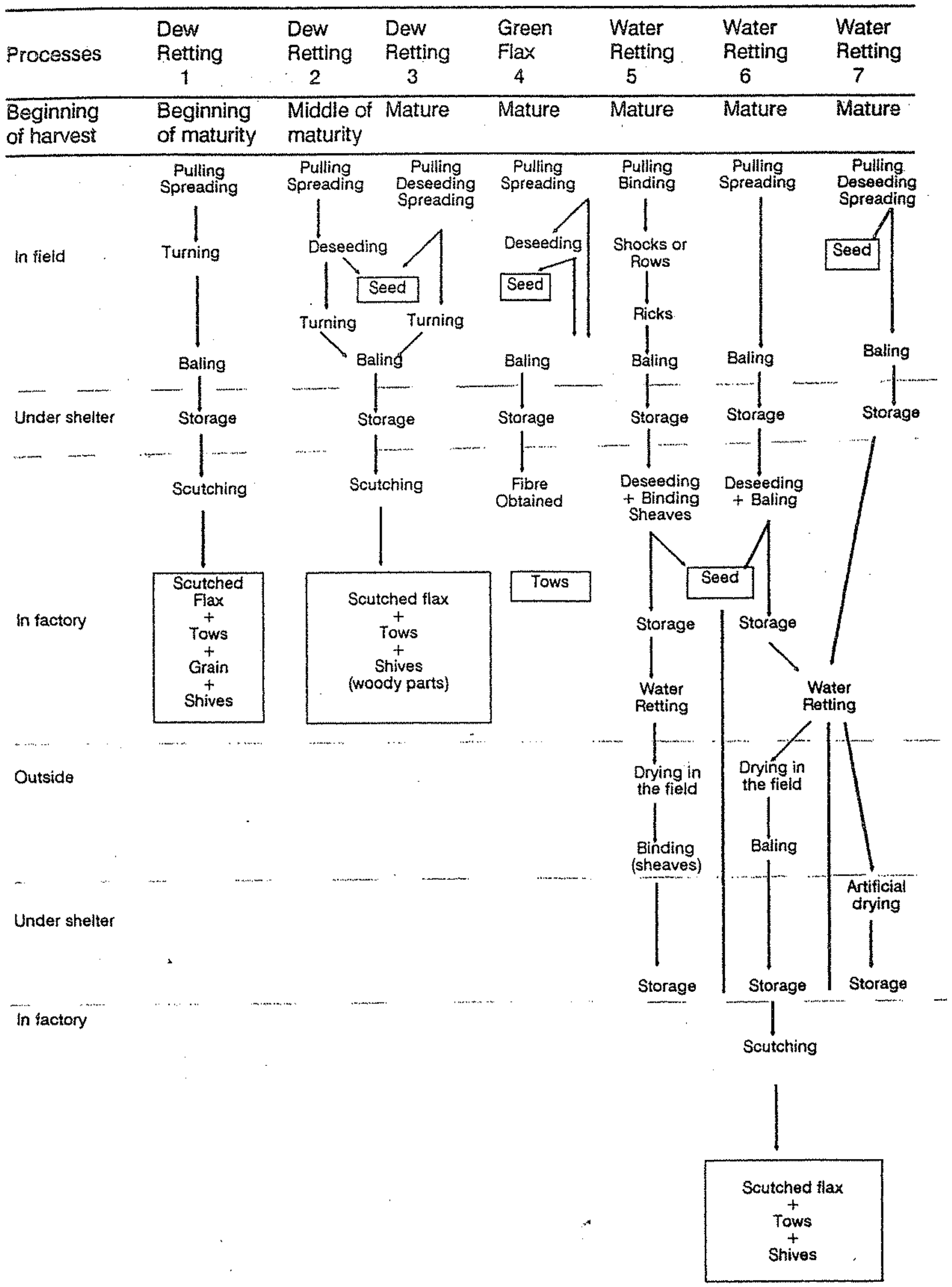

Figure 6. Methods for harvesting and handling of flax for fibre extraction (Sultana, 1992).

The first alternative in Figure 6 is one of the most common systems when textile fibres are the primary product. The flax is pulled and spread in swaths at the beginning of its maturity. It is then retted on the ground and turned at least once to allow the retting process to progress homogeneously in the swath. When the flax is well retted, but before the crop is over-retted and the fibres begin to degrade, it is baled and transported to storage. The point in time when retting has reached the right degree for baling, is determined empirically or by experience. The moisture content of the flax straw must also be lower than 16% (w.b.) when it is baled in order to avoid continued retting during storage, otherwise the yield and strength of the fibres are reduced (Sultana, 1992). The flax straw should be stored under shelter to maintain its quality during storage. Finally, the flax is transported to the factory, where it is scutched, resulting in scutched flax, tows, grain and shives.

For textile fibre use, the fibre bundles should be parallel throughout the handling operations in order to become acceptable for production of spinning yarn. This alignment of the straw must be maintained from pulling right up to the factory, which necessitates specially-designed machines. The most common machines used are further described in section 3.2.

In comparison with alternative 1, alternatives 2 and 3 are often used when seed is the primary product. The seeds are harvested in the fields in the autumn. Thus, the beginning of harvest is later, usually in the middle of the maturation process (alternative 2) or at full maturity (alternative 3). In alternative 2, the crop is decapsuled when it has been drying for 1-2 weeks and before the swaths are turned, or at the same time as the crop is turned. The capsules can then be threshed and used as sowing seed. In alternative 3, the decapsulation is carried out simultaneously with the pulling. The flax should be ripe and the capsules dry before the decapsuling operation, and the capsules may need further drying before threshing. The demand for crop maturity when the flax is deseeded delays the date of pulling, which, if the flax is to be dew retted, increases the risk of fibre loss due to poorer weather conditions. Alternative 2 is sometimes called the French dew-ret system, whereas alternative 3 sometimes is called the Russian dew-ret system (Leutscher, 1989).

Alternative 4 is an example of a system in which the flax is not, or almost not, retted. The stems are not treated in parallel, and the final product, the tow, can be used for non-textile applications, for instance, in production of paper. The mature crop is pulled (or in some cases mowed) and spread in swaths. The flax is then deseeded and baled when the moisture content is below 16% (w.b.). This system is often used when linseed is the primary product and the fibres a by-product. The system is also an alternative where dew retting is risky due to poor weather conditions.

In systems 5-7, the flax is pulled when it is mature and retted in water retting facilities. Alternative 5 is a classical system in which the flax is handled as sheaves. The system has a high demand for labour and is not common today in large-scale handling. The flax is bound in sheaves after pulling and is placed in shocks or rows for drying. The sheaves or bundles are then baled and transported to the stores. The flax is deseeded and re-bound in new sheaves before it is water retted in the following summer and dried outdoors in the field.

The difference between systems 5 and 6 is that the flax is handled as bales in system 6 instead of as sheaves or bundles as in system 5. The advantage of system 6 is that the labour requirements are lower. In system 7, pulling, deseeding and spreading are carried out in a single operation. Similarly to system 6, the flax is handled as bales, but the retted straw is here artificially dried, which makes it possible to carry out this operation independently of the weather conditions (Sultana, 1992).

3.2. Machinery equipment

3.2.1. Pulling

Pulling is the traditional way of harvesting flax, but mowing is also an alternative when short fibres are produced. The harvested stem yield is higher when a pulling machine is used, but the machine is usually more expensive than a mowing machine. The maintenance costs may be higher for mowing machines, because frequent sharpening and changes of cutting tools are necessary due to the difficulty in cutting the fibrous flax stem, and this may also reduce the productivity of the work.

The fibre loss when the flax is mowed may be as high as 15% (Sultana, 1995), but Leutscher (1989) states that the fibre loss may be less than 3% with low cutting. Some advantages with mowing are that the machinery required is available on most farms with production of hay or silage, and that the absence of hard roots and ground particles reduces the wear on processing machines.

A pulling machine is shown in Figure 7. The flax is grasped by a set of revolving belts and pulled vertically from the soil with its roots (Seyns, 1989). It is then placed crosswise on the ground in one or two swaths, or bound and set in a hedge, etc., for, as shown in Figure 6, the pulling operation can be combined with at least three other operations (Sultana, 1989):

1. with spreading in swaths of parallel stems for dew retting in the field.
2. with deseeding and spreading in the field when grain is harvested for production of seed
3. with simultaneous binding into sheaves when flax is water retted.

When the flax is to be dew retted, the pulling machine may have equipment for crushing the root end of the straw to reduce the retting time. Dew retting is slower in the root and in the lower parts of the stalk than in the rest of the stem. Seyns (1989) mentions three advantages with crushing: the retting process is shortened by about 14 days; the retting is more uniform over the whole stalk; and there is a refinement of the fibres where the crushing occurs.

It is important that the pulling machine, as well as all other machines from ploughing to harvesting, are driven in the same direction. This gives an even and regular surface of the ground, which is advantageous regarding speed and regularity of the work. A sudden jolt during pulling may, for example, result in an irregular thickness of the swath. It is also important that the width of the pulling machine is larger than the length of the straw in order to place the straw crosswise on the ground without overlap. If the stems are 90 cm high, the swath width should be 105-110 cm. If there is an uncovered strip between the swaths, there is a risk that weeds will grow on this area. Furthermore, if two swaths superimpose on each other, there is risk of non-uniform retting and also problems when turning the straw, and if the top-end of one swath is lying under the root-end of the adjoining swath, the capsules most likely will be lost due to faster retting (Sultana, 1992).

Figure 7. A modern pulling machine that pulls the flax across a width of 3 m (Dewilde, 1987).

Self-propelled pulling machines have come into general use in Western Europe, and advances in hydraulic transmission have improved the efficiency considerable (Sultana, 1992). Seyns (1989), for example, reports on a double row self-propelled pulling machine with hydraulic transmission, which allows a regular and step-less powered machine, as well as a quick and easy adjustment of the speed according to the conditions of the flax.

3.2.2. Turning

Turning is required to get a homogeneous retting process in the swaths, because the top layers of the swaths are retted faster than the lower layers. The swaths should be turned half-way through the retting process, and a further turning may be necessary if heavy rain has flattened the flax to the ground, or if weeds are growing through the swath (Sultana, 1992). Generally, the number of turnings should be minimized in order to avoid seed losses and irregular positioning of the swaths (Seyns, 1989).

The principle of a turning machine can be seen in Figure 8. The flax is lifted from the ground by a hollow cylinder with pins and an eccentric shaft. At the top of the cylinder, the straw is placed on a slanting crossed conveyer belt, and then turned through 180°. After that, the stems are dropped in parallel on the ground by means of a non-crossed conveyer belt. The stems should be dropped close to the ground in order to avoid them becoming entangled in the swaths by the wind. Most turning machines are self-propelled and have hydraulic transmission. Note that the turning operation can also be combined with decapsuling, for example by rippling (see alternative 2 in Figure 6 and section 3.2.3.) (Seyns, 1989).

