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Sweet Clovers, a Source of Fibers Adapted for Growth on Wet and Saline Soils

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ABSTRACT

Sweet clovers are legumes able to grow on most soils, and two sweet clover species, *Melilotus albus* and *Melilotus officinalis* have been introduced and are now cultivated on estuary land. We characterized the composition and morphology of sweet clover stems collected after the seeds had reached maturity. We also carried out histochemical analyses on transverse sections. The two species had similar morphological structures, which two fiber fractions: flexible long fibers and stiff, dense shives, accounting for about 12% and 88% of stem dry matter, respectively. Histological analysis revealed the presence of bundles of highly cellulosic bast fibers (lignocellulosic material: 71–78% of dry matter). The shives are a natural mesoporous material composed of 85–90% lignocellulosic fibers. Both fiber fractions displayed good thermal resistance to temperatures up to 225°C and a moderate affinity for water. These two types of fibers are similar to those of flax and hemp, suggesting their possible use for the same types of applications. Sweet clovers therefore constitute a new source of fibers that can be cultivated on wet and saline soils not otherwise suitable for agriculture.

摘要

草木樨是适宜在大部分土壤中生长的一种豆科植物，目前引入的有白花草木樨和黄香草木樨两个品种，现已在河口土地上栽培。本文主要研究草木樨在种子成熟后其茎部的特点和形态。我们还对其横截面进行了组织学分析。这两个品种有类似的形态结构，其纤维有两个组成部分：柔软的长纤维和粗硬的密植物性杂质，在干物质中分别约占12%和88%。组织学分析表明存在高纤维质韧皮纤维束（木质纤维材料：占干物质的 71–78%）。植物性杂质是一种天然孔状材料，包含 85–90% 的木质纤维。这两种纤维成分都表现出良好的耐热性（高达 225℃），对水具有中等亲和力。这两种类型的纤维类似于亚麻和大麻纤维，表明它们可用于与后者相同类型的用途。因此，草木樨可作为不适合其他农作物种植的潮湿和盐碱土壤上的新纤维来源。

KEYWORDS

Bast fiber; fiber crops; *Melilotus alba*; *Melilotus officinalis*; natural fiber; saline wet soil

关键词

麻类纤维；纤维作物；白花草木樨；黄香草木樨；天然纤维；潮湿盐渍土壤

Introduction

An increase in the demand for natural fibers to replace synthetic fibers in plastic composites, textiles, or insulation materials for buildings has been predicted for the coming years (Lucintel 2011; Meirhaeghe 2011). Natural fibers have a number of major advantages, including a low density, good mechanical properties, high levels of disposability and renewability. However, if food security is to be ensured, the production of natural fibers must not compete with agricultural food production systems. One of the best ways of achieving this objective is to explore the potential of new fiber crops capable of growing on soils that give low yields of food crops.

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In 2008, the FAO estimated that about 800,000 ha of emerged land was affected by salinity, a large proportion of this land bordering estuaries (FAO 2008). This land would be ideal for growing fiber crops, as it is largely unsuitable for arable crops and would therefore not compete with food production. However, most conventional fiber crops also have mediocre yields on such saline soils. Sweet clovers, such as white sweet clover (*Melilotus alba*) in particular, have been described as highly suitable for wet and saline lands (Evans 2001; Evans and Kearney 2003; Rogers et al. 2008), which are usually left fallow.

Sweet clovers (*Melilotus* ssp.) are Eurasian members of the Fabaceae, and this group includes at least 25 identified species (Allen and Allen 1981; Stevenson 1969; Turkington, Cavers, and Rempel 1978). They are strong, rustic plants that are both cold-hardy, even at very northerly latitudes, and able to tolerate high annual mean temperatures (Duke 1981; Klebesadel 1992; Madson 1951; Sparrow et al. 1993). For adequate growth, they require at least 7.8 dm of precipitation annually, although some varieties have been shown to be resistant to relatively dry conditions (Duke 1981; McLeod 1982). Sweet clovers can grow on most soils deep enough for the development of their root system (Duke 1981; Madson 1951; McLeod 1982). They can tolerate a pH from 4.8 to 8.2, (Duke 1981) but prefer neutral soils rather than alkaline soils, with some varieties being able to tolerate soil salinity (Duke 1981; Evans 2001; Evans and Kearney 2003; Rogers et al. 2008). Like other legumes, sweet clovers can fix atmospheric nitrogen to form proteins (Brandsæter et al. 2008; Sparrow et al. 1993) and can assimilate insoluble forms of phosphate and potassium (McLeod 1982). They therefore require very little fertiliser during the cropping season.

