Flax Fiber: Potential for a New Crop in the Southeast

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INTRODUCTION

Flax (*Linum usitatissimum* L., Linaceae), which has been grown throughout the world for millennia, is the source of products for existing, high-value markets in the textile, composites, paper/pulp, and industrial/nutritional oil sectors (Hamilton 1986; Sharma and Van Sumere 1992b). Flax is the source of industrial fibers and, as currently processed, results in long-line and short (i.e., tow) fibers (Van Sumere 1992). Long line fiber is used in manufacturing high value linen apparel, while short staple fiber has historically been the waste from long line fiber and used for lower value products. Retting, which is the separation of bast fibers from the core tissues, is preeminent in flax fiber processing, as it affects quality and yield (Pallesen 1996; Van Sumere 1992). Two traditional methods used commercially to ret flax for industrial grade fibers are water- and dew-retting (Sharma and Van Sumere 1992a,b). Water-retting results in high quality fiber (Van Sumere and Sharma 1991) but was discontinued in western countries several decades ago because of the extensive stench and pollution from fermentation products and the high cost of drying (Brown 1984). Dew-retting is now the accepted practice in most countries and supplies the linen used in high quality textiles. Enzymes have been considered as a method to improve retting (Van Sumere 1992).

In water-retting, flax stems are submerged in rivers and lakes, and anaerobic bacteria colonize the flax stems and degrade pectins and other matrix compounds, thus freeing fibers from the core tissues (Van Sumere 1992). Dew-retting is an art that depends upon the removal of matrix materials from the cellulosic fibers before cellulolysis, and therefore weakening, of the fibers occurs. This process is dependent mostly upon plant cell-wall degrading enzymes produced by indigenous, aerobic fungal consortia (Brown 1984; Van Sumere 1992; Henriksson et al. 1997a; Fila et al. 2001). In dew-retting, flax plants are pulled from the soil and laid out in fields for selective attack by the fungi over several weeks. Disadvantages of dew-retting are its dependence on particular geographical regions that have the appropriate moisture and temperature ranges for retting, coarser and lower quality fiber than water retting, poor consistency in fiber characteristics, and occupation of agricultural fields for several weeks (Van Sumere 1992). Further, dew-retting results in a heavily contaminated fiber that is dusty and particularly problematic in textile mills. Chemical retting (Van Sumere 1992), enzyme-retting (Akin et al. 1997), and steam explosion techniques (Kessler and Kohler 1996) are fiber extraction methods that have previously been investigated.

Because of problems with both water- and dew-retting, a long-term objective for improving the flax fiber industry has been development of enzyme-retting (Hamilton 1986; Van Sumere 1992; Schunke et al. 1995). In the 1980s, extensive research was undertaken in Europe to develop enzyme-retting as a method to replace dew-retting. The strategy of this research was to replace the anaerobic bacteria with enzyme mixtures in controlled tanks, thereby producing flax of water-retted quality but without the negative aspects of stench and pollution. Research resulted in development of the commercial enzyme mixture Flaxzyme from Novo Nordisk (Denmark), several patents pertaining to enzyme-retting (Van Sumere and Cowan 1987; Akkawi 1990), and a pilot scale, tank method (Van Sumere 1992). Enzyme-retting produced fibers having the fineness, strength, color, and waxiness comparable to the best water-retted fiber (Van Sumere and Sharma 1991). Advantages of the enzyme method were: (1) time savings of 4–5 days, (2) increased yield of ca 2% over water-retting, and (3) fiber consistency.

The flax plant supplies both industrial oil (i.e., linseed oil) and bast fiber used to produce textiles, composites, and paper/pulp. Linen has occupied a prominent place in textiles for centuries. Flax can be grown in many locations and is environmentally friendly. Flax production in the South Atlantic region has the potential to enhance rural economic growth and to supply a domestic source to the fiber industries of the United States. Flax is well known to grow in a cool and moist climate (Sharma and Van Sumere 1992b, Elhaak et al. 1999). Yields and production guidelines are available from recent research in Connecticut (Stephens 1997a,b). Traditional methods for harvesting flax require specially made, sole-purpose, and expensive equipment (Sultana...
Trends in New Crops and New Uses

1992) manufactured only overseas to pull and turn flax. This fact alone makes flax production in the US too costly. However, research and cost projections have shown that typical equipment used on US farms and familiar to farmers can be used to mow, rake, bale, and store flax (Dodd et al. 2000; Foulk et al. 2000).

