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Flax Research in the US: Production, Retting, Processing, and Standards

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ABSTRACT

Growing interest in use of natural fibers exists throughout many regions of the world. Flax (*Linum ustitatissimum* L.) provides bast fiber from diverse sources that can supply needs for multiple industrial applications. The US is a potentially large consumer of these fibers, and efforts are emerging to develop a flax fiber industry. While the opportunities bode well for such an industry, research is needed to overcome key limitations, and these efforts hopefully will be beneficial globally. Topics addressed in our research include: 1) improved retting particularly through use of enzymes for consistent, high-quality, and tailored fiber properties, 2) mechanical fiber cleaning integrated with retting, and 3) objective standards and test methods to judge fiber quality. Progress has been made in each of these areas. An enzyme-retting method has been developed to pilot plant level but must be improved based on cost and fiber properties. A USDA Flax Fiber Pilot Plant, based on the 'Unified Line' but modular and more flexible in design, has been established for the first stage of mechanical cleaning. Four standards have been approved and listed through ASTM International and work continues on other test methods for fiber properties.

INTRODUCTION

The opportunities for developing a US source of flax fiber are great. The US historically has been one of the largest importers of flax fiber in textiles, most recently as yarns and fabrics. Production of textile-grade fiber by US farmers could provide a value-added fiber and thereby improve farm economies. In the northern US and particularly North Dakota, straw is a by-product of the linseed industry and a potential source for flax fiber under certain conditions. Now a small proportion of the straw is removed to make specialty paper, while most straw is burned to clean the fields. The same situation exists to a much greater extent in Canada, which globally is the largest producer of linseed, with reported straw amounts greater than a million Mg annually (Domier, 1997). The current method of disposal of most of the linseed straw by burning is becoming an environmental problem. Rather than being an environmental problem, research could transform the straw into useful fiber sources. Fiber from linseed straw is not expected to provide long fiber for linen but instead provide a total fiber for use in composites and other technical applications and possibly for textile blends. Commercial production of flax as linseed is centered in the northern US plains as a summer crop, but flax as a winter crop in the southeastern US produces good seed and fiber yields (Frederick et al., 1993). In this climate, farmers can double crop and harvest flax in the spring without jeopardizing their high value summer crops, such as cotton, peanuts, and soybeans.

Single-purpose, expensive equipment is used in pulling and turning flax for traditional linen production in Europe and was used earlier in the US (Fig. 1 a,b). With a goal of total fiber that is non-aligned and non-uniform in length from straw, common and multi-use farm

machinery (e.g., mowers, rakes, and balers) can be employed to harvest flax not destined for the linen industry (Fig. 1 c,d,e; Foulk et al., 2002). Cultivars and conditions for growing fiber flax are established, although agronomic improvement is needed in some regions. Linseed and total flax fiber could provide two major economic streams from one crop.

Research is required to take advantage of the opportunities for a flax fiber industry in the US. Three areas in particular have been identified for research. 1) Retting is a microbial process that depends upon the degradation of pectins and other matrix compounds to free fiber from non-fiber components in the flax stems. An improved retting method is needed to ensure a high and consistent quality fiber. 2) Processing equipment to clean retted flax is generally not available in the US. Research is required to develop mechanical cleaning procedures and to integrate retting and cleaning to optimize fiber quality for various applications. 3) Standards to judge flax fiber quality are not available universally. The development of a system based on objective standards is needed to judge the quality of flax from different sources, to promote commerce, and to optimize processing equipment. This paper reports results in each of the three areas of research.