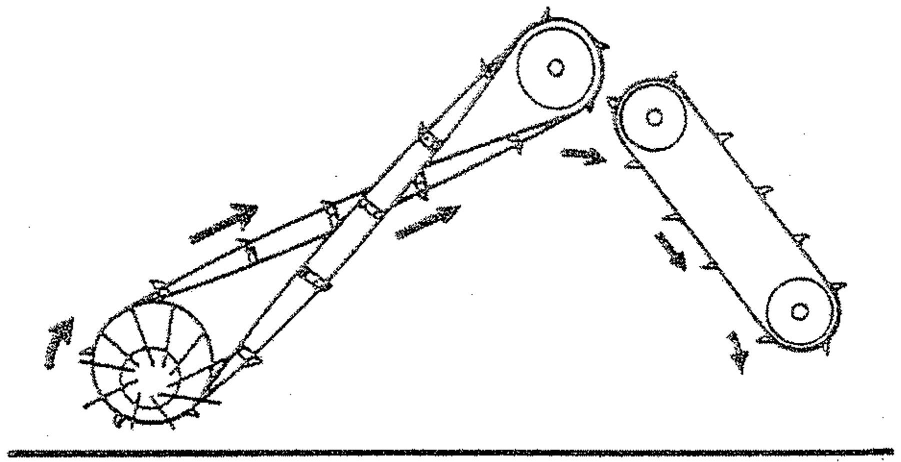

Figure 8. Principle of turning (Sultana, 1992).

3.2.3. Descapsuling

Decapsuling is the process by which the capsules are separated from the flax straw. Only the bolls are harvested, and to obtain the seeds, further processing is necessary, e.g. drying, threshing and cleaning. Decapsuling can be performed via rippling either during pulling (alternative 3 in Figure 6) or while turning (alternative 2 in Figure 6). The former method originates from Russia, whereas the latter originates from Western Europe.

The seed must be ripe if the flax is to be decapsuled during pulling. Thus, the pulling is postponed and the risk of fibre damage due to poor weather conditions is higher. The capsules should also be quite dry, but they usually need further drying because the moisture content may be 40% (w.b.). The pulling-decapsuling machines are rather expensive, and they can be tractor-driven or self-propelled. After pulling, the stalks are combed by a rippling unit from bottom to the top, and then placed in parallel on the ground. The stems have already reached their ripeness and their cuticule has become more resistant, so crushing of the lower parts is recommended to accelerate the retting process (Seyns, 1989; Sultana, 1992).

The flax is pulled earlier in the season if it is to be decapsuled during turning. The capsules remain in the swaths for 1-2 weeks after pulling for drying. A disadvantage with this method is, however, that the seed losses may be high if the crop has to wait too long in the field for the decapsuling/turning machine (Seyns, 1989). Therefore, the yield of capsules is usually lower with this method in comparison with the Russian method. The decapsuling/turning machine is expensive and only used for harvest of sowing seeds. The machine lifts and decapsules the flax by means of a pick-up and two transfer belts, which compress it tightly, followed by two threshing cylinders, which remove the capsules from the straw. The aligned stems are then turned and placed on the ground. The capsules remain intact, which ensures good conservation before the subsequent crushing and cleaning processes of the seeds (Sultana, 1992).

The flax can also be deseeded with a third method, namely in the processing plant after harvest and storage (see alternatives 1, 5 and 6 in Figure 6). The grain obtained may, however, be of lower seed quality and the losses may amount to 50% (Balkow & Ingler, 1997).

3.2.4. Baling

Baling of flax straw was introduced in the 1960s, and it resulted in a considerable reduction of the labour required in flax handling. Round balers with variable chamber volumes are suitable for baling of flax. Sultana (1992) lists some modifications of the conventional round baler necessary when harvesting flax:

1. Two twines must be led in during baling. These twines allow separation of each single turn during the unrolling of the bale in the scutching mill.
2. The width of the pick-up must be narrowed to 60/70 cm in order to avoid the uptake of the next swath.
3. The thickness of the swath must be increased by a factor of 3 to 4, so as to correspond to the requirements of the scutching turbine. This can be done by both reducing the speed of the belts and increasing the speed of the pick-up.
4. A wheel must be set before the pick-up. This facilitates the adjustment of the teeth above the ground without picking up soil particles.
5. The side belts must be removed. This limits seed loss and is also useful for short stalks.
6. When baling, the top of the swath must always be on the left, viewed from the direction of the baler, in order to ensure a correct presentation of the stems at the scutching mill.

Balers and pick-ups especially built for baling of flax have been constructed, for example, machines that are set slantwise to avoid driving over the swaths. Self-propelled balers have also been developed, as well as machines that bale two swaths at the same time (Sultana, 1992).

3.2.5. Transport and loading

The use of round bales has allowed a complete mechanisation of flax handling. This has reduced the amount of work required to a tenth of that required before these baling machines were introduced (Sultana, 1992). The bales can be loaded by front loaders or by self-propelled loaders, and transported on trucks carrying a large number of bales. However, flax straw is a voluminous material even when it is compacted in round bales, and the space-capacity of transport vehicles is in most cases the limiting factor, rather than their weight-capacity. The low transport densities can be enhanced by using rectangular high-density bales, at least for non-aligned straw.

3.3. Alternative harvesting and handling systems

One alternative method tested in Western Europe, and foremost in Northern Ireland, was to use herbicides to desiccate the flax and then ret the stems in a standing posture (Easson and Long, 1992). The most commonly used herbicide was the phloem-mobile glyphosate. One advantage with stand-retting of flax is that it becomes less weather-dependent, in comparison with traditional dew retting. Under dry weather conditions, however, Sharma (1986) showed that desiccated stand-retted flax retted more slowly than dew retted flax, irrespective of whether the dew retted flax was desiccated or not. This was probably a result of the fungicidal properties of glyphosate (Sharma, 1986; Brown and Sharma, 1984).

The most important problems with this method were associated with uneven desiccation of the flax and thus uneven and unsatisfactory retting (Easson and Long, 1992). Reasons for the uneven desiccation are: little downward translocation of the herbicide, because the plant is near maturity at seed harvest, and difficulties in applying sufficient glyphosate to every stem.

In the Nordic countries, the growing period is short and the autumns often very rainy and cold. This makes it difficult to harvest a high quality flax with sufficiently low moisture contents. In Finland, a system has been developed (the so-called dry-line method), in which the seed is harvested with a modified combine harvester in the autumn, and the stems with modified hay harvesting machines in the following spring when the crop is driest (Figure 9) (Pasila, 1998). In normal winter conditions, the stems are stored in the snow without severe damage or contamination, but unexpectedly mild winters may destroy the fibres. One advantage with the method is that the processing properties of the material are improved (Pasila, 1998).

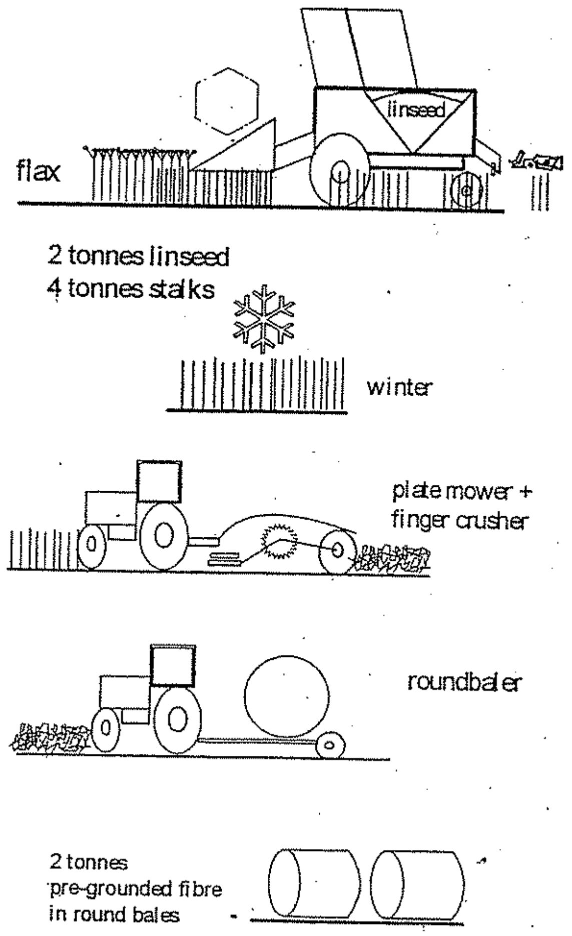

Figure 9. Outline of the dry-line method for the production of seed and flax fibres (Pasila, 1998).

In Laholm in Southern Sweden, a flax processing plant for the production of non-textile fibres was inaugurated in 1999 (Isaksson, 2000). However, the production ceased a few years later due to technical problems and a negligible demand for fibres. The main part of the flax straw used was un-retted, but partly retted or completely retted straw was also used if there was a demand for such fibre qualities. If the autumn had been rainy, the share of retted straw was, of course, higher. The flax was cut instead of pulled. The main reason for cutting the stems was to minimize the quantity of soil particles, partly to reduce the wear of processing machines, and partly to avoid soil contamination in the final product (Isaksson, 2000; L. Jacobsson, personal communication).

The flax was cut 5-10 cm above the ground by a windrower and then laid in a swath for drying (Figure 10). The windrower had been modified to be able to cut and handle the stems without tangling problems. The flax straw was laying in the field for about one week until dry enough for baling. Before it was baled, however, it was often turned to get an even moisture content. If the weather was damp during this period, the flax had to stay longer in the field, and the retting process began (Isaksson, 2000; L. Jacobsson, personal communication).

The straw was baled with round balers or high-density balers, and then stored on the farms until delivery to the processing plant. In the plant, the twines were removed manually and the bales then fed into a shredder. There were no restrictions regarding parallel handling of stems through the handling and processing systems, although unneeded stem tangle was not desirable. The processing unit was made by TEMAFA and had a nominal capacity of 2 tonnes of straw per hour. About 20-30% of the straw was processed to fibres, about 50-60% to shives and 10% was dust (Isaksson, 2000; L. Jacobsson, personal communication).

Figure 10. The modified windrower used at Laholm (Isaksson, 2000).

Tests with early cutting of the flax for fibre production with a drum-mower have been carried out in the USA (Foulk et al., 2002). The costs for a self-propelled puller is about $160,000, about $45,000 for a self-propelled turner and about $100,000 for a self-propelled large round baler (Irwin, 1998). Thus, the use of readily available agricultural equipment such as mowers reduces the costs. The harvest capacity is also increased with such equipment, because the straw is not handled aligned. For the harvest of seeds when the crop is mature, a stripper header attached to a combine harvester can be used. The crop can be combined at a rate of 5 ha/h, mowed at a rate of 1 ha/h, raked at a rate of 2.5 ha/h and baled at a rate of 2 ha/h. With stubble heights at 6.0-7.3 cm, the fibre loss is 3-10% at mowing (Foulk et al., 2002). Readily available farm equipment for harvest and handling of flax, instead of traditional harvest systems based on pullers, is now evaluated in the USA (Foulk et al., 2002).

4. QUALITY ASPECTS

In addition to the costs for machinery and labour, there are also indirect harvesting and logistics costs. These indirect costs may, for example, result from quality losses due to untimely harvesting. If the machinery capacity is too low, the flax straw may be over-retted and the fibres useless. On the other hand, if the machinery capacity is too high, the total harvest and handling costs increase, which may result in poorer economic competitiveness. Such indirect costs, or timeliness costs, are very important to consider when designing cost-effective harvesting and logistics systems.

The most important quality factors related to the timeliness of harvesting and handling operations are the straw moisture content and the degree of retting. The baling work must wait until the straw moisture content is sufficiently low to avoid mould growth during storage, and the degree of retting must be at a suitable level at baling for securing a high quality fibre adapted for its specific use. It is clear from many studies that the degree of retting has a strong influence on the fibre quality (Turner, 1954; Pallesen, 1996; Sharma and Faughey, 1999; Sharma et al., 1999). A literature review on the processes for moisture content changes and dew retting is presented below.