In the southeastern US, the warm climate allows this crop to be grown in the winter to produce flax seed and fibers on traditionally dormant fields or to double crop for higher economic benefits. Bio-based agriculture includes environmentally friendly processing methods for new crops and value-added products needed to develop sustainable agriculture, enhance farm economy, and improve global competitiveness. Flax is a well-established, versatile plant that addresses the above priorities and supplies into existing markets: fiber (e.g., textiles, composites, and paper/pulp) and linseed (e.g., industrial and nutritional oil and bran). Despite the fact that globally the US is the largest per capita consumer of flax fiber, no flax is grown for fiber in the US and all fiber for textiles and composites is imported. Major technical problems associated with establishing a flax fiber industry in the US are the efficiency of harvest methods, fiber extraction (retting), and the lack of standards for judging fiber quality. As in the US, interest exists in Europe to further develop flax for industrial use (Van Dam et al. 1994).

Establishing a flax fiber industry in the southern US will enhance farm economy through production of a winter crop and value-added products that directly complement traditional high-value summer crops. Improved economy will occur through production and sale of flax as well as by associated agricultural sectors, including processing facilities, related maintenance services, and seed production/distribution industries. Flax fiber production in cotton’s off-season permits more efficient use of labor, buildings, and some equipment. Flax fiber, as a new crop supplying a value-added product, will improve global competitiveness in supplying US textile and composite industries with a domestic source of clean, consistent quality fiber in place of imported fiber of unknown quality. The use of enzymes to extract fibers provides an environmentally friendly method toward developing reliable and sustainable agriculture using bio-based fibers.

OBJECTIVES

The long-term goal is to develop an environmentally friendly, processing method to deliver flax fiber with specific characteristics required for US industries. These flax fibers may aid in the sustainability of US agriculture by providing an alternative crop (winter crop for double-cropping in the south; new fiber products from linseed straw in the north). To develop and support a US flax fiber industry requires consist quality fibers for various industrial applications, an environmentally friendly fiber crop (no insecticides, low herbicide and fertilization needs) grown and harvested using traditional agricultural equipment, and an environmentally friendly enzyme-retting system. Specific objectives are to: (1) to evaluate traditional farm equipment for flax production, (2) develop an enzyme-retting pilot plant method to replace traditional methods thus producing flax fibers with specific properties for industrial uses, and (3) test fibers for manufacturing performance and/or aesthetic properties.

METHODOLOGY AND RESULTS

An agricultural operation and a fiber separation process must be developed and optimized in order to produce quality flax fibers. Ideally, a crop grown for its seed could also be processed for refined fiber, which could then be used in industrial products. While interest is increasing, currently little flax from the whole of North America is used in producing industrial fibers. A new two-step procedure is being developed for producing low cost flax fibers. The agricultural operation has been designated Clemson Fiber Flax (CFF) (Foulk et al. 2000) with the retting process termed Crimped Enzymatic-Retting (CER) (Foulk et al. 2000) or Spray-Enzyme-Retting (SER) (Akin et al. 2000a). CFF methods are operational and only require flax cultivation. CER and SER techniques are currently only available in batch studies of flax stalks.

Agricultural Operations

The southeastern region of the United States has been the site of recent interest into growing fiber flax. Flax has been grown for paper production along the southeastern coastline of South Carolina since the 1960s, typically producing yields from 4,483 to 6,725 kg/ha (Frederick, pers. commun., 1999). Field tests conducted
in South Carolina indicate that flax plants requires low nitrogen levels (78 kg/ha) with herbicides and insecticides rarely needed (Frederick, pers. commun., 1999). As a versatile crop, the seeds are removed for their oil content and the fibers are separated from the stem for industrial applications. Cultivars and cultural practices (e.g., seeding density, harvest method) determine the final products, and research to develop “dual-purpose” cultivars is published (Keijzer and Metz 1992). Several hundred flax cultivars are available through USDA with germplasm now stored in Ames, Iowa (Brothers 2000).