RETTING

Water-retting that was practiced in Europe for many years produced very fine, strong fiber for linen. When water-retting was mostly discontinued due to pervasive pollution of lakes and rivers, dew- (or field-) -retting became the method of choice for most commercial production of flax fiber. Fiber quality, however, is lower and less consistent with dew-retting, and a replacement method has been sought for some time (Sharma and Van Sumere, 1992). Since early work with water- and dew-retting microorganisms showed conclusively that pectinases were required for effective retting (Van Sumere, 1992), pectinase-rich enzymes mixtures have been extensively researched as a possible replacement for dew-retting. Chemical chelators, especially ethylenediaminetetraacetic acid (EDTA) (Adamsen et al., 2002; Henriksson et al., 1998; Sharma, 1987, 1988) have been used alone and with enzymes for retting. The value of chelators *per se* for retting is further shown by Sharma (1987), who patented a chemical-retting method using chelating agents. However, no commercial method exists with either enzyme or chemical retting methods. Our attempt at enzyme retting differed from previous work in Europe, where pectinase-rich enzyme mixtures were substituted for bacteria in water-retting, in that we sprayed flax stems to soaking with an enzyme-chelator formulation. This spray method facilitated the action of pectinases, resulting in reduced enzyme amounts, and required a fiber: liquid ratio of about 2:1. This method was published (Akin et al., 2000a), and has undergone refinement and modification since then (Akin et al., 2004c). The basic method as it now stands is as follows: a) crimp stems through rollers or calenders to disrupt the integrity of the cuticle and allow enzyme penetration, b) spray or soak ca 2 min to saturate crimped stems with a pectinase-rich commercial enzyme mixture plus a commercial EDTA solution at specific pHs, c) incubate in humid conditions for enzyme-retting to occur, d) after incubation, wash off enzyme formulation and dry fibers. To date, we have not noticed microbial contamination in the unsterilized mixtures, likely due to the short duration of retting (not over 24 h). Further, the washing appears to inactivate the enzyme, since re-testing for strength after 30 mo showed no loss in fiber tenacity.

Many commercial pectinases, including Flaxzyme (Van Sumere, 1992) are mixtures of plant cell wall degrading enzymes, including cellulases. The cellulases are especially effective at attacking the transverse fiber dislocations (i.e., fibernodes or kink bands), thus weakening the fiber (Evans et al. 2002; Khalili et al., 2003). Fiber tenacity, therefore, can be reduced after

retting with these enzymes. Due to the possibility of continuing action of cellulases on fiber, extensive rinsing or further oxidative treatments are required to inactivate the enzymes (Sharma and Van Sumere, 1992). A common situation we encountered in enzyme-retting with several commercial enzymes is weaker tenacity compared to dew-retting. Laboratory studies using pectinases without cellulases for retting resulted in a stronger fiber than those retted with the cellulase-containing mixtures (Evans et al., 2002).

Recently, a series of retting formulations using Viscozyme L (Novozymes North America, Inc., Franklinton, North Carolina) plus EDTA from Mayoquest 200 (Callaway Chemical Co., Smyrna, Georgia) was compared (Akin et al., 2004b). Fine fiber yield, strength (g/tex), and fineness by airflow methods of Ariane flax varied with formulations (Table 1). Research will continue along the following lines: 1) determine application of tailored fiber types in woven and non-woven products, 2) scale up and automate the enzyme-retting system and integrate with cleaning procedures, and 3) evaluate other enzymes and formulations for tailored properties and best cost efficiencies.

MECHANICAL CLEANING

Processing equipment for flax fiber was not available in the US when research began in the 1990s. Without an established industry to develop, test, and manufacture flax fiber equipment in the US, we cooperated with industry in the Czech Republic. Trial tests on a series of enzyme-retted fiber and seed flax indicated that the 'Unified Line' was suitable for cleaning retted straw for total fiber that was non-aligned and non uniform in length (Table 2). Such fibers could be used "as is" in particular applications or further shortened and refined, i.e., cottonized, by additional equipment for higher value fibers, such as textiles (Akin et al., 2001). As a result of these tests, a USDA Flax Fiber Pilot Plant (Flax-PP) comprised of four individual modules was designed and established at the Cotton Quality Research Station, ARS-USDA, Clemson, SC (Akin et al., 2004a). These modules represent the essential processing steps of the commercial 'Unified Line' (Czech Flax Machinery, Měřín, Czech Republic). Figure 2 shows the four modules, which are as follows: 9-roller calender, scutching wheel, 5-roller calender, and top shaker. The modular design allows cleaning in any order and multiple runs through a particular module. Variable speed drives permit changes in speeds of top and bottom rollers to maximize flexibility. The first tests of the Flax-PP reported the efficiency of each stage at removing non-fiber components (mostly shive) produced fiber from a variety of sources (Table 3).