4.1. Moisture content

4.1.1. The drying and rewetting processes of flax straw

When the flax is cut, transpiration ceases because the connection between the stem and the root is broken. The stomata close some time after cutting, and the rate of the drying process then depends on the resistance of the cuticule and the microclimate in the surrounding environment. The driving force for the drying process is the difference in partial vapour pressure between the plant and the surrounding air. When the internal vapour pressure is in equilibrium with the vapour pressure of the environment, the material has reached its desorption equilibrium moisture content (Atzema, 1992).

The moisture content of the material increases if intercepted precipitation or water condensed from the air (dew) is absorbed. The quantity of rain intercepted can be described by linear relationships, as well as by exponential decay functions (Thompson, 1981; Nilsson, 1999; Lankreijer et al., 1999). The straw moisture content also increases due to formation of dew, or condensation of water from the surrounding air. Water condenses when a surface is cooled to a temperature below the actual dew point temperature of the surface air. Furthermore, the straw moisture content increases if the environmental vapour pressure increases, because the moisture content of the material increases until it reaches its corresponding adsorption equilibrium moisture content.

4.1.2. Equilibrium moisture content

Hygroscopic materials like flax adsorb moisture when the vapour pressure within the material is lower than the vapour pressure of the surrounding air. When the internal vapour pressure is equal to the vapour pressure of the surrounding air, the moisture content of the material is equal to the equilibrium moisture content. The internal vapour pressure is dependent on the surrounding environment, i.e. its temperature and relative humidity, as well as on the plant material, i.e. species, variety and maturity. The equilibrium moisture content of a specific product can therefore be defined as the moisture content of the product after it has been exposed to a particular environment with a constant temperature and relative humidity for an infinitely long period of time (Brooker et al., 1992). For a certain temperature, there is always an equilibrium relative humidity that corresponds to the equilibrium moisture content.

If the flax straw loses moisture due to a lower vapour pressure in the environment than within the material, it reaches its desorption equilibrium moisture content. The value of the desorption equilibrium moisture content is always higher than the value of the adsorption equilibrium moisture content for given values of temperature and relative humidity due to the so-called hysteresis effect (Figure 11). The hysteresis effect may be explained as a result of the control mechanisms in emptying (desorption) and filling (adsorption) capillaries in biological materials (Brooker et al., 1992).

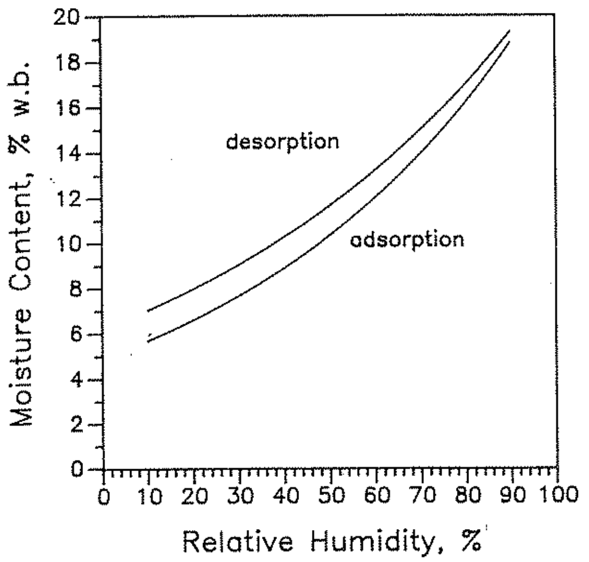

Figure 11. Desorption and adsorption moisture equilibrium curves for a specific temperature and material (yellow dent corn at 22°C) (Brooker et al., 1992).

In the Nordic countries, humidity during autumn and winter is often high, which means that the equilibrium moisture content of the fibre crop is also high. This may cause problems in harvest, storage and processing operations of the crop. Retted flax straw can, for example, be preserved for several years if the moisture content is below 15% (w.b.). However, if the moisture content is above 16%, there is a risk of the retting process continuing during storage, resulting in fibre quality deterioration (Sultana, 1992). Furthermore, damp fibre crop stems are more difficult to process due to higher friction coefficients (Pasila, 1998).

It is obvious that a deeper knowledge of the equilibrium moisture content properties of flax is useful for optimising drying, harvest and post-harvest operations, as well as for improving quality control during storage. However, no studies on the equilibrium moisture contents for this crop were found in the literature. Fibre and shive fractions of flax and hemp have been investigated regarding equilibrium moisture contents (Kymäläinen & Pasila, 2000) and capillarity properties (Kymäläinen et al., 2001), but these authors did not study the properties of the whole straw or stalk. ASAE regularly publishes data and coefficients for isotherm equilibrium moisture content equations for agricultural products, but no data for fibre crops were found (ASAE, 2000). The advantage with the isotherm equations is that the equilibrium moisture content can be calculated for given values of temperature and relative humidity. Examples of such equations are the modified Henderson equation (Thompson et al., 1968):

$$RH = 1 - \exp\left[-A(T+C)(MC_D)^B\right]$$

the modified Chung-Pfost equation (Pfost et al., 1976):

$$RH = \exp\left[-\frac{A}{T+C}\exp(-B \cdot MC_D)\right]$$

the modified Halsey equation (Iglesias and Chirife, 1976):

$$RH = \exp\left[-\frac{\exp(A + B \cdot T)}{(MC_D)^C}\right]$$

the modified Oswin equation (Chen and Morey, 1989):

$$RH = \left[\left(\frac{A + B \cdot T}{MC_D}\right)^C + 1\right]^{-1}$$

and the Guggenheim-Anderson-deBoer (GAB) equation (Jayas & Mazza, 1993; van den Berg, 1984):

$$MC_D = \frac{A \cdot B \cdot C \cdot RH}{(1 - B \cdot RH)(1 - B \cdot RH + B \cdot C \cdot RH)}$$

where *RH* is the relative humidity (decimal), *T* the temperature (°C), MC_D the moisture content (percent, d.b.) and *A, B, C* constants.

4.1.3. Dew formation

Dew is of great significance as a water source for the micro-organisms involved in the dew retting process. It is also important for the harvesting operations, because it determines the point in time when the machines can start and have to stop their daily work. Dew can be defined as "water condensed onto grass and other objects near the ground, the temperatures of which have fallen below the dew point of the surface air due to radiational cooling during the night, but are still above freezing" (Rosenberg et al., 1983). The rate of the cooling of the surface depends mainly on the following energy fluxes: the net radiation (which is determined by the net solar radiation and the net long-wave radiation), the convective sensible heat flux and the latent heat flux. More theoretical aspects of dew formation and measurement techniques are described in greater detail by Monteith (1957) and Rosenberg et al. (1983).

The duration and quantity of dew can be about 0-12 hours and about 0.1-0.4 mm, respectively, under Swedish autumn conditions (S. Karlsson, personal communication). There are many examples in the literature of models for estimation of the duration and formation rate of dew. Pedro and Gillespie, for example, used micrometeorological data (1982a), and standard weather data (1982b), to estimate the duration of dew. Furthermore, there are examples of empirical models (Gleason et al., 1994) in the literature, as well as models based on energy balance approaches (Luo and Goudriaan, 2000; Madeira et al., 2002). A model that also includes soil evaporation is presented by Wilson et al. (1999).

4.1.4. Modelling the moisture content of flax straw

There are models describing the moisture content changes of flax fibres (e.g. Efremov, 2001; Kohler et al., 2003), but no model describing the moisture content changes of flax straw were found in the literature. However, several models to simulate the moisture content changes of hay and cereal straw were found. These models are usually based on energy balance approaches, which consider mass and energy flows, or empirical approaches based on diffusion equations (Jenkins et al., 1984). The energy balance models for drying of hay presented by Brück and van Elderen (1969), Thompson (1981), Smith et al. (1988) and Atzema (1992) are complex and require frequent observations of several weather variables that may be difficult to obtain from standard weather stations.

Most diffusion models originate from the semi-empirical thin layer drying equation proposed by Lewis (1921):

$$dM/dt = -k(M-M_{eq})$$

where M is the moisture content (d.b.), k the drying constant, and M_{eq} the equilibrium moisture content (d.b.).

Savoie et al. (1982), for instance, adopted this expression in their model for field drying of hay. They showed that the drying constant is mainly a function of solar radiation, temperature, hay density and machinery treatment. The drying effects of sunlight, temperature, wind and humidity were combined into one variable by Pitt (1984) as pan evaporation and by Kemp et al. (1972) as latent evaporation. They both used diffusion equations to estimate the field drying of hay. An exponential decay function was also proposed by Hayhoe and Jackson (1974), requiring only daily potential evaporation and precipitation as inputs. Dyer and Brown (1977) rewrote their expression to a linear form, and also considered dew formation. Some empirical models for field drying of straw were also found in the literature (Stewart and Lievers, 1978; Jenkins et al., 1985; Hadders, 1999; Nilsson, 1999). The main features of the model developed by Nilsson (1999), and also ways to improve it and adapt it to flax straw, are reviewed below.

In the Nilsson model, it was assumed that the moisture content in the flax straw (M, d.b.) can be divided into internal (i.e. bound water, M_i, d.b.) and external moisture (i.e. free water from precipitation and dew, M_e, d.b.) as described by $M = M_i + M_e$. The change of the internal moisture content was based on the Lewis (1921) semi-empirical equation for thin-layer drying. It was assumed (Nilsson, 1999) that the release of internal moisture can be described by:

$$dM_i/dt = -a_d E(M_i-M_{eq})$$

where a_d is an empirical coefficient and E the rate of potential evapotranspiration, which was assumed to summarize the drying power of the ambient air into one variable. When $M_i < M_{eq}$, it was assumed that the straw absorbs internal moisture until it reaches its corresponding equilibrium moisture content.

In the model by Nilsson (1999), the evapotranspiration was obtained from some weather stations (calculated from measured weather data). However, it is also possible to use the pan evaporation in a model. The pan evaporation E_p can be calculated by the Kohler-Nordenson-Fox equation (Kohler et al., 1955; Burman & Pochop, 1994):

$$E_p = \frac{\Delta R_n + \gamma_p E_a}{\Delta + \gamma_p}$$

where R_n is the net radiation, Δ the slope of the saturation vapour-pressure versus temperature curve at the air temperature, γ_p the psychrometric coefficient, and E_a an aerodynamic function. Equations for calculation of R_n, Δ, γ_p and E_a are presented by Burman and Pochop (1994). One alternative is to use the Penman-Monteith equation directly with data from weather stations. This equation states that water evaporates and condenses according to (Monteith, 1965):

$$L_v E = \frac{(R_n - G)\Delta + \rho_a c_p (e_s - e_a)/r_a}{\Delta + \gamma(1 + r_c/r_a)}$$

where L_v is the latent heat of vaporisation, G the soil heat flux, ρ the density of air, c_p the specific heat at constant pressure, e_s the saturated vapour pressure, e_a the actual vapour pressure, r_a the aerodynamic resistance and r_c the crop resistance. If $L_vE>0$, there is evaporation ($E=E_e$), and if $L_vE<0$, there is condensation ($E=E_c$). The potential evaporation can be calculated, assuming that the evaporation takes place from a constantly wet surface, which implies that $r_c=0$. The net radiation can be calculated from the equation proposed by Hotschlag & van Ulden (1983),

$$R_n = \frac{(1-\alpha)R_g + c_1 T^6 - \sigma T^4 + c_2 N}{1 + c_3}$$

using the albedo (α), the global radiation (R_g), the Stefan-Boltzman constant (σ), the air temperature (T), the cloud cover (N) in octas, and c_1 ($5.31 \cdot 10^{-13}$ W/m^{2}K^6), c_2 (60 W/m^2) and c_3 (0.12) as inputs.