The new southern agricultural operations, designated Clemson Fiber Flax (CFF), involves carefully preparing the seedbed for planting between October and December, examining soil moisture and nutrients, planting with a drill or broadcast planter, combining to remove and collect seed using a stripper header, drum-cutting the stalks, field-drying the stalks, raking the stalks for even drying or dew-retting, and baling for processing (Foulk et al. 2000).

Frost or drought can damage flax so proper planting times are required in optimizing fiber yields and quality. Flax is planted along the coast in South Carolina between Oct. 20 and Nov. 10 (Parks et al. 1993) to benefit from cool and wet weather since flax requires good soil moisture in earlier growth stages. Sharma and Van Sumere (1992b) stated that for maritime areas rainfall should be evenly distributed throughout the growing season, totaling approximately 701 mm. Parks et al. (1993) reported that 124 kg/ha is the desired seeding rate for South Carolina.

A well-prepared field is required because flax grows from small seeds planted 1.9 to 2.5 cm deep. Initially, flax does not compete well with other plants, and yield and quality are improved with weed control (Friesen 1986). The growing season in South Carolina (Parks et al. 1993) for fall-planted fiber flax ranges from 100 to 130 days. ‘Ariane’ fiber flax grown at the Pee Dee Experiment Station in Florence, South Carolina has yielded 6726 kg straw and 1255 kg seed/ha (Parks et al. 1993). ‘Wiera’ fiber flax grown at the Pee Dee Experiment Station in Florence, South Carolina produced 7292 kg straw and 410 kg seed/ha (Loadholt 1965).

Traditionally, flax harvesting was performed by hand with the plants pulled from the ground. Today, expensive pullers and turners are used in Europe to harvest flax for long-line fibers. European harvesting equipment is specialized equipment and only used for flax. Individually, equipment costs are about $160,000 for a self-propelled puller, $45,000 for a self-propelled turner, and $100,000 for a self-propelled large round baler (Irwin 1998). In the United States flax is not harvested commercially for its fiber, but experimental methods in South Carolina have been developed for short staple fiber with flax stalks cut using a drum-mower and then baled. Using redesigned techniques over those traditionally used in flax production, fiber production begins at the farm using readily available agricultural equipment but tailored for flax harvesting. Drum cutting, raking, and baling requires less operator attentiveness than European pullers, turners, and balers which decreases harvesting time. No costly, specialized, and imported harvesters are required with equipment low cost, readily available, rapid, and well understood by US farmers.

As briefly outlined by Foulk et al. (2000), the seedbed can be prepared using an 8.23 m International disc harrow (Model no. 3900) and a Perfecta II 4.57 m Unverferth field cultivator. Depending upon soil conditions fertilizers can be spread prior to field disking and on well maintained fields no pre-plant herbicide is typically required. The seeding date must coincide with optimal soil moisture conditions for flax germination. The seeding depth should be less than 0.6 cm, with a seeds closely planted to generated thin flax stems in close proximity. Again depending upon conditions additional fertilizer may be supplied for plant growth. No other treatments are typically required.

Flax can be harvested as an early crop for fiber, with attached immature seeds, or harvested as a late, mature crop, for both seed and fiber production. Harvests of flax have been performed using a Model No. 167 drum mower (Fella Werke, Feucht, Germany). For the late harvest of flax, seeds have been removed from stalks with a Shelbourne-Reynolds stripper header (Colby, Kansas) attached to a Model No. 1660 CASE IH (International Harvester, Racine, Wisconsin) combine. After stripping, the flax was mowed, allowed to dry and evenly spread across the soil surface using a HSR 200R rake (JF Fabriken, Sonderborg, Denmark). Following harvest the flax can be field dried and baled for enzyme-retting or dew-retted prior to baling. Flax was baled using a CASE IH baler Model No. 8430 (International Harvester, Racine, Wisconsin).
PROCESSING