The four modules produce a total fiber from the straw, which may be better in quality than a tow by-product. This non-aligned and non uniform length fiber, which still contains some shive, could be used "as is" in particular applications. A further refinement to "cottonize" (i.e., refine and shorten) the fiber is required for use in textiles or for higher grade industrial fibers. This secondary cleaning stage is being developed as an addition to the Flax-PP. The pilot plant will be able then to produce sizable amounts of fibers with tailored properties (e.g., cleanliness, fineness, length) for use in variable applications.

STANDARDS

Standards are needed to assure uniform quality and performance. Natural fibers, such as cotton and flax, by their nature are variable, and standards are particularly useful for manufacturers of textiles and composites. With a global economy, fibers can be produced in extremely different climates and under myriad production systems, further contributing to variations in fiber properties and quality. Without standards, manufacturers are without

knowledge of how to set equipment for optimum production, which affects efficiency (e.g., downtime) and product quality, or of how best to use available resources.

Even though flax is considered the oldest textile fiber known, objective standards recognized for the flax fiber industry do not exist for the most part (van Dam et al., 1994). The need for such standards and a classification system for judging quality, for commerce, and for processing efficiency is widely recognized (Kozlowski, 2002). Flax is traditionally bought and sold by the subjective judgment of experienced graders who appraise by look and feel, i.e., organoleptic tests. Various classification schemes that include the source (e.g., Belgium, France, Russia, or China), processing history (e.g., water- or dew-retted), or application (e.g., warp or weft yarn) have been used within an industry segment. Grading systems for traditional linen assess fineness, length and shape of fibers, strength, density, luster, color, handle, parallelism, cleanliness, and freedom from neps and knots (Ross, 1992). Within particular countries, measurement of flax fibers is done by consistent means and, therefore, a limited classification system may exist. For example, in past years Russia used an elaborate judging and grading system for commerce and processing of flax (Pfefferkorn, 1944). Various grades of flax fibers are identified for marketing within a company.

The Textile Quality and Biotechnology group of the European Union COST 847 project reported that "the situation regarding the characterization of flax and other bast fibres is certainly not satisfactory" (Kozlowski, 2002). The development of standards for judging flax fiber quality has been held back by difficulty in assessing flax due to its complex physical structure, inconsistent measurement practices, lack of industry support, and a rather small, confined market for traditional long-line flax and tow. The early efforts by ISO, which resulted in International Standard 2370 (1980) for fineness and working documents for other properties, have been discontinued. Current interest in expanding the use of flax fiber in various composites and for blending with cotton in efficient short staple spinning systems, however, requires the establishment of standards, much like those which have helped the cotton industry (Agricultural Handbook 566, 1995). The need for standards, therefore, is certainly recognized by many groups. COST 847 has as a stated objective of acquiring knowledge "to set up quality standards for assessing flax fibre" (Kozlowski, 2002).

Several instruments that objectively and rapidly analyze cotton were evaluated for application to testing flax fiber in trials with Zellweger Uster (Knoxville, TN) and the IAF (Reutlingen, Germany) (Anja Schleth, personal communication). While some success occurred with modifications in hardware and software of the cotton equipment, the performance required was not reached. In order to measure flax fibers successfully with cotton equipment, a major redesign in the mechanics and software of instruments, such as the AFIS (Automated Fiber Information System) and HVI (High Volume Instruments), was needed. The amount of development necessary, along with predicted small market size and lack of standards, caused Zellweger Uster to discontinue work. Other groups, e.g., IAF and Applied Science Division, Dept. Agric. Northern Ireland, continue to research rapid methods for flax fiber assessment.