For flax, the equilibrium moisture content M_{eq} can be calculated from some of the commonly used equilibrium moisture content equations described in section 4.1.2. In these equations, M_{eq} is a function of the air temperature, the relative humidity and three material-specific empirical coefficients.

Nilsson (1999) used a linear relationship between the change in the content of external moisture (w.b.) and precipitation (wetting) and evapotranspiration (drying). It may also be possible to calculate the change in the external moisture content on a dry basis and include dew (Jenkins et al., 1985). A non-linear relationship for describing the rewetting of rain can also be used. For, example, the quantity of rain intercepted by living plants is dependent on the orientation and surface structure of the leaves, which gives the plant a specific capability (κ_P) to intercept water per leaf area unit (LAI). Thus, the quantity of intercepted rain (P_I) in relation to the total quantity of rain (P) can be described by an equation of the form (Eckersten et al., 1998):

$$P_I = P(1 - e^{-\kappa_P LAI})$$

To calculate the duration and quantity of dew, the Penman-Monteith equation above can be used. Other models can also be used, for example that by Madeira et al. (2002). They based their model on the following energy balance for a surface exposed to dew:

$$LE = (1-\alpha)S_g + L_d - L_u - C$$

where LE represents the latent heat flux density from (evaporation) or towards (condensation) the surface, α the albedo, S_g the incident short-wave radiation, L_d the downward long-wave radiation, L_u the upward long-wave radiation and C the sensible heat flux density. The downward long-wave radiation and the sensible heat flux were calculated from the equations presented by Monteith & Unsworth (1990), and the upward long-wave radiation was calculated from the well-known Stefan-Boltzman law. The equation for the aerodynamic resistance required to calculate the sensible heat flux can be found in Monteith and Unsworth (1990).

4.2. The dew retting process

The main purpose of dew retting is to decompose the pectic substances, which attach the fibre bundles to the woody core. A cross section of a flax stem, together with a cross section of a fibre bundle, is shown in Figure 12. The outer layer of the stem is the epidermis, which consists of a protective one-cell layer covered with waxes (cuticule). Thereafter, there are 2-3 layers of parenchyma cells with chlorophyll grains, and then the bast section with fibre bundles follows. The next layer consists of phloem cells for transport of nutrients, cambium cells for growth, xylem (wood) cells, pith cells, and innermost, a hollow space (Fröier and Zienkiewicz, 1979; van Sumere, 1992).

The bast section consists of 20-50 ring-shaped fibre bundles, and each fibre bundle consists of 10-40 spindle-shaped elementary fibres, i.e. fibre cells. The fibre bundles intertwine in each other at different levels and in this way stabilise the stem. The elementary fibres usually have a length of 25-30 mm and a diameter of 0.012-0.035 mm. The elementary fibres are linked to each other by means of the schlerenchyma middle lamellae (the inner middle lamellae), and the bundles are linked to the bast section by means of the parenchyma middle lamellae (the outer middle lamellae). The inner middle lamellae consist of pectin, lignin and hemicellulose, whereas the outer middle lamellae consist of hemicellulose and pectin. The pectin in the inner middle lamellae seems to be more resistant to biological and chemical degradation in comparison with the pectin in the outer middle lamellae (Danielsson, 1988; Liljedahl and Smeder, 1992; Isaksson, 2000).

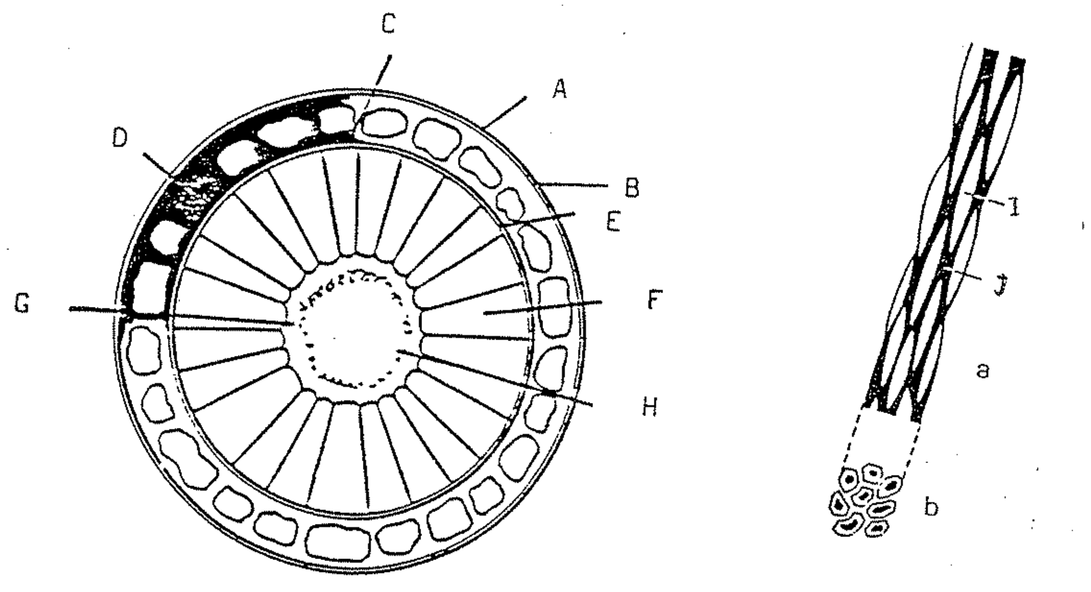

Figure 12. Cross section of a flax stem (left) and a fibre bundle (right; a – longitudinal section, b – cross section) (Danielsson, 1988). A - cuticule with wax layer, B - epidermis, C - parenchyma cells, D - fibre bundles, E – cambium cells, F - woody cells, G – pith cells , H – hollow space , I - cellulose cells, J - schlerenchyma middle lamellae.

The chemical composition of flax fibres varies in different literature sources. Composition data presented by Danielsson (1988) are shown in Table 8.

Table 8. The chemical composition of flax fibres (Danielsson, 1988)

	Un-retted flax (% of DM)	Retted flax (% of DM)
Cellulose	62.8	71.3
Hemicellulose	17.1	18.5
Pectic substances	4.2	2.0
Lignin	2.8	2.2
Fat and waxes	1.4	1.7
Water soluble components	11.9	4.4

The pectic substances are degraded by different enzymes. The most important pectolytic enzymes are pectin esterase (PE), polygalacturonase (PG), pectin lyase (PL), and, to some extent, pectat lyase (PAL). The enzymes xylanase and cellulase are also often present in the degradation process. Xylanase degrades hemicellulose and its presence is desirable as long as the fibre cell walls are not affected. The presence of cellulase is, on the other hand, less desirable because it degrades the cellulose. The chemical components that are formed in the degradation process are galacturonic acid, methanol, galactose, arabinose, glucose, lactose, xylose, etc., which are transformed in turn into organic acids such as butyric acid, propionic acid, acetic acid, valeric acid and carbon dioxide (Danielsson, 1988; Smeder, 1993b). Examples of how the enzymatic activities change over time for various retting methods are shown in Figure 13.

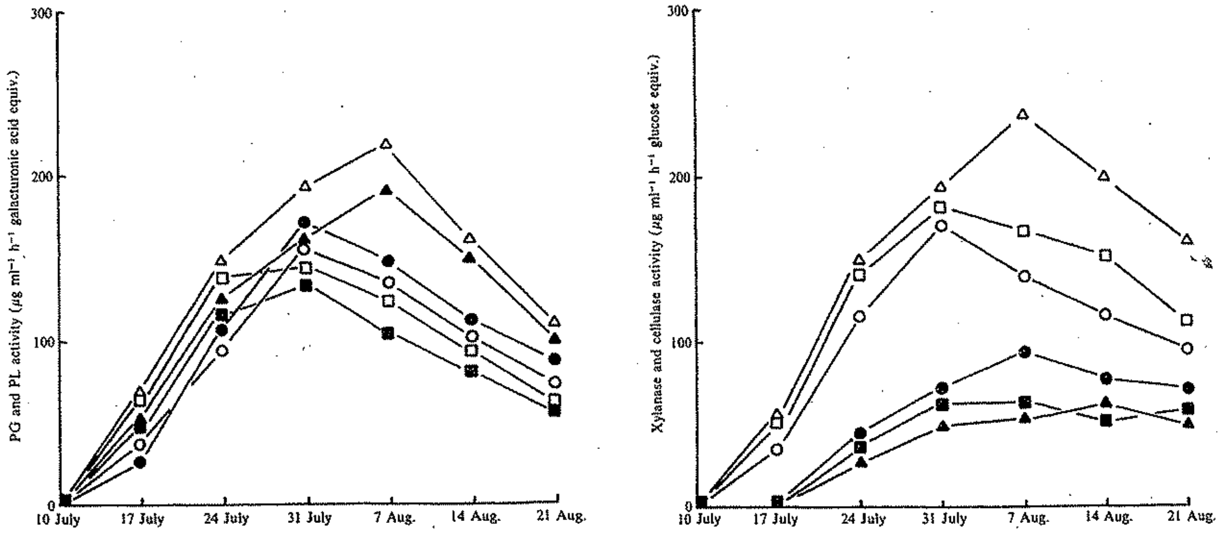

Figure 13. Mean activities of polygalacturonase (open symbols) and pectin-lyase (closed symbols) in glyphosate-desiccated stand-retted flax stems (triangles), glyphosate-desiccated dew retted stems (squares) and traditionally dew retted stems (circles), in the left figure. The activities of xylanase (open symbols) and cellulase (closed symbols) for the same stem treatments are shown in the right figure (Sharma, 1986).

The enzymatic degradation of the polysaccharides results in a reduction in the pectic substances in the stems from 3-4% to 0.5-1% (% of dry matter content) (Chesson, 1978). Meijer et al. (1995) showed that the content of pectins in the stems is 25-30 g/kg DM at the beginning of the retting and 7-10 g/kg DM when the retting is complete. Figure 14 shows how the content of pectins was reduced in dew retting in their study. About 30% of the initial pectic substances seemed to be resistant to the pectinase activity, and the degradation ceased when the content of pectins was 7-10 g/kg DM, irrespective of retting method (dew or water retting) (Meijer et al., 1995). Furthermore, it seems that lower initial contents of pectic substances reduce the retting time (Brown et al., 1986).

In dew retting, the pectolytic enzymes involved are mainly produced by aerobic saprophytic fungi. Bacteria may also play an important role, especially in cold and damp weather (Sharma, 1986; Sharma, 1988) The dew retting process can be divided into three main stages, in which the real pectic degradation occurs in the second stage. In the first stage, the stem is colonized mainly by bacteria, which decompose water soluble substances. In the second stage, fungi are the predominant degradation microbes, but there may also be some bacteria active. In the third stage, the cellulose is degraded by means of cellulase. These retting phases can run smoothly into each other, and all stages may be present at the same time (Frederiksen, 1968; Kozlowski, 1992).