Fundamental knowledge of the structural and chemical characteristics of flax are important for designing a strategy using enzymes to produce fibers with specific properties required for industrial applications. Flax fibers, which occur in the bast (i.e., cortex) region of the stem, lie between the protective cuticle/epidermis barrier and the lignified core tissues (Van Sumere 1992). The ultimate fibers (i.e., individual elongated fiber cells) occur in bundles that, intermixed with parenchyma tissues, form a ring around the lignified core cells of the stem (Akin et al. 1996). Pectin serves as a glue to hold fibers together in bundles and the bundles to non-fiber tissues (Van Sumere 1992). Calcium levels are especially high in the protective barrier of the flax stem and likely help stabilize pectins and thereby plant tissues in that location. These structural/chemical characteristics indicate specific regions that serve well to protect the stem and must be breached by enzymes for effective retting.

The new environmentally friendly processing system requires harvested flax stems to be crimped between fluted rollers thus splitting the stalk both longitudinally and transversely. Briefly, the procedure uses a pectinase-rich, commercial enzyme mixture plus chelator, e.g., 50 mM ethylenediaminetetraacetic acid (EDTA), applied to crimped flax stems that are then incubated for 24 hr at 40°C. Enzyme was required for ease of fiber removal with a chelator (e.g. EDTA) scavenging and binding exposed calcium ions. During incubation, the chelators and enzymes work concurrently to further separate the fiber bundles. Following incubation, the enzyme-retted flax stalks are rinsed with water to remove the enzyme solution and the solubilized portion of stalk. Retted flax stalks are then dried with circulating heated air. By controlling all processing steps, uniform flax fibers of known properties are produced. Enzyme-retted fibers were then mechanically cleaned and characterized for properties relevant to textile fibers.

In contrast to traditional linen production, the current US textile industry requires short staple, refined fibers. Enzyme-retting and additional processing produces short staple fibers of more consistent quality, reduces the environmental pollution through excess dirt and dust of dew-retted flax, does not limit the process to geographical regions of particular temperature and moisture, and allows fields to be harvested and made ready for subsequent crops in a known time-frame. This retting could be carried out in facilities near farms to reduce transportation costs (as in done with gins for cotton) or potentially in smaller lots directly on farms. Further work is now needed to optimize the retting formulation for cost and fiber quality and to integrate enzyme-retting with varieties, harvesting, and subsequent cleaning stages.

POTENTIALS AND PROBLEMS

Agricultural Operations

Differences exist between flax grown for fiber and flax grown for its seed due to variety differences as well as harvesting methods. Preparing the seed bed for planting is perhaps the most important step in growing flax. A well-prepared field avoids herbicides thus reducing field time and benefiting the environment. The seeding depth, drill spacing, and seeding rate are important to growing a healthy, dense, uniform, and high quality flax crop. Yields of flax appear to be influenced by proper field management and by the climate throughout the growing season. Elhaak et al. (1999) states that low levels of soil organic matter, available nutrients, and high calcium concentrations decreased flax yields and reduced quality fibers.

‘Ariane’ fiber flax was grown along the coastal plains of South Carolina under varying environmental conditions using equipment and fertilizers typically available on farms in the United States. Our results reveal that traditional farm equipment suitable for multiple crops could be utilized to produce acceptable flax yields (Foulk et al. 2000). This equipment is low cost, readily available, and well understood by US farmers. New methods of harvest may obtain lower flax fiber yields than traditional methods, but the rate of harvesting is much higher and most agricultural operations currently have the required equipment. Traditional harvest methods including mowers, rakes, and balers produce plants of good yield and quality for fiber (Foulk et al. 2000). Speed is perhaps CFF’s greatest advantage allowing fields to be combined at a rate of 5 ha/hr, mowed at a rate of 1 ha/hr, raked at 2.5 ha/hr, and baled at 2 ha/hr. Mowing results in lower flax fiber yields than pulling. Flax harvested with drum mowing gave favorable dry straw yields (3383 to 7050 kg/ha), with stubble heights between 6.0 and 7.3 cm contributing to fiber losses of about 3% of the plant (about 10% of the potential fiber
yield). This indicates the potential to produce flax for fiber as a winter crop in the southeastern US. The loss in fiber yield must be considered in conjunction with advantages of mowing using traditional farm equipment.