Cotton as a model. As far back as the early 1900s, the cotton industry recognized the need for standards to address problems related to marketing. A resolution was adopted in the US in 1907 to establish uniform cotton standards "to eliminate price differences between markets, provide a means of settling disputes, and make the farmer more cognizant of the value of his product, and, therefore, put him in a better bargaining position, and in general be of great benefit to the cotton trade" (Agricultural Handbook 566, 1995). Over the next several years, laws were enacted authorizing the United States Department of Agriculture (USDA) to develop cotton

grade standards. Considerable evolution related to grading methods has occurred over the years and work continues to modify and improve standards for cotton (Schneider et al., 2002). The Agricultural Marketing Service, an agency of USDA, uses the term "cotton classification" to refer to application of standardized procedures for measuring physical and aesthetic attributes of raw cotton that affect quality of products or manufacturing efficiency. Currently, properties of almost every bale of cotton produced in the US are analyzed and classified within just a few seconds by HVI (High Volume Instrumentation). Properties included in this analysis are: strength, length and length distribution, fineness, color, and trash.

Methods to derive objective values for various parameters, such as fiber strength, length, and fineness, are available (Archibald, 1992; van Langenhove and Bruggeman, 1992) and routinely used by research and industrial organizations for in-house testing of flax samples. The Stelometer, for example, provides data for fiber strength, but the method is time-consuming and no standards for flax fibers are available with this method as there are for cotton (van Langenhove and Bruggeman, 1992).

Terminology standard. Development of a terminology standard is rather straight forward but does require some research to assure terms are not "re-invented" or, even worse, modified from already accepted definitions in ASTM Standard D 123 ("Terminology Related to Textiles") or in Europe and other regions with a long history of flax. Patricia A. Annis, Department of Textiles, Merchandising & Interiors, University of Georgia, and long-time member of ASTM, agreed to lead in developing a terminology standard for flax. A document entitled "Standard Terminology Relating to Flax and Linen" was the first submission of the Flax and Linen subcommittee and was approved by the Textile Committee and ASTM International in 2002 as D- 6798-02.

Color standard. Color differences in flax retted by various means are obvious and well-known to researchers (Akin et al., 2000b; Sharma and Van Sumere, 1992). Water-retting, which is brought about by anaerobic bacteria when flax is immersed in water, is lightly colored. In contrast, dew-retting, which is due to colonization and partial degradation by fungal consortia, produces dark and non-uniform fibers. Enzyme-retting results in a light-colored flax that is similar but not identical to water-retted flax. Color determination is well-established, and the use of CIELAB measurements provides an efficient means for objective color determination (Epps et al., 2001). The color of flax, with lightness from black to white (L* value), green to red (a* value), and blue to yellow (b*) is influenced by retting, processing, cleaning, and cottonizing. Problems related to color matching can be more objectively addressed and provide better use of flax from a broadened production system. A document entitled "Standard Test Method for Color Measurement of Flax Fiber" utilizing the CIELAB method was authored by Helen H. Epps, Department of Textiles, Merchandising & Interiors, University of Georgia, and was approved by ASTM Committee D13 as D-6931-03.

Fineness standard. Fineness is one of the most important properties for fibers. The International Standard (ISO) 2370 (1980), "Textiles - Determination of Fineness of Flax Fibres-Permeametric Methods to Determine Fineness", is based on resistance to airflow for a known fiber mass in a known volume. The resistance is related to the surface area of the fibers. With constant mass and volume, fine fibers have more surface area than coarse fibers and, therefore, greater resistance to airflow. Proper assessment of airflow with calibrated gauges and appropriate equations, such as the Kozeny equation used in ISO 2370, permits comparisons of fiber fineness. ISO 2370 allows for analysis of both parallel (reference method) and random fibers. The Index of Fineness Standards (IFS), using reference samples and based on the tex

system, "permits compensation for the fact that the fineness of flax fibers cannot be defined in an absolute manner" (International Standard (ISO) 2370, 1980). A series of sets of fibers, ranging from IFS values of 21.7 to 72.1 is available from the Institut Textile de France, Lille.