Sweet clovers have long been used, at the pre-floral bud stage, as forage crops (Maddaloni 1986). Some *Melilotus* species contain large amounts of coumarin and its derivatives, mostly in the floral buttons and the young leaves (Linton et al. 1963. For example, *Melilotus officinalis* is among the four plants with the highest known coumarin concentrations (Keating and O'kennedy 1997). Unfortunately, in the presence of certain moulds (e.g., *Penicillium* spp.) and under specific conditions, this coumarin may be transformed to yield dicoumarol (Alstad et al. 1985; Benson et al. 1981; Cheeke and Shull 1985), which can cause severe, potentially fatal haemorrhages, particularly in cattle (Blakley 1985; Cheeke and Shull 1985). For this reason, sweet clovers are generally considered not to be a suitable forage crops, and their cultivation has become marginal. The problems caused by coumarin can be circumvented by harvesting sweet clovers after flowering, and by using these crops for other non-food and non-feed applications, such as the production of fibers for industry. Late harvesting, after flowering, is advantageous in honey plants, such as sweet clovers, which attract many beneficial pollinator insects, such as bees, with their aroma compounds (Ogle et al. 2007), together with auxiliary insects that help to defend the crop against its natural enemies. Sweet clovers are, therefore, often included in populations of plants grown for honey production (Baldridge and Lohmiller 1990; Decourtye et al. 2006). The expansion of sweet clover cultivation could therefore be included in agricultural policies for bee protection.

We investigated the potential of sweet clover stems to serve as a source of fibers. We observed the two commonest biennial sweet clovers, *M. officinalis* and *Melilotus alba*, harvested when the seeds were mature ("old" plants).

Materials and methods

Plant material

White and yellow sweet clover seeds were provided by Phytosem (France). The clovers were cultivated in the Loire Estuary, between Saint-Nazaire and Nantes, in the "Coeur d'Estuaire" territorial Community area (France). The soil was a moderately wet muddy clay, with a pH of 5.9. The soil was ploughed and harrowed, to obtain a good seedbed. The white and yellow sweet clover seeds were inoculated with the same rhizobial species used for alfalfa (*Rhizobioum meliloti* bacterial strain 2011, provided by De Sangosse, France). Seed were sown at a depth of 1–1.5 cm, in April 2011, in a randomised complete block experimental design with fourteen replicates. The plots used were 50–100 m long and 3 m wide. Each complete block was separated from the others by a strip of uncut grass. The sowing density was 23 kg/ha.

Emergence is slow in sweet clovers, which are therefore particularly sensitive to competition from weeds. The sweet clover was sown under a barley crop to prevent weed competition during the first year and to improve clover establishment for harvesting during the second year. The barley was harvested at the start of August 2011, and sweet clover seeds and stems were harvested at the end of August 2012. The seeds were harvested by beating and the stems were left in windrows to dry in the sun and were then baled.

The proportion of cortical fibers present in sweet clover stems was determined by manually separating the two types of fibers from 5 cm sections of stems and then weighing them separately.

Histochemical analyses of sweet clover stem samples and observations

Transverse sections were cut free-hand from freshly harvested basal stem regions. Sections were stained with Weisner reagent (phloroglucinol-HCl), resulting in red staining in the presence of the lignin cinnamaldehyde group (Satiat-Jeunemaitre and Hawes 2001), and with methylene blue and potassium alum, giving a blue colour in the presence of lignin. Pectins were detected as red-pink staining after incubation of the section with ruthenium red and potassium alum. The stained sections were observed under an Axio Zoom V16 motorised fluorescence stereo zoom microscope for large fields equipped with a Plan-NEOFLUAR Z 1.0x objective (magnification 7x to 112x). Images were acquired with an AxioCam HRm camera. The samples were sputter-coated with a thin layer of silver and SEM observations were made with a LEO 435 VP scanning electron microscope.