In the southern US, an emerging flax fiber industry, based on production of flax as a winter crop for rotation with traditional summer crops, is being developed in one of the most impoverished regions in South Carolina. The most recent agricultural operations were demonstrated in Williamsburg County, South Carolina. This county has a poverty rate of 28.3%, and unemployment rates averaging 14.9% ± 2.7 for 1994–1998 (data from Economic Research Service, USDA). Kingstree, South Carolina, in Williamsburg County has been chosen for a newly organized flax processing company, which will involve a farmers/producers cooperative integrated to a commercial processing plant. Regional farmers began testing flax production in small areas (ca 3–4 ha plots) from 1999 to 2001, with anticipation of delivery of the cleaning system for late 2001.

**Processing**

The inclusion of chelators in retting formulations substantially reduced amounts of pectinase-rich enzyme mixtures required for retting (Henriksson et al. 1997b, 1999). Removal of these ions allows easier access by the enzyme formulation into the stalk’s interior, preferentially degrading the pectins, and leaving the cellulose fibers intact. Chelators are thought to improve retting by removing Ca++ that bridges and stabilizes pectins (Sakai et al. 1993). Currently, EDTA in a commercial product (i.e., Mayoquest 200, Callaway Chemical Co., Smyrna, Georgia) was effective, when used at pH 5 with pectinase-rich enzyme mixtures, at levels of 10 to 20 mM and resulted in fibers with high yields and suitable strength and fineness. However, other chelators, such as oxalic acid (Henriksson et al. 1997b), are less expensive, and further research could optimize the enzyme-retting formulations and add additional properties.

Commercially available enzymes have been shown to promote a controlled retting of flax in a laboratory setting (Van Sumere 1992; Akin et al. 1997). These enzymes provide a key step in the economic development of a controlled and scientific approach to rapidly and efficiently produce flax fibers of high and consistent quality. Though enzymes accelerate reaction rates, additional procedures such as chelating agents and mechanical pretreatments increased the efficiency of enzymes (Henriksson et al. 1997b). Small fluted rollers mechanically break the stem allowing the enzyme solution to be more quickly adsorbed into the fiber and accelerate the degradation process (Akin et al. 2000a). For flax, any of the processing methods (i.e., retting and/or subsequent cleaning) potentially could further divide the bundles and result in ultimate fibers and finer bundles. Therefore, the retting and mechanical processing steps work together to produce fibers, which are more precisely fiber bundles, of a particular fineness distribution. Variations in enzyme formulations used in retting can modify fiber properties, e.g., color, strength, and fineness (Akin et al. 2001, 2002), and information is needed on the specific fiber properties resulting from enzyme modifications, particularly related to subsequent cleaning. Table 1 contains properties of flax retted and processed by various means.

With enzyme-retting, field dew-retting is not required and the time of land occupation is shorter so farmers can be assured of the availability of the land for planting other crops. As an enclosed facility, enzyme-

<table>
<thead>
<tr>
<th>Sample</th>
<th>Strength (g/tex)</th>
<th>Fineness (micronaire)</th>
</tr>
</thead>
<tbody>
<tr>
<td>European long line, dew-retted</td>
<td>38 ± 5</td>
<td>8.0</td>
</tr>
<tr>
<td>South Carolina grown, dew-retted, cottonized</td>
<td>24 ± 2</td>
<td>4.2</td>
</tr>
<tr>
<td>Ariane fiber flax, spray-enzyme-retted</td>
<td>27 ± 4</td>
<td>7.1</td>
</tr>
<tr>
<td>Shirley-cleaned†</td>
<td>18 ± 2</td>
<td>4.6</td>
</tr>
<tr>
<td>Ariane fiber flax, spray-enzyme-retted</td>
<td>33 ± 5</td>
<td>7.8</td>
</tr>
<tr>
<td>Shirley-cleaned‡</td>
<td>27 ± 2</td>
<td>4.8</td>
</tr>
<tr>
<td>Seed flax, spray-enzyme-retted, Shirley-cleaned</td>
<td>21 ± 1</td>
<td>4.1</td>
</tr>
<tr>
<td>Upland cotton (included as reference)</td>
<td>21 to 25</td>
<td>3.7 to 4.2</td>
</tr>
</tbody>
</table>