The ASTM Standard D1448 (1999) for cotton fineness, measured in micronaire, was modified (flax fibers cut to 2.54 cm and loaded at 5 g) to test the IFS flax samples (Akin et al., 1999). Good agreement occurred between the two methods ($R^2 = 0.99$). Variations in fineness of these fibers, as well as a series of other samples derived from various retting procedures, were verified by image analysis that gave average fiber widths and width distributions based on physical dimensions (Akin et al., 1998, 2000c). Based on studies with a wide variety of samples, a document authored by Jonn A. Foulk, ARS-USDA, Clemson, South Carolina, entitled "Standard Test Method for Assessing Clean Flax Fiber Fineness," was approved by ASTM Committee D13 as D-7025-04a.

Trash (non-fiber) standard. Bast fibers are formed in the cortex of the stem and are surrounded with a considerable amount of non-fiber tissues closely associated with fiber bundles. Stephens (1997) reported total fiber yields of about 20-30% for 44 cultivars grown in small plots, with the fiber varieties often producing nearly 30% fiber. Therefore, at least 70% of the cultivar can be non-fiber components. Chemical analyses indicate substantial differences in flax stem tissues that could be exploited in standards. Flax fiber is mostly cellulose, but considerable amounts of lignified shive materials contribute to total stem weight. Shive contains about 3 to 4 fold more lignin and aromatics that does the bast fiber (Morrison et al., 2003). A chemometric method using near infrared spectroscopy was developed to determine fiber content in stems (Barton et al., 2002). A similar approach has now been developed for shive (i.e., trash) content in retted flax fiber. A document authored by W. Herbert Morrison III, ARS-USDA, Athens, Georgia, entitled "Standard Test Method for the Measurement of Shives in Retted Flax" was the latest standard submitted by the Flax and Linen subcommittee and was approved by ASTM International as D-7076-05 in 2005.

The Flax and Linen subcommittee of ASTM International continues to meet and is addressing other flax fiber properties for development of standards. Results of this work have been presented previously (Akin, 2002, 2004).

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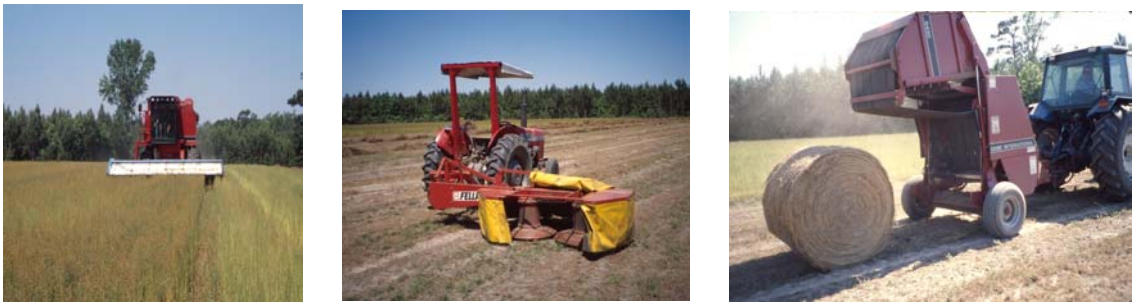
Mention of commercial product names is for identification only and does not constitute an endorsement of these products over other, similar products.