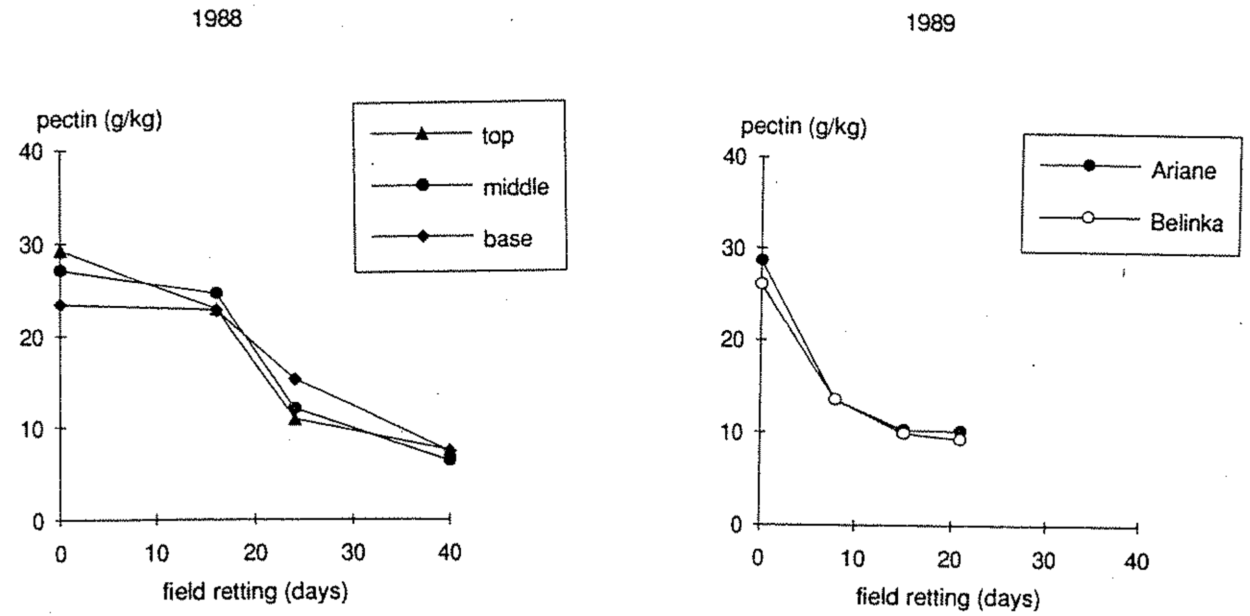

Figure 14. The pectin content of flax stems during dew retting. Samples from the top, middle and base of stems for the Belinka cultivar in 1988 (left), and a comparison between the cultivars Ariane and Belinka in 1989 (right). The retting season was dry in 1988, and the retting process slower in comparison with the year 1989, in which the autumn was damp (Meijer et al., 1995).

The most important fungi in the retting process are *Alternaria alternata*, *Botrytis cinerea*, *Cladosporium herbarum*, *Fusarium culmorum*, *Mucor* sp., *Penicillium* spp. and *Phoma* spp. (Brown and Sharma, 1984). All these species produce polygalacturonase, pectin lyase and xylanase. In addition, *A. alternata*, *C. herbarum*, *F. culmorum* and *Phoma* spp. also produce cellulase (Brown and Sharma, 1984; Sharma, 1988). The fungus that seems to occur most frequently in the retting process is *C. herbarum* (Frederiksen, 1968; Brown and Sharma, 1984), especially during summer (van Sumere, 1992). In retting during autumn and retting under snow, *Mucor stolonifer* and *Mucor hiemalis*, respectively, are important fungi (van Sumere, 1992).

Henriksson et al. (1997) identified fungi that are involved in dew retting under the climatic conditions of South Carolina (two species of *Fusarium*, *Rhizomucor pusillus*, *Trichoderma virens*, *A. alternata*) and Connecticut (*Fusarium lateritium, C. herbarum*) in the USA, France (*Fusarium oxysporum*) and the Netherlands (*Epicoccum nigrum*). Of those fungi, *R. pusillus, F. lateritium, T. virens* and *E. nigrum* had high retting efficiency. Furthermore, they found that *E. nigrum* caused high losses in fibre strength, and that *R. pusillus* and *F. lateritium*, to some degree, also weakened the fibres (Henriksson et al. 1997).

The various fungi involved may differ considerably regarding, for example, enzyme production activity and rate of retting (Brown and Sharma, 1984), grey-colouring of the stem substrate (Frederiksen, 1968), occurrence on the upper or lower side of the swath due to different light preferences (Frederiksen, 1968), growth depending on the accessibility of the nutrients in the substrate (Frederiksen, 1968), and growth depending on the season of the year (Frederiksen, 1968).

The occurrence and growth of fungi depend on three main factors: the type of substrates present, the environmental conditions (Ayerst, 1969) and the interactions with other organisms (Deacon, 1997). In dew retting, the substrate is the flax stem and its contents of various components, but the type of fungi present depends on the content of fungi and substrates in the soil. The most important environmental factors are the temperature, the pH value, light conditions and the availability of water and oxygen. The interactions with other organisms can be divided into three types: the ability of one species to exclude another by competition (e.g. by being faster or more efficient in exploiting a resource), the ability of one species to exclude or replace another by antagonism (e.g. by directly affecting another organism through antibiotic production), and the ability of two species to interact to the benefit of one or both with no negative impact on other species (Deacon, 1997).

4.3. Methods to assess the degree of retting

The retting process affects molecular as well as micro-structural characteristics of the flax. It may therefore be difficult to objectively measure the progress of retting, i.e. the degree of retting, due to variations in chemical composition and morphology for different flax varieties, grown with different cultivation and harvest techniques under various soil and weather conditions. This may be a reason for the current lack of a generally accepted definition of the concept of degree of retting, and also the lack of an international standard to which the degree of retting can be related. Traditionally, the degree of retting has been determined by means of various subjective (organoleptic) methods. Some more objective methods have, however, been developed recently. A number of traditional and new methods for the determination of the degree of retting are presented below.

4.3.1. Subjective assessment

The stems are held between the forefingers and thumbs with a distance of about 1 cm and then rotated and shaken until the fibres begin to release from the woody core. The ease with which the fibres are released indicates the degree of retting (van Sumere, 1992). This is the traditional method used since long ago. Experience is required for accurate assessments.

4.3.2. Visual colour comparisons

The colour of the stems is changed from green-yellow to dark grey as the retting progresses. Pallesen (1996) used these changes when she assessed the degree of retting visually with a 10-grade colour scale. The method is simple and fast, but it is not clear how variations in moisture content, variety, maturity at harvest, etc, may impact on the results.

4.3.3. The braking test

In this method, dried flax stems are placed between two opposing serrated surfaces. The flax is squeezed between these surfaces a number of times until the fibres are released. This number is a measure of the degree of retting, and the lower the number, the higher the degree of retting (van Sumere, 1992).

4.3.4. The scutchability index

Bundles of flax stems are beaten mechanically until the fibres begin to separate from the bast and from each other (Anon., 1942; Seaby and Mercer, 1984; van Sumere, 1992). The scutchability index is obtained by dividing the time needed by the weight of the stems before they are beaten.

4.3.5. The stem firmness test

In this simple test, described by Fischer and Topf (1988), the stem firmness is related to the degree of retting (Figure 15). However, this method has not yet been fully developed and needs further confirmation The moisture content may, for example, be a critical factor (van Sumere, 1992).

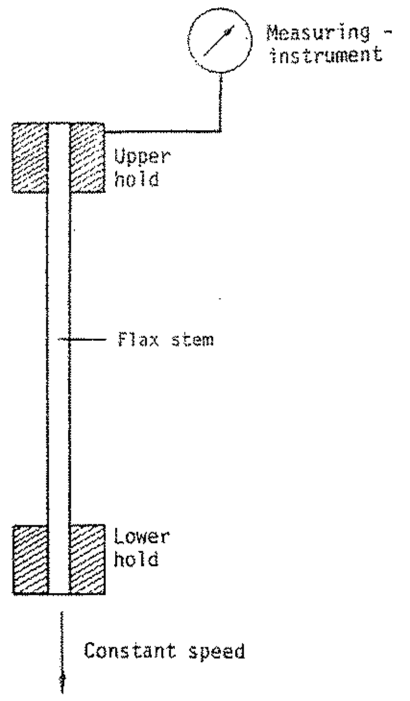

Figure 15. Principle of stem firmness measurements (van Sumere, 1992).

4.3.6. The fibre grade test

Scutched flax is examined regarding tensile strength, fibre length, fineness and general appearance. The results are then compared with results from investigations of other samples (van Sumere, 1992; Seaby and Mercer, 1984). The lower the values, the higher the fibre quality and the more retted the material, according to Seaby and Mercer (1984). This method is very laborious.

4.3.7. Microscopic investigations

Danielsson (1988) proposed that microscopic investigations be used to assess the degree of retting. In this test, dried stems are laid in water for 24 hours, and then cut with a razor blade. Breaks or cracks in the parenchyma middle lamellae can then be observed in a microscope, and the larger the cracks, the more retted the material (Fraser et al., 1982; Danielsson, 1988). Danielsson (1988) points out, however, that cracks may also arise as a result of strain forces when the material is dried or cut. To get a more accurate view of the retting process with this method, the material probably should be in-baked in paraffin and plastics or frozen and cut with specially-designed instruments (Danielsson, 1988).

4.3.8. Fried's test

In this test, three pieces of flax stems, 5-10 cm long, are put in a test tube. About 8 ml boiling water is added to the tube. The tube is then stoppered and shaken vigorously by means of a Super mixer (Lab Line Instruments Inc., USA). The degree of retting is determined visually by assessing how much the fibres have separated in comparison with a standardized 4-grade scale. This scale was constructed by Fried (1939), and is shown in Figure 16. The value 0 means that the stem is not retted, the value 1 that retting has started, the value 2 that retting is nearly completed, and the value 3 that retting is completed. The method is described further by Fried (1939), Dujardin (1942) and van Sumere (1992), and it has been used by, for example, Henriksson et al. (1997), Henriksson et al. (1999), Archibald and Akin (2000) and Ulrich (2002). Some advantages with this method are that un-scutched stems can be used, and that the actual degree of ease with which the fibres are decorticated is estimated, independent of variety, moisture content and maturity at harvest. Typical variations in the degree of retting of enzyme-treated flax are shown in Figure 17.

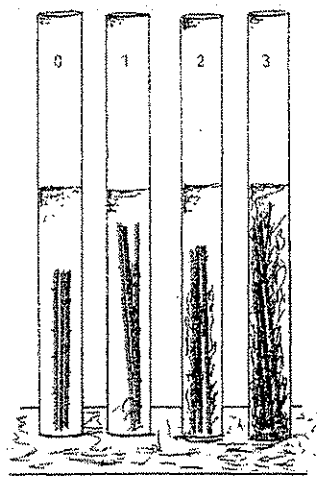

Figure 16. The four different degrees of retting in Fried's test (van Sumere, 1992).

It has been observed that Fried's test may have limitations in later stages of dew retting due to binding of fibres by mycelium. In a study by Henriksson et al. (1997), the degree of retting measured by the Fried test increased for pure cultures of fungi the first two weeks, and then levelled off or decreased the following four weeks. For example, it was shown that *A. alternata* had low retting rates according to the test, while the mycelial growth was heavy. A possible explanation for the low Fried score is that the mycelium from this fungus prevents the fibres from loosening from the stem (Henriksson et al., 1997).