†Enzyme-retted with 0.3% v/v enzyme mixture supplied by Novozymes, Franklinton, North Carolina.
‡Enzyme-retted with 0.05% v/v enzyme mixture supplied by Novozymes, Franklinton, North Carolina.
retting allows retting year round and eliminates risks associated with dew-retting such as prolonged periods of dry weather. The fibers produced by enzyme-retting were lighter in color than dew-retted fibers, which is determined by the indigenous fungi and bacteria (Akin et al. 2000b). Color was measured for both dew-retted and enzyme-retted fiber and seed flax (Table 2). Enzyme-retting produced fibers that were substantially lighter than dew-retted fibers for both fiber and seed flax, with enzyme-retted fiber flax the lightest. Color data for the samples varied, with the seed flax having considerably greater redness and yellowness (Table 2). Results suggest opportunities to modify color properties of flax by retting methods and flax type. Comparing various enzyme- and dew-retted fiber samples indicated that significantly different properties of strength and fineness resulted with the various formulations. These data indicate the potential to tailor fiber properties for composites by specific enzyme formulations.

**FUTURE PLANS**

**Standards**

While characterization of flax fibers is frequently reported (Sharma and Van Sumere 1992b), standards currently do not exist. The dissemination of standards will proceed through the Flax (Linen Content) Products Subcommittee (D13.17), which meets semiannually as part of the Textile Committee of the American Society for Testing and Materials (ASTM). In 1999, ASTM established this subcommittee to develop the following flax standards for properties deemed important to the textile industry: trash (non-fiber) content, strength, length, fineness, and color. Of major concern related to trash content is the amount of woody shive (i.e., the inner, lignified core tissues [Akin et al. 1996] of the stem) present. Strength, length, and fineness were grouped for consideration by one task group, since these properties are closely related. Color standards are needed to provide objective data. Development of standards will be subject to the review of the Flax (Linen Content) Products Subcommittee and the Textile Committee of ASTM, which operates under a strict set of guidelines for review and follow-up of critiques. Each standard has a 5-year mandatory review under ASTM guidelines. Fiber properties will be determined using standard tests developed for cotton and modified for flax.

Work is in progress on standards for color, strength, fineness, and terminology, which will be submitted for subcommittee balloting within a year. Methods used for assessing cotton fiber quality, e.g., strength and fineness, have been successfully modified and used as a basis for measuring flax fiber properties (ASTM 1997a,b). Fineness of fibers was also directly measured using an image analysis system associated with a light microscope. Color measurements were made using a visible range spectrophotometer having a 1° standard observer and illuminant D65, which represents average daylight over the range of 300–830 nm (Epps et al. 2001). CIELAB values (L*, a*, and b*) were obtained from xyz tristimulus values calculated by the instrument using industry accepted techniques (Billmeyer and Saltzman 1981; Epps et al. 2001). Substantial work is required for a trash standard, as background work is not available. A method for trash (non-fiber) content is under development at the Russell Research Center, ARS-USDA based on spectroscopy. Research using chemical analysis as a basis for near infrared spectroscopy has shown promise and this method will be explored to develop a standard. Lengths measurements based on the cotton standard would provide a basis for studies on flax fiber.