Chemical analyses

The dry matter content of the samples was determined according to the French NF V 03–903 standard, by heating at 103°C for 24 h. The samples were burnt at 550°C for 5 h for ash content determinations (French standard NF V 03–322). Lipids were determined by Soxhlet extraction, with cyclohexane as the solvent (French standard NF V 03–908). Protein content was determined by the Kjeldahl method (French standard NF V 18–100). The three principal components of the cell walls (cellulose, hemicelluloses, and lignins) present in the solid fraction were determined by the acide and neutral detergent fiber (ADF-NDF) method of Van Soest and Wine (Van Soest and Wine 1967, 1968). The water-soluble components present in the stem were determined by calculating the loss of test sample mass after boiling for 1 h in water. This method was adapted from the Technological Association of the Pulp and Paper Industry (TAPPI) 204 cm-97 standard, for a Fibretec Tecator M1017. Pectins were removed by acid treatment (Marechal and Rigal 1999), as follows. The sample was ground and added to hydrochloric acid at pH 1.5, and was then incubated for 2 h at 70°C. The sample was filtered and the filtrate was recovered and neutralised. Pectins were precipitated by adding ethanol to a 70/30 (v/v) ethanol/water ratio and incubating at 4°C for 48 h. The precipitated pectins were isolated by filtration and washed, first with 95% ethanol and then with acetone. The purified pectins were dissolved in water. The percentage of galacturonic acid in the pectins was determined as described by Blumenkrantz and Absoe-Hansen (Blumenkrantz and Asboe-Hansen 1973).

All determinations were carried out at least in triplicate.

Physical analyses

The sorption isotherms of natural fibers were determined with a DVS Advantage from Micrometrics Instrument Corporation. Samples were finely ground and, at the start of each moisture sorption cycle, the fibers (more than 90% of the dry matter) were dried by heating at 103°C for 5 h. Once the weight of the fibers had stabilised, the moisture sorption cycle was started and the humidity was gradually increased, from 0 to 90%, in 15% increments (Xie et al. 2011).

Tapped densities were determined with a Densitap ETD-20 from Granuloshop. The sample was finely ground (less than 1% retained on a sieve with 250 µm mesh) and poured into a 250 mL tarred graduated cylinder. The cylinder was then tapped at rate of 250 taps/min, until no further change in

volume was observed. The volume of the sample was read directly from the cylinder and used to calculate the bulk density according to the mass/volume relationship. This method was adapted from the ASTM D4164 standard.

The thermal degradation of sample components was analysed in a TGA (SDT-Q600 Thermo Gravimetric Analyser with Differential Scanning Calorimeter from TA Instruments). The sample was heated to 500°C at a constant rate of 10°C/min, with nitrogen gas at a constant flow rate of 100 mL/min used to provide an inert atmosphere for pyrolysis (Yang et al. 2007).

Results and discussion

Crop yield

The yields of yellow and white sweet clover stems were 2980 kg/ha for an area of 0.34 ha harvested (90.9 ± 1.2% of dry matter) and 3970 kg/ha for an area of 0.35 ha harvested (90.8 ± 1.5% of dry matter), respectively. White sweet clover appeared to provide better yields on this type of soil, consistent with the findings of Rogers and coworkers (Rogers et al. 2008).

Macroscopic observations

At seed maturity, the stems of sweet clover were upright, with about 10 branches off the main stem. The stems were partly hollow, with a diameter of about 1–2 cm at their base, and a height of about 180–200 cm for white sweet clover and about 160–170 cm for yellow sweet clover.

After a manual decortication (Figure 1) of "old" stems, we identified two classes of fibrous material. The first class consisted of long fibers accounting for about one eighth of total stem mass (13 ± 2% for white sweet clover and 12 ± 3% for yellow sweet clover; Figure 2a). The large range of values obtained was due to the difficulties encountered in the separation of fine terminal branches. These fibers were brownish yellow to grey in colour and were relatively soft, silky and flexible. They were generally less than 1 mm thick and had a length/width ratio of more than 50,