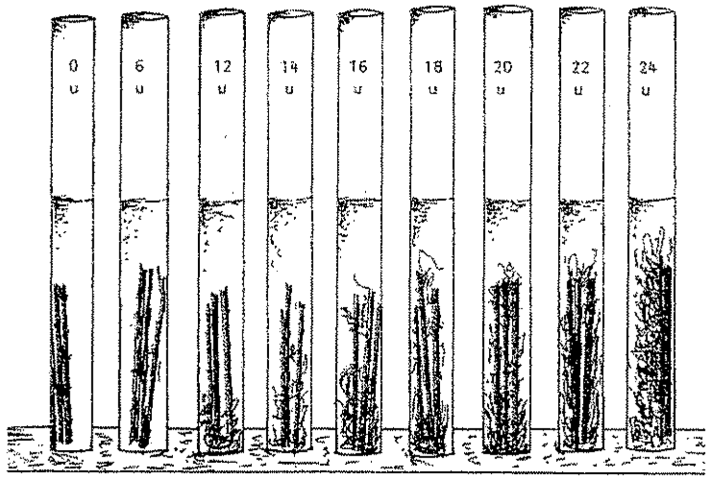

Figure 17. Variations in fibre release with Fried's test for enzyme-treated flax stems. The retting time is indicated in hours (u) (van Sumere, 1992).

4.3.9. Measurement of bend and shear forces

A hand tool for measuring the forces required for separating the fibres from the stems has been developed in Ireland by Seaby and Mercer (1984). Like most other methods, these forces estimate the degree of retting indirectly. In this case, it is assumed that the higher the forces, the less retted the flax.

The tool mimics the scutching process by first bending the stem, after which the fibres are separated by crushing and shearing forces. This is accomplished with a hook, which pulls a piece of a stem through narrow gaps between two fixed hooks. The forces required are measured: Firstly, the force required for the initial collapse of the bast and secondly, the force required for the crushing of the bast and shearing away of fibres (Seaby and Mercer, 1984). A sketch of the tool is shown in Figure 18.

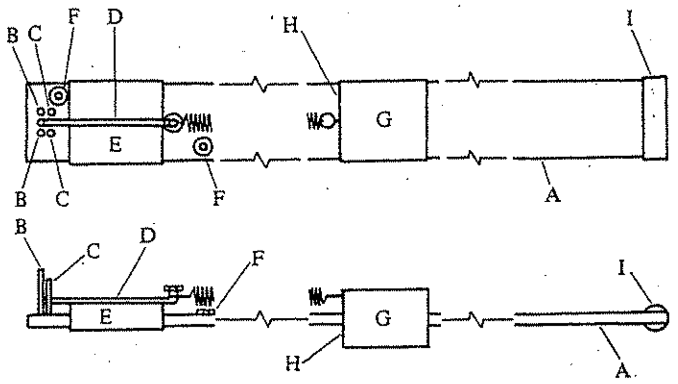

Figure 18. Top and side views of the hand tool (Seaby and Mercer, 1984).

Repeatability tests of the tool showed satisfactory results, and it was shown that the readings for fibre detachment were little affected by the moisture content of the stems. The tool was also compared with other methods for estimating the degree of retting (subjective assessment, scutchability index, fibre grade test and caustic weight loss). It was shown that the correlation was good for both bast collapse and fibre detachment with the caustic weight loss method, and less good with the fibre grade test and subjective assessment. There was a poor negative correlation with the scutchability index (Seaby and Mercer, 1984).

One advantage with the method is that the degree of retting can be estimated in the field on intact stems. Some problems may be, however, that many replications are required to get a representative value, that the scale is not related to other methods, and that the forces may be dependent on maturity, variety, and also on moisture content (Goodman et al., 2002). It should also be mentioned that there are other variants of the force measurement principle. Goodman et al. (2002), for example, assessed the degree of retting by measuring peel and tear forces (Figure 19). They showed that the moisture content has a significant impact on the forces required to peel the stem.

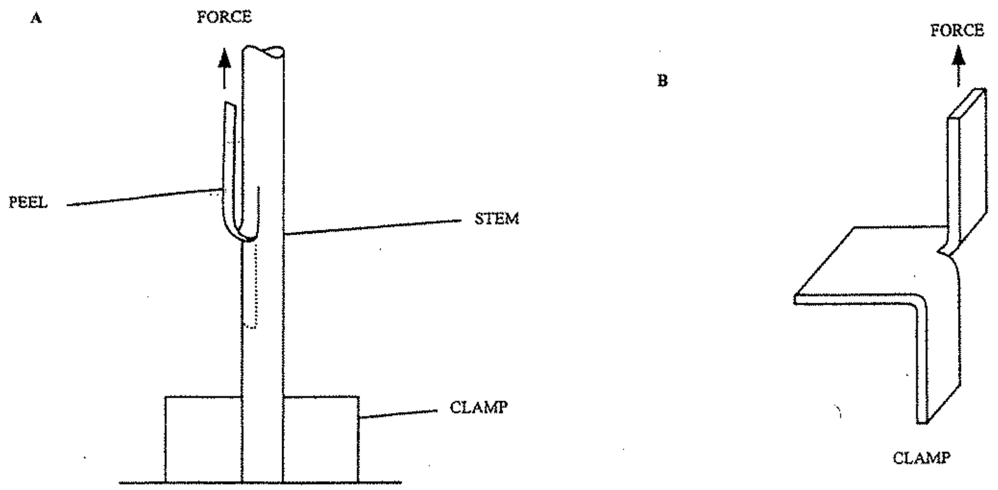

Figure 19. Sketch of the peel test (left) and the tear test (right) (Goodman et al., 2002).

4.3.10. Chemical analyses of ash, lipid and nitrogen content

It has been shown that the contents of ash, lipids and nitrogen are reduced as retting progresses (Sharma and Faughey, 1999). These losses are mainly a result of the microbial degradation of non-cellulosic components during retting. Kessler et al. (1993) have also shown that the ash content decreases as retting progresses, see Figure 20 (analysed at 1200°C, 15 min). They also showed that the water retention decreases as the degree of retting increases (analysed at 70°C, 80% RH, 24 hours).

The difficulties in using the ash content as an indicator of the degree of retting can be understood from a study by Sharma and Faughey (1999). The ash content was reduced by 34% to 17.5 g/kg when the variety Evelin was dew retted, whereas it was reduced by 52% to 12.4 g/kg when the variety Laura was retted. The cultivation and harvest conditions were the same for both varieties, as well as the degree of retting (subjectively assessed). Similar variations in the reduction of the lipid and nitrogen contents were observed. Although it may be difficult to use the ash content as a measure of the degree of retting, it was shown by Sharma and Faughey (1999) that there is a correlation between reduction in ash content and fibre strength. Therefore, they claim that the ash content, together with the lipid content, might be an important objective factor for assessing fibre quality.

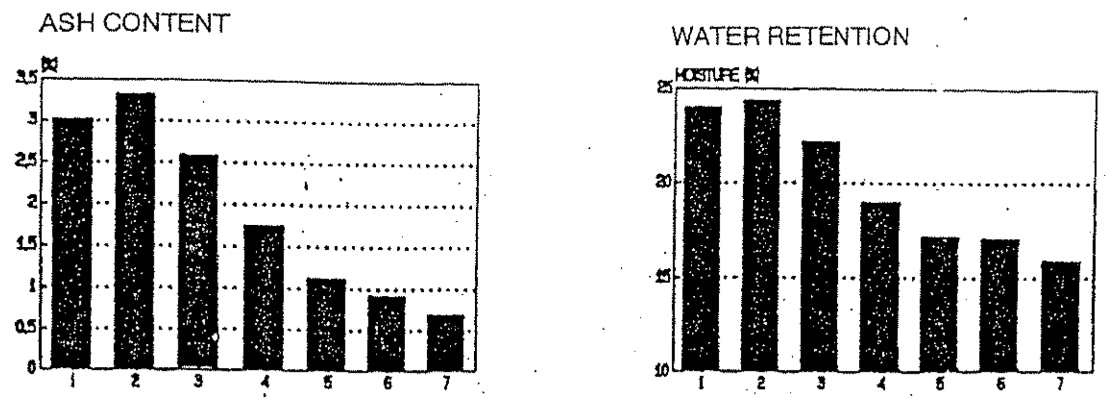

Figure 20. The ash content and the water retention decrease as retting progresses (Kessler et al., 1993).

4.3.11. Caustic weight loss

As stated before, the flax straw loses hemicellulose and pectic substances when it is retted. By boiling flax in a solution of NaOH, the remaining content of hemicellulose and pectin can be determined and thus the degree of retting. A fibre sample, about 3 g, is dried in an oven to constant mass, and then boiled in 250 ml 2% NaOH for 4 hours. The fibre is then dried and weighed once again. The larger the mass boiled off, the lower the degree of retting. The caustic weight loss test has been used as a standard method in Northern Ireland since 1929 (Turner, 1954; Sharma and Gilmore, 1989). Sharma and Faughey (1999) are of the opinion that the caustic weight loss test, together with thermogravimetric analyses, are important objective methods for quality assessments of retted flax.

The caustic weight loss method has been used by Brown et al. (1986) (1 g fibre boiled in 50 ml 2 M NaOH), Sharma (1987) (3 g fibre boiled at 100°C in 100 ml 2% NaOH for 4 hours) and Danielsson (1988) (2 g fibre boiled at 92°C in 80 ml 2 M NaOH for 4 hours; see Figure 21). There are also examples in the literature in which cut stems are boiled instead of scutched fibres. Seaby and Mercer (1984), for instance, boiled cut stems when they compared their hand tool with the caustic weight loss test (see above).

One problem may be that this method is time consuming. Sharma and Gilmore (1989) report, however, on experiments in which they reduced the boiling time from 4 hours to 0.5 hours. They used an autoclave with a pressure of 103.4 kPa, which in addition to reducing the boiling time, also increases the overall efficiency, because 50 or more samples can be boiled at the same time in an oil bath.

Meijer et al. (1995) are of the opinion that the caustic weight loss for intact stems is too small for sensitive measurements of the degree of retting. One alternative is to measure the dry matter losses without boiling the material (Donaghy et al., 1992). This method may, however, be unreliable for dew retting, because there may be losses of plant parts during the retting period. On the other hand, if there were no losses of plant parts, the dry matter losses might be too small for sensitive measurements of the degree of retting (Meijer et al., 1995).