REFERENCES

1. Adamsen, A.P.S., Akin, D.E., Rigsby, L.L., Chelating Agents and Enzyme Retting of Flax. *Textile Res. J.* **72,**296-302 (2002).
2. Agricultural Handbook 566, Agricultural Marketing Service, U.S. Department of Agriculture, Memphis, TN (1995)
3. Akin, D. E., Enzyme Retting of Flax for Linen Fibers: Recent Developments, in "Book of Papers," Am. Assoc. Textile Chem. Colorists, Research Triangle Park, NC, 1998, pp.273-280.
4. Akin, D. E., Rigsby, L. L., and Perkins, W., Quality Properties of Flax Fibers Retted with Enzymes, *Textile Res. J.* **69,** 747-753 (1999).
5. Akin, D. E., Dodd, R. B., Perkins, W., Henriksson, G., and Eriksson, K.-E., L., Spray Enzymatic Retting: A New Method for Processing Flax Fibers, *Textile Res. J.* **70**, 486-494 (2000a).
6. Akin, D. E., Epps, H. H., Archibald, D.D., and Sharma, H. S. S., Color Measurement of Flax Retted by Various Means, *Textile Res. J.* **70,** 852-858 (2000b).
7. Akin, D. E., Rigsby, L. L., Hardin, I. R., and Epps, H.H., Enzyme Retted Fibers from Fiber and Seed Flax, *Textile Chem. Colorists* **32,** 12-39 (2000c).
8. Akin, D.E., Foulk, J.A., Dodd, R.B., and McAlister, D.D. III., Enzyme-Retting of Flax and Characterization of Processed Fibers, *J. Biotechnol*. **89**, 193-203 **(**2001).
9. Akin, D.E., Standards for Flax Fiber, in "Proceedings of the 59th Flax Institute of the United States," North Dakota State University, Fargo, ND, 2002, pp. 92-101.
10. Akin, D.E., Update on Standards for Flax Fibers, in "Proceedings of the 60th Flax Institute of the United States," North Dakota State University, Fargo, ND, 2004, pp. 44-50.
11. Akin, D.E., Dodd, R.B., and Foulk, J.A., Pilot Plant for Processing Flax Fiber, *Indust. Crops Prod*. doi:10.1016/j.indcrop.2004.06.001 (2004a).
12. Akin, D.E., Foulk, J.A., Dodd, R.B., and Epps, H.H., Enzyme-Retted Flax Using Different Formulations and Processed Through the USDA Flax Fiber Pilot Plant. *J. Natural Fibres* (in press). (2004b)
13. Akin, D.E., Henriksson, G., Evans, J.D., Adamsen, A.P.S., Foulk, J.A., and Dodd, R.B., Progress in Enzyme-Retting of Flax, *J. Natural Fibres*, (in press) (2004c).
14. Archibald, L. B., Quality in Flax Fibre, in "The Biology and Processing of Flax," H.S.S. Sharma and C.F. Van Sumere (eds.), M Publications, Belfast, Northern Ireland, 1992, pp. 297-309.
15. ASTM D 1448-97. Standard Test Method for Micronaire Reading of Cotton Fibers, Annual Book of Standards, section 7, Textiles, ASTM, West Conshohocken, PA, 1999, pp. 374-376.
16. Barton, F.E., II, Akin, D.E., Morrison, W.H., Ulrich, A., and Archibald, D.D., Analysis of Fiber Content in Flax Stems by Near-Infrared Spectroscopy, *J. Agric. Food Chem.* **50,** 7576-7580 (2002).
17. Domier, K. W., The Current Status of the Field Crop, *Euroflax Newsletter* **8 (2),** 8-10, Institute of Natural Fibres, Poznan, Poland (1997).
18. Epps, H. H., Akin, D. E., Foulk, J. A., and Dodd, R.B., Color of Enzyme-Retted Flax Fibers Affected by Processing, Cleaning, and Cottonizing, *Textile Res. J.* **71,** 916-921 (2001).
19. Evans, J.D., Akin, D.E., and Foulk, J. A., Flax-Retting by Polygalacturonase-Containing Enzyme Mixtures and Effects on Fiber Properties, *J. Biotechnol*. **97,** 223-231 (2002)