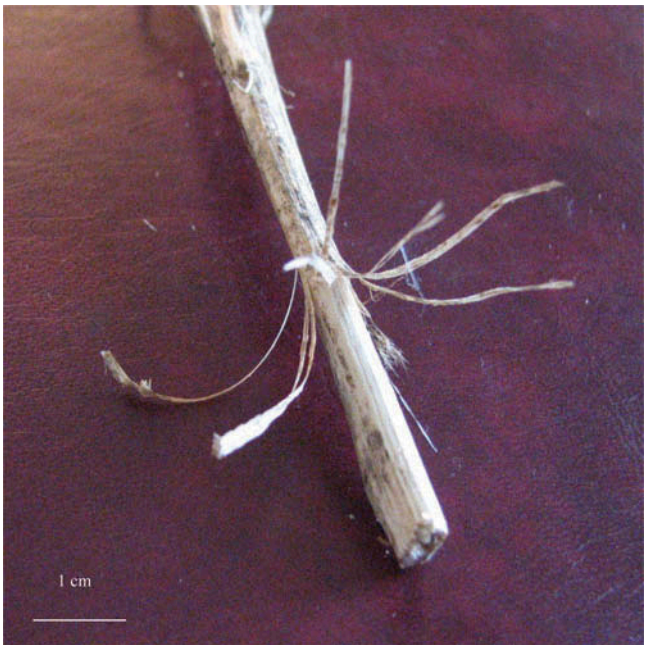

Figure 1. Partially decorticated fragment of a white sweet clover stem harvested at seed maturity.

Figure 2. Two fibrous materials isolated from sweet clover stems (a) cortical fibres. (b) shives.

with some fibers more than 30 cm long. The second class of fibrous material was the shives (Figure 2b). These fibers were light yellow, rough, brittle and highly variable in size, depending on the decortication, but they were generally rod-shaped, with a length/width ratio between 3 and 10.

The traditional fiber plants cultivated for the textile sector in France are flax, which has 15.7–20.0% long fibers in its stems (ADEME—Agrice 1998), and hemp, which has 29.4–36.8% long fibers in the stem (CETIOM 2011).

We considered the fibrous material isolated from the cortex of the stem to correspond to cortical fibers and the fibrous material isolated from the heart of the stalk to correspond to shives.

Microscopic observations

The stems of white and yellow sweet clovers had similar structures. Both were organised into two layers: a weakly ligneous bark layer and a central wood consisting mostly of strongly lignified xylem (Figure 3a). The stems were essentially hollow, but with traces of pith. Islets of weakly lignified long, tapering sclerenchyma cells known as bast fibers were identified towards the outside of the stem, at the periphery of the phloem. Each of these islets included about a hundred cells, as observed for both hemp and flax (Bouloc 2006; Day et al. 2005). As in flax, there was an almost total absence of phloem.

The most external bast fibers were almost circular in transverse section, with a diameter of about 1 µm diameter, generally with no lumen. The innermost fiber cells were larger: 15–20 µm by 20–30 µm, with lumens of various sizes. Cell wall thickness was fairly constant, at about 5 µm.

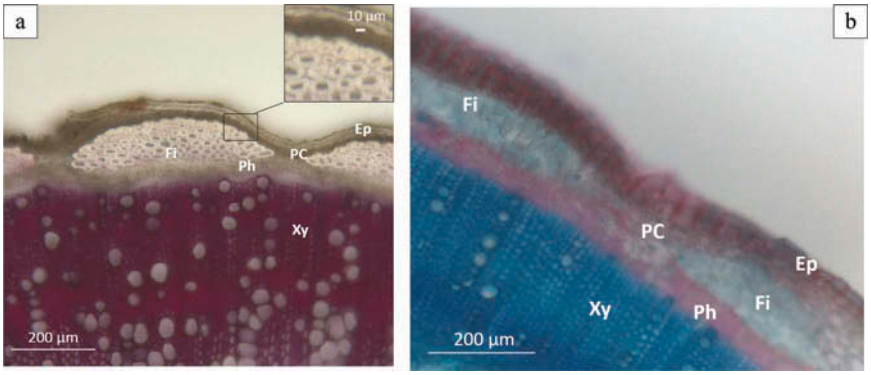

Figure 3. Histochemical and cytochemical detection of lignin and pectin in sweet clover stems at the seed maturation stage, (a) Staining with phloroglucinol- HCl (b) Staining with methylene blue and ruthenium red. Xy: xylem, Ph: phloem, PC: cortical parenchyma, Ep: epidermis, Fi: bast fibres.

The distribution and organisation of the bundles of bast fibers are similar in sweet clover and flax stems. Unlike hemp, in which the fiber bundles are homogeneously distributed throughout the entire width of the bark, sweet clovers and flax have fiber bundles organised into a single ring. However, sweet clover bast fibers include larger numbers of bast fibers (10–40 for flax, versus about a hundred for sweet clovers) (Reis et al. 2006; Yan et al. 2014). Bast fiber sizes were largely similar to those reported for flax, although the innermost bast fibers of sweet clover had a larger lumen.