These methods, with modifications as required, have provided the tools to objectively assess and compare the priority properties in enzyme-retted fibers. Fibers having such specific properties have been blended with cotton, and test yarns were made and evaluated (Akin et al. 2001). Further work with enzyme-retted fiber in laboratory tests showed that flax improved moisture absorbance of knitted fabrics (Table 3). More recently, pilot scale tests of commercially cleaned flax indicated that fiber strength, fineness, and yield could be varied by enzyme/chelator levels (Akin et al. 2001). These

<table>
<thead>
<tr>
<th>Retted sample</th>
<th>CIELAB values</th>
</tr>
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<tbody>
<tr>
<td>Fiber flax</td>
<td>L* 59.9  a* 2.5  b* 10.3</td>
</tr>
<tr>
<td>Dew</td>
<td>L* 76.2  a* 2.3  b* 14.0</td>
</tr>
<tr>
<td>Enzyme</td>
<td>L* 60.5  a* 3.9  b* 13.0</td>
</tr>
<tr>
<td>Seed flax</td>
<td>L* 67.9  a* 4.6  b* 17.1</td>
</tr>
</tbody>
</table>

Table 2. CIELAB color of dew- and enzyme-retted flax fibers. Data from Akin et al. 2000b.
data suggest that different enzyme formulations can modify fiber properties, thus providing opportunities for diverse applications. Once standards are in place, fiber quality as determined by production methods, enzyme-retting, and cleaning can be objectively determined, with economic and marketing decisions by producers and processors more effectively made. These standards are urgently needed to support the emerging company in Kingstree. As with cotton, flax standards in the long-term would help market decisions on the utilization of flax for various applications and expand the industry.

**USDA Flax Pilot Plant**

A USDA Flax Pilot Plant, with a version of a commercial flax cleaning system, is near completion at ARS–USDA, Clemson, South Carolina with specific funding from USDA. Concurrently, an Eastern Flax facility located in Kingstree, is in the process of organizing the farmer/producer cooperative in South Carolina around a recently purchased cleaning system built on the same principle as the USDA pilot plant system. Both pilot plant and commercial systems involve the use of the Unified Line (Czech Flax Manufacturing, Merin, Czech Republic), plus an additional cleaning system to produce cottonized flax. Research on flax fiber production, enzyme-retting, and standards development is urgent to support new industry initiatives in Kingstree, as well as for long-term economic development of the flax fiber industry. Post-retting enzyme treatment, or addition of other enzymes to retting formulations, could tailor dew-retted fiber properties for specific applications.

The USDA Flax Pilot Plant will likely provide a better understanding of fiber quality parameters, fiber standards, processing costs, and eliminate uncertainties of raw material supply that have limited the use of flax fibers in industrial applications. Flax fiber can be blended with cotton and spun by rotor, vortex, and ring-spinning equipment at the Cotton Quality Research Station (CQRS), ARS–USDA, Clemson. This facility has the ability to test yarn strength and evenness. Test results and processing changes may identify new steps, eliminate current steps, or focus on present steps to lower the economic costs while producing better fibers and yarns. This work allows the integration of production/harvesting, retting, and cleaning to produce fibers of specific properties. Sound bases will be established from harvesting/production to fiber assessment and market decisions through research and education linked to an emerging commercial enterprise and a farming community. A flax fiber industry can then expand into a formidable rural economy in the southern US through production, processing, and distribution sectors for supplying a domestic source of high and consistent quality fiber to a variety of industries.

From a general perspective, a fundamental body of knowledge on interactions of enzymes and plant tissues will be acquired that has a broad relevance to adding value to fiber crops. Research will provide basic knowledge on properties on fiber plants imparted by specific enzymes when processed through enzyme-retting and commercial-type cleaning for both fiber and seed flax types. Results should then identify both enzyme formulations that impart particular properties and the important fiber properties required for industries. Further, because fiber and seed flax may vary in enzyme requirements for retting, with seed flax more difficult to ret and require additional components, a series of formulations tailored for specific flax types would be developed. Results will support a newly emerging flax fiber industry in South Carolina to produce a domestic fiber industry.