20. Foulk, J.A., Akin, D.E., Dodd, R.B., and McAlister, D.D. III., Flax Fiber: Potential for a New Crop in the Southeast, in "Trends in New Crops and New Uses," J. Janick and A. Whipkey, Eds., ASHS Press, Alexandria, Virginia, 2002, pp. 361-370.
21. Frederick, J.R., Porter, P.M., Murdock, E.C., Dodd, R.B., and Todd, M.A., Growing Flax in South Carolina, Clemson Univ. Coop. Ext. Service. Clemson, SC, (1993).
22. Henricksson, G., Akin, D.E., Rigsby, L.L., Patel, N., and Eriksson, K.-E. L., Influence of Chelating Agents and Mechanical Pretreatment on Enzymatic Retting of Flax, *Textile Res. J.* **67,** 829-836 (1998).
23. International Standard (ISO) 2370. Textiles - Determination of Fineness of Flax Fibres- Permeametric Methods, International Organization for Standardization (1980).
24. Khalili, S., Akin, D. E., Pettersson, B., and Henriksson, G., Fibernodes in Flax and Other Bast Fibers, *J. Appl. Bot.* **76**,133-138 (2003).
25. Kozlowski, R. (ed), Euroflax Newsletter, No.17, Institute of Natural Fibres, Poznan, Poland, (2002).
26. Morrison, W.H. III, Himmelsbach, D.S., Akin, D.E., and Evans, J.D., Chemical and Spectroscopic Analysis of Lignin in Isolated Flax Fibers, *J. Agric. Food Chem.* **51**,2565-2568 (2003).
27. Pfefferkorn, R., Oregon Fiber Flax for an American Linen Industry, O. S. C. Cooperative Association, Corvallis, Oregon, 1944.
28. Ross, T., Preparation and Spinning of Flax Fibre, in "The Biology and Processing of Flax," H.S.S. Sharma and C.F. Van Sumere (Eds.), M Publications, Belfast, Northern Ireland, 1992, pp. 275-296.
29. Schneider, T., Heap, S. A., and Stevens, J.C., 26th International Cotton Conference Bremen. Faserinstitut, Bremen, Germany, 2002.
30. Sharma, H.S.S., Treatment of Flax, British Patent Application 2,186,002, (1987).
31 Sharma, H.S.S., Chemical Retting of Flax Using Chelating Compounds, *Ann. Appl. Biol.* **113,**159-165 (1988).
32. Sharma, H.S.S., and Van Sumere, C. F., Eds., "The Biology and Processing of Flax," M. Publications, Belfast, Northern Ireland, 1992.
33. Stephens, G. R., Connecticut Fiber Flax Trials 1994-1995, Bulletin 946, The Connecticut Agric. Experiment Station, New Haven, CT, (1997).
34. van Langenhove, L., and Bruggeman, J.P., Methods of Fibre Analysis, in "The Biology and Processing of Flax," H.S.S. Sharma and C.F. Van Sumere (Eds.), M Publications, Belfast, Northern Ireland, 1992, pp. 311-327.
35. Van Dam, J.E.G., van Vilsteren, G.E.T., Zomers, F.H.A., Shannon, W.B., and Hamilton, I.T., Industrial Fibre Crops, Increased Application of Domestically Produced Plant Fibres in Textiles, Pulp and Paper Production, and Composite Materials, ATO-DLO, Wageningen, The Netherlands, 1994.
36. Van Sumere, C.F., Retting of Flax with Special Reference to Enzyme-Retting, in "The Biology and Processing of Flax," H.S.S. Sharma and C.F. Van Sumere (Eds.), M Publications, Belfast, Northern Ireland, 1992, pp.157-198.

a b



c d e

Figure 1. Flax harvesting equipment. a. Pulling machine dedicated to uprooting flax plants. b. Back side of puller showing the laying out of flax in swaths for dew-retting. c. Stripper-header for harvesting seed. d. Drum mower for cutting flax stems close to the ground. e. Baling machine for processing mowed, dried, and perhaps dew-retted flax stems into round bales for transport and storage.

a b c d

Figure 2. Four modules comprising the USDA Flax Fiber Pilot Plant. a. Nine-roller crushing calender. b. Scutching wheel that aggressively cleans and shortens fibers. c. Five-roller calender with grooved surfaces to further clean fibers. d. Top shaker with arching prongs and pinned apron to remove shive and partially align fibers.
Adapted from Akin et al., 2004a

Table 1. Yield and properties of fine fiber from mature Ariane flax treated with various levels of Viscozyme L and 18 mM EDTA from Mayoquest 200.