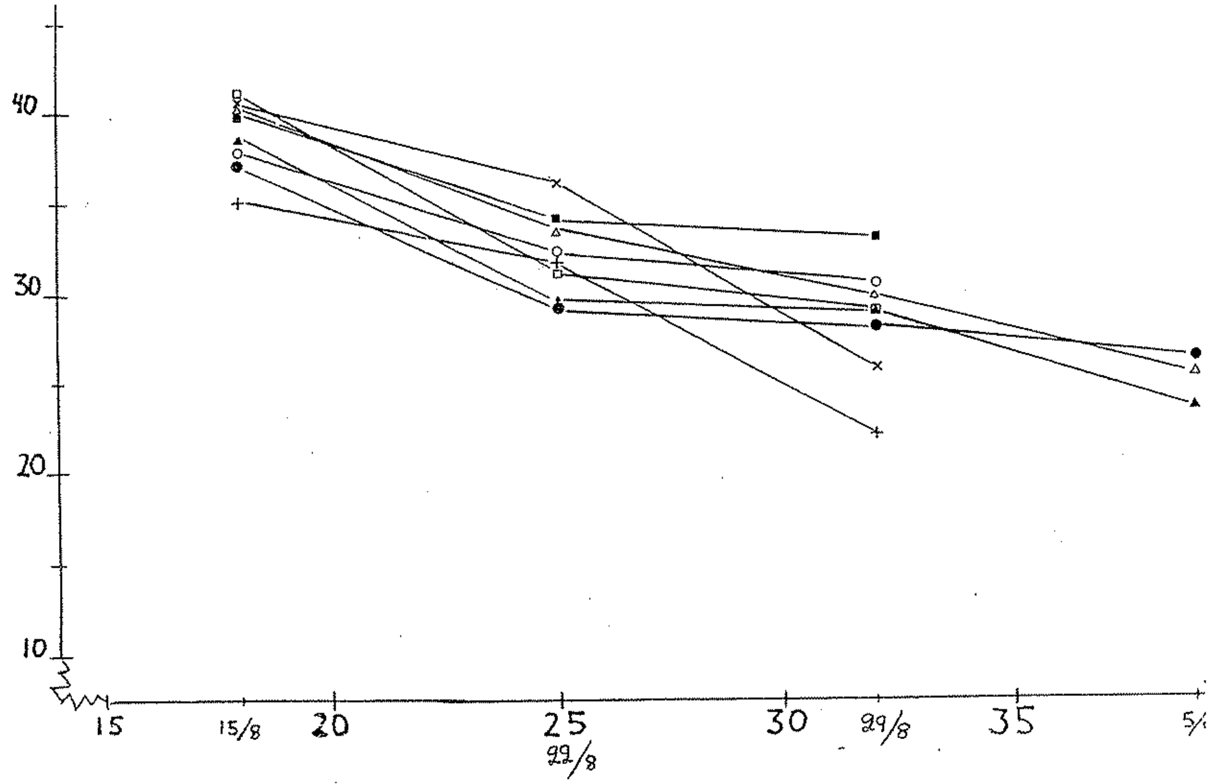

Figure 21. Caustic weight loss in % (y-axis) as a function of the number of retting days (x-axis). The different curves represent various treatments in a retting experiment. The triangles symbolize the retting on bare soil with turned (open symbols) and un-turned (close symbols) flax straw (Danielsson, 1988).

4.3.12. Concentration of galacturonic acid

For water retting, the content of galacturonic acid can be used as an indicator of the degree of retting (Rosemberg and de Franca, 1967). The content of galacturonic acid increases to a maximum, at which time retting should be complete. When the concentration has reached its maximum value, it cannot increase further due to the absence of pectins to be hydrolysed and it starts to decrease due to the utilization of the acid by bacteria (van Sumere, 1992). Meijer et al. (1995) claim, however, that the method is uncertain because the acid is metabolised during the retting process and its concentration therefore does not depend solely on the retting process. The method is not applicable for dew retting, because the concentration is measured in closed tanks for water retting.

4.3.13. Content of pectic substances

The content of pectic substances can be determined in various ways. Meijer et al. (1995) cut and ground 12-cm samples, after which 0.6 g of the ground material was extracted three times with 50 ml 80% alcohol at 75°C. The pectin, which was extracted from the residue with 0.5% ammonium oxalate at 100°C, saponified in 0.05 N NaOH at 28°C and reacted with carbazole, was measured as galacturonic acid at 520 nm with a Vitatron spectrophotometer (Meijer et al. 1995). Brown et al. (1986) dissolved the pectic substances from the crude cell wall material with 0.1 M citrate oxalate and then precipitated it from the solution with ethanol.

The pectin analysis method is laborious and expensive, and is therefore most likely not suitable for practical estimations of the degree of retting as a matter of routine. The pectin content may, however, be suitable as a basis for a generally accepted definition of the degree of retting, and some of the more simple methods could be related to the pectin content for accurate comparisons. One problem is that the pectin content varies between different varieties, and perhaps also between years because of different weather-conditioned environments.

Analyses have shown that younger stems contain more pectins and ret faster (Meijer et al., 1995). The increasing lignification of the cell walls at later harvest dates seems to have a restrictive influence on the degradation rate of pectic substances. Thus, the retting will be slower when the harvest is delayed until the point in time of maximum seed yield, because this occurs about three weeks later than the maximum fibre yield. The initial content of pectins and the rate of retting seem to be independent of the plant density (Meijer et al., 1995). It was also shown by Meijer et al. (1995), somewhat surprisingly, that crushing of the stems did not accelerate the retting process, although crushed stems became darker than un-crushed stems. Drying of the stems before swathing them in the fields resulted in a more homogeneously retted flax with lower final pectin contents (Meijer et al., 1995).

It is not only the pectin in the middle lamellae in the parenchyma cells around the fibre bundles that is degraded in the retting process, but also that in the schlerenchyma middle lamellae, resulting in splitting of the fibre bundles. Consequently, the fibres are weaker, but also cleaner and finer, in over-retted flax. However, the relationship between pectin content and fibre strength and fibre fineness seems to be complex and not fully clear (Meijer et al., 1995). In contrast, there is a clear negative linear relationship between pectin content and fibre cleanness (Meijer et al., 1995).

4.3.14. NIR spectroscopy

The Near Infrared Reflectance (NIR) spectroscopy technique can be used to analyse solid and liquid substances with respect to chemical components. The spectroscopic methods are particularly suitable for analysis of biological materials, because they are sensitive to changes in chemical composition as well as changes in molecular structure and microstructure (Archibald and Akin, 2000). The most commonly used infrared technology is based on diffuse reflectance measurements, but techniques based on transmission measurements are also in use. Diffuse reflectance arises when the surface of a sample is penetrated by electromagnetic radiation, which results in molecular excitation. The radiation is spread in all directions, and those wavelengths that are absorbed are absent from the reflected spectra. The measured reflectance (R) from the samples is transformed to absorbance (A) through the relationship $A = \log(1/R)$. Each measurement results in an absorbance value for each wavelength (Osborne et al., 1993).

The advantages with NIR are that it is a non-destructive, fast and simple method to use, and that the variable costs are comparatively low. The most important disadvantage may be the comprehensive calibrations with many known references. The reference samples must be prepared and vary in all the potential ways in which the samples may vary (Osborne et al., 1993).

Among the first to introduce NIR technology for the assessment of flax fibre quality were Kessler et al. (1993). Later, a standard method based on NIR was developed in Germany for determination of the degree of retting (Müssig et al., 1998). In this method, the degree of retting is expressed as a A1000-quota, where A1000 is defined as: A1000 = Abs.(1000 nm)/Abs.(1370 nm). Abs.(1000 nm) is the absorption at a wavelength of 1000 nm and can be viewed as a measure of the colour changes in the material due to the mycelium growth. Abs.(1370) describes the absorption at a wavelength of 1370 nm and is a reference wavelength in the cellulose band to consider morphological variations that may occur between different samples. It is assumed that the cellulose content is constant during the retting period. The method was originally developed for flax (Quint, 1996; Bluhm and Müssig, 1999), and a handheld NIR sensor that can be used in the field was developed by Kessler and Kohler (1996). However, the method is now also used for the determination of the degree of retting in hemp (see Figure 22) (Müssig et al., 1998; Müssig and Martens, 1999; Hahn et al., 2000).

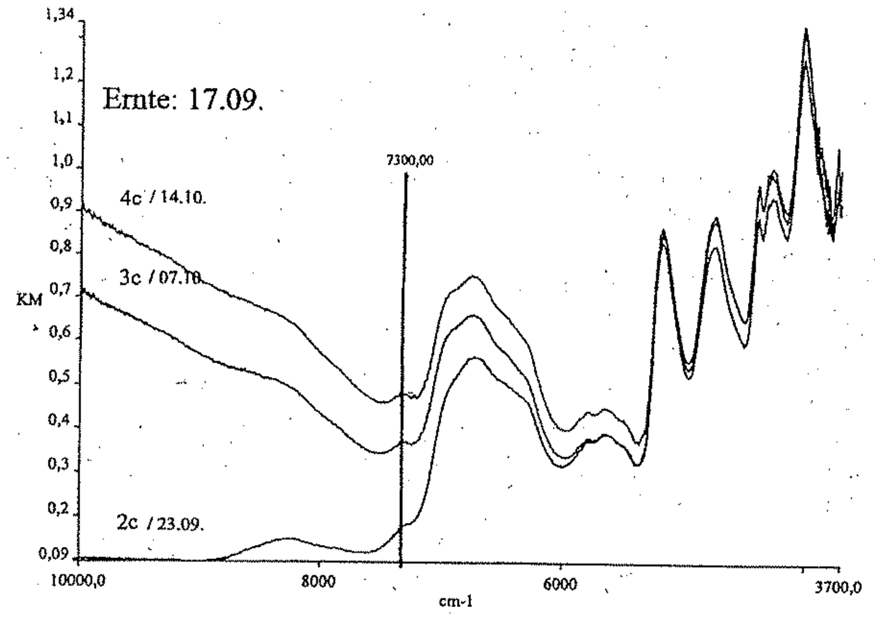

Figure 22. Absorption according to Kubelka/Munk (KM), as a function of wavelength^{-1}, for hemp measured on three occasions (10 000 cm^{-1} corresponds to the wavelength 1 000 nm, and 7 300 cm^{-1} to the wavelength 1370 nm). The more retted the material, the more dark-grey it becomes, and the higher the KM 10 000 cm^{-1}/KM 7300 cm^{-1} ratio, i.e. the A1000-value (Bluhm & Müssig, 1999).

The method describes the degree of retting indirectly, because Abs.(1000) measures the grey-colouring due to growth of fungal mycelium and not chemical changes in the material. Bluhm and Müssig (1999) showed that the A1000-value increases as the content of pectins is decreased, but the relationship is not fully clear and should be investigated further. They also found that the A1000 value begin to decrease when the flax has retted for a longer period. One probable reason is that the content of cellulose decreases for over-retted flax. Another result in their study was that the A1000 value is often higher for the stem than for scutched fibres (Bluhm and Müssig, 1999).

A preliminary evaluation of NIR spectroscopy to assess different physical and chemical characteristics of hackled flax fibres was carried out in Northern Ireland by Faughey and Sharma (2000). Regarding fibre fineness and fibre strength, they found a correlation between NIR measurements and measurements with traditional methods using airflow and Instron instruments. They also estimated the fibre fineness with derivative thermogravimetry (DTG), from 25°C to 600°C with 20°C/min, because there is a relationship between weight loss from DTG analyses and fibre fineness (Sharma et al., 1996; Faughey et al., 1999). The results showed that there is a clear correlation between DTG and NIR measurements (Faughey and Sharma, 2000), and it was shown in another study that both DTG and NIR are effective tools for measuring and monitoring fibre quality (Sharma et al., 2001). Determination of fibre components using acid and neutral detergent methods seems to have a poor correlation with NIR spectroscopy assessments (Faughey and Sharma, 2000).

Archibald and Akin (2000) used NIR for the determination of the degree of enzymatic retting of intact flax stems. One main advantage is that the retting process can be monitored on intact stems without scutching. The calibrations were based on Fried's test (see section 4.3.8, and Figure 23), and the calibration models obtained were insensitive to variations in material orientation and moisture content.