### Table 3. Moisture absorption of cotton/flax knitted fabrics.  

<table>
<thead>
<tr>
<th>Blend (cotton/flax)</th>
<th>Description</th>
<th>Moisture absorbed (g/g fabric)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton only</td>
<td>Control</td>
<td>2.7 ± 0.3 a y</td>
</tr>
<tr>
<td>90:10</td>
<td>Enzyme-retted; Shirley 1×</td>
<td>3.0 ± 0.8 a</td>
</tr>
<tr>
<td>90:10</td>
<td>Dew-retted; Shirley 1×</td>
<td>3.3 ± 0.5 ab</td>
</tr>
<tr>
<td>90:10</td>
<td>Enzyme-retted; Shirley 2×</td>
<td>4.1 ± 0.9 bc</td>
</tr>
<tr>
<td>70:30</td>
<td>Enzyme-retted; Shirley 2×</td>
<td>4.2 ± 0.7 bc</td>
</tr>
</tbody>
</table>

\*Cotton Shirley-cleaned 1×. Fibers carded 1× and passed through a drawframe 2× before ring spinning and yarn knitting.

\*Mean separation by Duncan’s New Multiple Range Test, 5% level.
source of clean, high, and consistent quality fiber for US textile and composites industries. The success of this commercial operation would have great importance for improved rural economy through a fiber producing industry, associated industries such as processing and seed production. US industries will be guaranteed a domestic source of clean, high, and consistent quality fiber for use in a variety of uses, such as blends for apparel in textile industries, composites, and other non-woven applications.

Composites

Flax fiber composites geared particularly to the huge market potential for automotive components (Domier 1997; Lepsch and Horal 1998) present an opportunity to use the vast resources of linseed straw for a value-added use. More than 1 million tonnes annually of flaxseed straw, as a byproduct of the linseed industry in western Canada, constitute a major environmental disposal problem (Domier 1997). Dew-retting is very inefficient due to cold, dry weather at harvest time in this region, and estimates of 85% (after a small amount is used for fibers in specialty papers) of this straw is burned, creating a substantial environmental problem. Further research where enzyme-retting and subsequent cleaning is optimized for linseed straw potentially could produce a value-added natural fiber tailored for composites, while concomitantly reducing pollution from burning millions of tons of straw.

Composite stiffness values for flax are comparable to E-glass fiber composites and are suited for low cost engineering uses (Heijenrath and Peijs 1996; Bledzki and Gassan 1997). Flax fibers produced through traditional dew-retting methods typically cost from $0.22 to 1.10/kg with a tensile strength of 1.1 GPa and a density of 1.5 g/cm³ (Bledzki et al. 1996). Although flax fibers have a lower strength, they have a lower density and cost, which reduces the load-bearing cost. Current technical data suggest that dew-retted flax fibers can compete with glass fibers in specific composite materials (Wittig 1994; Burger et al. 1995; Heijenrath and Peijs 1996; Bledzki and Gassan 1997). These plastic components reinforced with flax fiber have typically been considered for parts exposed from low to middle high levels of stress (Munker et al. 1998). Mapleston (1997) states that flax composites absorbs sound well and provide safety attributes because they do not splinter or leave sharp corners under impact. According to Van Dam et al. (1994), processing flax fibers exposes processing equipment to less wear, less fiber fracture in melts, post molding workability, and lower or no health risks to workers. However, the lack of fiber quality parameters, fiber standards, uncertainties of raw material supply, unpredictability of flax composite processing, possible long production cycles, and processing costs have likely limited further use of flax fibers in composites.

SUMMARY

Although traditional linen in Europe is constructed with long-line fibers, many industry analysts indicate that the largest use for US textiles will be as short staple flax fibers blended with cotton or other fibers. The low load-bearing cost of flax fibers in composites might predict its potential use in composites and other industrial products. Agricultural operation of flax is currently feasible with available US equipment. Crop yields are acceptable and may lead to the establishment of a flax industry in the US. US grown flax stems are suitable for dew- or enzyme-retting to be utilized in the textile, composite, or paper/pulp industries. ASTM test methods and practices are currently being developed to grade flax fibers for length, strength, fineness, color, fineness, and trash to aid in marketing. Results suggest that enzymes-retting could produce fibers with particular properties, thus providing diversity in fiber characteristics for various applications. This retting can be performed utilizing commercial enzyme and chelator products. Enzyme-retting and processing can currently be performed at the USDA Flax Pilot Plant with a large scale industrial process coming on-line in Kingstree.

REFERENCES