Viscozyme (%)	Total Fine Fiber [a] (% straw)	Strength[b] (g/tex)	Fineness[c] (air flow)
0.05	6.0 ∀ 0.3	24.5 ∀ 6.0	6.4 ∀ 0.1
0.1	4.8 ∀ 1.1	21.6 ∀ 3.0	6.2 ∀ 0.1
0.2	4.7 ∀ 0.1	20.1 ∀ 1.4	6.1 ∀ 0.3
0.3	4.8 ∀ 0.3	16.9 ∀ 0.6	6.4 ∀ 0.1

[a] Calculated as % of initial straw weight of fiber that had been processed through the Flax-PP and then passed 1X through a Shirley Analyzer. The low yield is from experimental systems and is used only to compare retting formulations and does not represent yields from commercial systems.

[b] Six values were obtained for each duplicate sample by Stelometer.

[c] At least three values were obtained for each duplicate sample using a modified micronaire system of 5 g. Data adapted from Akin et al., 2004b. Values are averages and standard deviations for duplicate samples each treatment.

Table 2.
Properties of enzyme-retted and commercially cleaned and cottonized seed and fiber flax straw.

Sample [a]	Fineness (air flow) [b]	Strength (g tex $^{-1}$) [b]	Fine fiber yield (%)
Seed flax straw	5.9 ± 0.1	25.9 ± 2.9	25.3 ± 1.0
	6.1 ± 0.1	24.7 ± 1.9	
Ariane	5.8 ± 0.1	24.0 ± 2.0	30.7 ± 8.8
	5.5 ± 0.1	25.0 ± 4.5	
Ariane (dew-retted)	5.3 ± 0.1	36.2 ± 2.3	43.0 ± 1.1
	5.3 ± 0.2	32.5 ± 2.2	
Ariane (mature)	6.7 ± 0.1	26.8 ± 3.4	32.3 ± 0.3
	7.1 ± 0.1	28.6 ± 3.7	

[a] Seed flax straw is a commercial variety from North Dakota. Ariane was grown in the winter (1998/1999) in South Carolina and harvested optimally for fiber unless indicated mature for a seed crop. Except for the dew-retted Ariane, all samples were spray enzyme-retted using 0.05% Viscozyme L plus 50 mM EDTA.
[b] The first number in each column is for samples tested in August,1999 (2-4 months after retting), and the second number is for the same samples tested April, 2002 (30 mo later). Data adapted from Akin et al., 2001.

Table 3.
Efficiency of cleaning stages flax samples through the USDA Flax Fiber Pilot Plant

Source of flax fibers[a]	Cumulative weight loss at successive processing stages (%)						Recovery (% of starting material)
	9-roller crusher	Top shaker	Scutching wheel	Top shaker	5-roller calender	Top shaker	
Unretted	40	45*	72	ND	ND	71*	29
Dew-ret	13	63*	68	ND	ND	74*	26
Enz-ret	13	41	47	52	53	55*	45

[a] Unretted was Neche linseed straw grown to full seed maturity and stored inside without retting (1 sample). Dew-ret was Natasja grown to full seed maturity, baled, and stored (3 replicates). Enz-ret is Jordan enzyme-retted with 0.1% Viscozyme plus 18 mM EDTA from Mayoquest 200 for 24 h (2 replicates).

* Passed through stage 2 times.

Adapted from Akin et al., 2004a.