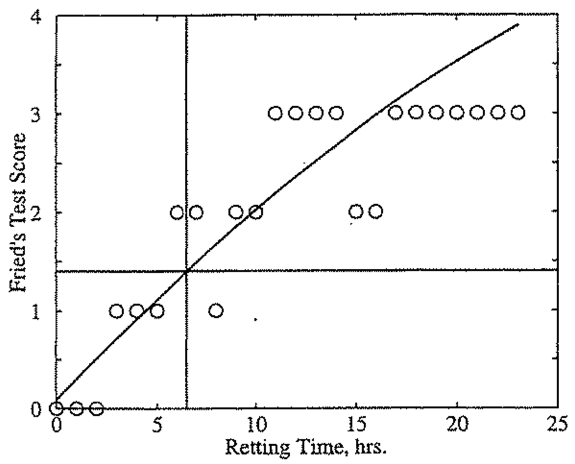

Figure 23. Estimation of the degree of retting for flax stems retted with enzymes for times ranging from 0 to 23 hours. The circles represent the values obtained with Fried's test. The horizontal and vertical lines divide the under- and over-retted samples, while the curve is a fit line to generate smoothed Fried's test score reference data used in the NIR calibration (Archibald and Akin, 2000).

5. DISCUSSION

5.1. Earlier Swedish projects

After the closure of the last flax fibre processing plant in Laholm in 1966, the large-scale cultivation and production of flax fibres ceased in Sweden. There was still some small-scale production of flax fibres for handicraft purposes, but the total quantity of fibres produced was negligible. Up to that time, the main product had been textiles, and the weaving industry that still existed after 1966 used imported raw materials. At the beginning of the 1990s, however, interest in non-textile uses of flax fibres began to develop in Sweden. Some important reasons for this increased interest concerned the environmental and sustainability advantages of natural fibres in comparison with synthetic fibres, the possibility of creating rural employment and the opportunity to use surplus agricultural land. Several projects were begun, which are reviewed in Chapter 2, often with the ultimate aim of restoring the Swedish flax industry in the long term.

The studies by Liljedahl and Smeder (1992; 1994), Smeder and Liljedahl (1996) and Berggren (1995) were important contributions for understanding the possibilities and obstacles, from an industrial- and market-orientated point of view, regarding use of short flax fibres in non-textile products. The development of various decortication methods (Schölin, 1991; Ihrsén and Sundberg, 1995) was innovative, although so far no equipment has been developed commercially. Projects concerning the use of flax fibres as reinforcement in composites have been reported by Oksman (2000; 2003) and Hagstrand and Oksman (2003). All these examples show the wide range of interesting projects in Sweden during the past decade, and it is important that Swedish research and development on this topic continue in the future.

The Swefibre flax fibre processing plant in Laholm, which was inaugurated in 1999, ceased production a few years later due to technical problems and a negligible demand for fibres. From this, it can be concluded that it is important to create a demand for fibres before new flax processing plants are established. In an initial stage, this demand could be filled by imported fibres. After that, a well-functioning processing plant should be established to serve as a good example for both producers and users of the fibres and to further increase the demand. An alternative to centralised processing plants is small-scale processing on farms, at least for short fibre applications with lower quality demands regarding e.g. cleanness. Small-scale technologies have been investigated by Ihrsén (1993), Rosenqvist (1993), Ihrsén and Sundberg (1995), and there is also development of small-scale technologies in other countries (Nilsson, 2003). However, a prerequisite for such future markets is the development of an international standard for objective quality characterisation of short flax fibres regarding cleanness, strength, length, fineness and colour.

Future research and development projects should also include the production and use of hemp fibres. Cultivation of hemp was previously prohibited in Sweden, but it is now permitted provided that some regulations are followed (Land, 2003). The advantages with industrial hemp are that the yield is very high (9-13 tonnes dry matter per hectare), the fibre content high (30-32%), and that the need for fertilisers and pesticides is comparatively low (Svennerstedt, 2003).

The use of flax and hemp fibres in various products should also be evaluated from an environmental life cycle assessment (LCA) point of view. The aim should be to compare the use of these fibres with the use of synthetic fibres and also to improve the production chains.

A pilot plant for enzyme-retting of flax is developed in theUSA (Foulk et al., 2002). The advantages of enzyme-retting are that the fibre quality is more consistent, the yield increased, and the environmental pollution reduced (in comparison to water retting). Furthermore, the fields are cleared earlier and can be prepared for subsequent crops, and the processing can be carried out all year round. The fibre strength and fineness can be varied by enzyme and chelator levels, (chelator removes Ca that bridges and stabilizes pectins) (Akin et al., 2001), and the fibres can be tailored for specific applications, e.g. for use in composites that require a high and consistent fibre quality. The costs for enzymatic retting is higher than for dew retting, but this method is nevertheless very interesting and the possibility for using it in Sweden should be evaluated.

5.2. Harvesting and handling methods

The traditional machinery systems for harvest of flax were primarily intended for the production of textile fibres and seeds. These machines have been continually improved, and there are now, for example, modern self-propelled pullers with very high capacities, e.g. in Belgium and France (Dewilde, 1987). The labour requirements in flax harvesting have also decreased considerably with modern methods, for instance with the introduction of the round baler (Sultana, 1992). It should be noted, however, that there are important differences between systems for harvest of flax for the production of long textile fibres and systems for the production of short fibres for industrial applications.

The production of textile fibres requires aligned straw, which necessitates special-design or modified machines for turning and baling. On the other hand, the production of short fibres does not require aligned straw, and conventional farming machines can be used for these operations. If the seeds not are used, the harvesting operations can be simplified, but an income from this product is also lost. The retting process is necessary in the textile fibre production, whereas "half-retted" or even un-retted or green flax can be used for short fibre production. The quality requirements may also differ. Flax for the production of short fibres may in some cases have lower quality requirements regarding cleanness, whereas the requirements regarding strength may be higher, especially when used as a reinforcement material.

The cutting of flax instead of pulling is an interesting idea, and the experiences from Laholm with cut flax (Isaksson, 2000; L. Jacobsson, personal communication) should be evaluated technically and from an economic point of view. With this method, the yield per hectare is lower in comparison with pulled straw, but the content of soil particles in the straw is also lower. These soil particles may cause wearing of the processing machines, and may also contaminate the final fibre product. If tangling problems could be avoided, the harvest could be carried out with existing windrowers, and the capacity might be higher in comparison with pulling machines. The dry-line method (Pasila, 1998) should also be evaluated under Swedish conditions. It is likely that the method is less suitable for the conditions in southern Sweden, where the winters often are mild, with consequent degradation and destruction of the fibres.

5.3. Quality aspects

The straw moisture content is a crucial factor in harvest of flax. It determines when the flax straw can be baled, because too high moisture contents at baling result in mould growth during storage, and consequent spoilage of the straw. Furthermore, the moisture content has an important influence on the field retting process, and indirectly also on other quality factors such as fibre strength and cleanness. The flax straw moisture content at a certain point in time is dependent on weather factors, such as the actual evaporation, rain and dew, and on material-specific factors, such as its equilibrium moisture contents in different climatic conditions.

Knowledge about the equilibrium moisture contents of flax straw is important in designing quality-preserving storage systems. No studies on the equilibrium moisture contents of non-processed flax straw were found in the literature. It is therefore recommended that such studies are carried out for not only flax straw, but also for other Swedish fibre crops such as hemp and reed canary grass.

Frequent in-field measurements of the straw moisture content are time-consuming, and modelling and simulation of the moisture content is therefore an attractive approach, at least for scientific purposes. The powerful computers of today, together with the ease in transferring historical or real-time weather data, makes it possible to simulate the moisture content variations during a number of years in a few minutes. Such models would enable comprehensive studies on how different harvest strategies impact on the quality and costs. However, no models describing the moisture content changes in flax straw were found in this literature study. One reason may be that most of the flax is pulled and laid on the bare soil, and the moisture interactions between the soil and the material are difficult to model.

The modelling approach proposed in section 4.1. is intended for cut flax straw laid on stubble. After a certain time, it can be expected that the ventilated space between the soil and the straw will disappear due to pressure by rain, etc., but such a model nevertheless considers the moisture interactions on top of the swath including evaporation, interception of precipitation and formation of dew. There are several examples in the literature of successful models for simulation of the drying and rewetting of hay (see section 4.1.4), and the feasibility of applying such dynamic models to the drying and rewetting of flax straw should be investigated.

The retting process affects molecular as well as micro-structural characteristics of the flax, and the degree of retting is therefore an important quality factor that determines the usefulness of the fibres obtained. One reason for the lack of an generally accepted international standard to objectively assess the degree of retting may be the variations in chemical composition and morphology for different flax varieties grown with different cultivation and harvest techniques under various soil and weather conditions. However, it is reasonable to assume that an effective, quick and inexpensive method to assess the degree of retting will be required in a future large-scale production of flax fibres, at least to meet the quality demands from the industries using flax fibres in their products, and also to determine a price for the raw material delivered by the farmer. It is therefore recommended that the reliability, the validity and the cost be evaluated for the most interesting methods to assess the degree of retting described in section 4.3.

Most of the pectolytic enzymes involved in dew retting are produced by different aerobic saprophytic fungi. The growth of these fungi is dependent on environmental factors such as the temperature, the pH value, light conditions, and the availability of water and oxygen. The temperature and the water availability are the most important factors in dew retting, and it is a well-known fact that flax straw is retted faster in warm and moist autumn conditions than in cold and dry conditions. The growth of various fungi as a function of temperature and water activity has been analysed for many species (Deacon, 1997). However, no micro-biological studies to investigate which fungi are involved in dew retting under Swedish conditions were found in the literature. It would therefore be interesting to identify the fungi involved in the different stages of retting under different weather conditions, and the degree to which they produce the various pectolytic enzymes.

Furthermore, if an appropriate method for determining the degree of retting could be established, it would perhaps be possible to simulate the retting process, using the air temperature and the straw moisture content as inputs. Such simulations have been impossible to carry out previously, because of the difficulties in accurately estimating the water activity or the moisture content. However, as the air temperature can easily be obtained from nearby weather stations, and the moisture content can be obtained from a model like that proposed in section 4.1., it would be possible to simulate the progress of retting on a daily basis.

5.4. Simulation of flax delivery systems

The autumns in Sweden are often rainy, and it may be difficult in some years to harvest the flax at an optimal point in time if the machine capacity is too low. The choice of machinery system for the harvest and handling is, however, a question of prioritising between higher costs and increased sensitivity to unfavourable weather conditions and decreased supply reliability. The costs for lack of a high-quality raw material for an industrial fibre process are high, even if they arise rather seldom, and such situations should be avoided. Furthermore, flax straw is a very bulky material and the transport work may therefore be extensive, and the storage space needed large. Therefore, more cost-effective and reliable logistics systems are necessary if flax is to become a more competitive fibre crop.

A powerful tool for analysing complex handling systems is the discrete event simulation approach (Law & Kelton, 1991; Pegden et al., 1995). It can be used to gain understanding of how the corresponding real system behaves, instead of or complementary to conducting full-scale experiments with this system. These types of simulations are in particular useful in identifying bottlenecks and critical points in the studied systems, and in evaluating the performance of various alternatives as a basis for more accurate cost calculations. The dynamic behaviour of discrete event simulation models makes it possible to simulate the daily work, which would give completion dates for various operations and the quality status (e.g. moisture content and degree of retting calculated with the models described in section 5.3.) of the raw material harvested.

A discrete event simulation model was developed by Nilsson (1999) for designing logistics systems for delivery of cereal straw to district heating plants. The model used historical weather data from 15 years for different locations in Sweden. The model output included the quantity of straw that the machine sets were able to harvest during these years, together with the times the straw "waited" in "queues" for different operations, and the number of hours the machines were working, idle or broken-down, etc. Based on these performance data from the model, the total harvest and handling costs were calculated. A similar model applied to harvest and handling of flax would be a useful tool to design cost-effective and reliable flax delivery systems.

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