Observations of cortical fibers at the highest magnification (Figure 4a–c) confirmed that they consisted of bundles of bast fibres associated with cortical parenchyma and pieces of epidermis. However, these two tissues are relatively fragile and it was easy to separate them from the fibres. The "knees" (Figure 4c) observed on sweet clover bast fibres are also visible on flax bast fibres (Baley 2004; Bos et al. 2004; Reis et al. 2006). According to Chernova and Gorshkova (Chernova and Gorshkova 2007) these knees are artefacts due to intrusive diffuse growth.

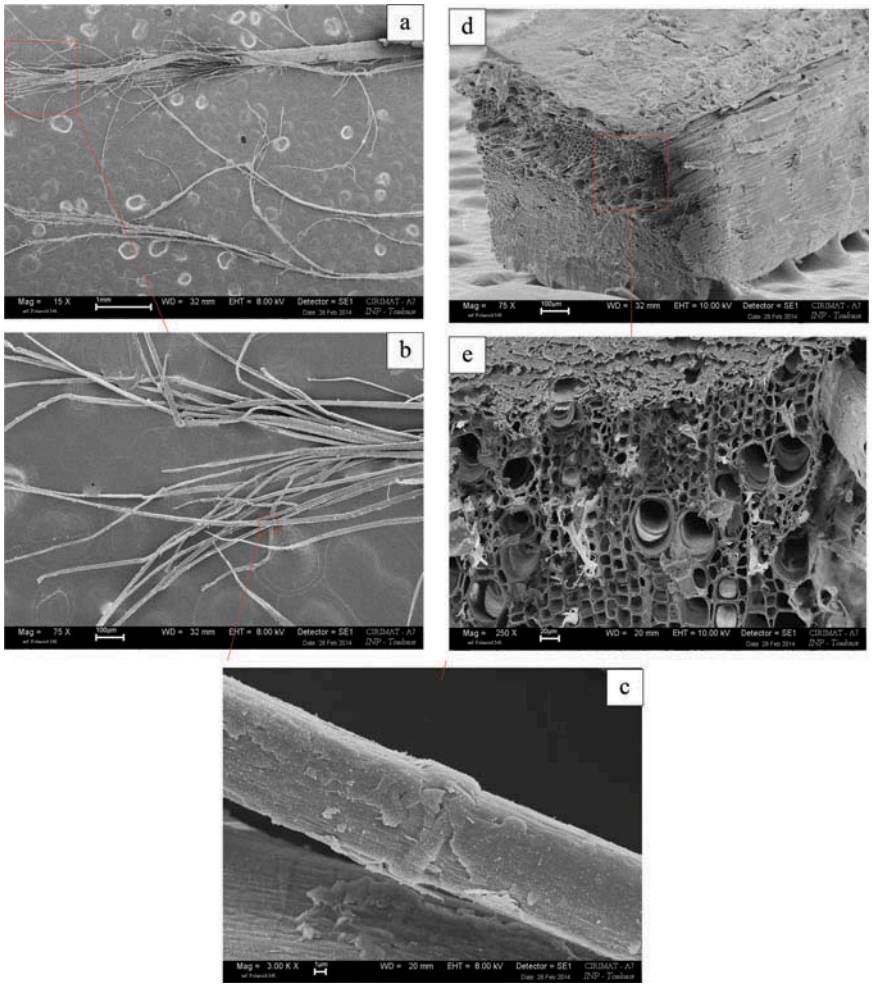

Figure 4. Scanning electron micrographs of the two fibrous materials isolated from sweet clover stems, at different magnifications. (a) General view of sweet clover cortical fibres (magnification 15×). (b) Open bundle of bast fibres (magnification 75×). (c) Bast fibres with kink bands (magnification 3000×). (d) General view of sweet clover shives (magnification 75×). (e) Broken ends of sweet clover shives (magnification 250×).

The central pith was largely destroyed during manual decortication. The shives consisted principally of xylem tissues, with vertically oriented fibres lacking observable structures for reinforcing their sides. Cell lumen diameter was between 15 and 30 µm. The cell walls were thin, with the entire cell wall-middle lamella-cell wall structure measuring between 1 and 3 µm across (Figure 4d and e).

Chemical composition

We determined the chemical composition of sweet clover stems and the identified fibrous fractions (Tables 1 and 2). On a dry weight basis, the stems of the two species studied consisted of approximately 50%-55% cellulose, 11%-14% lignins and 16%-18% hemicelluloses. They contained mostly lignocellulosic cell walls, with a low lignins content. When harvested at seed maturity, the stems of sweet clovers had a composition similar to that of traditional fiber crops. They contained less cellulose but more hemicelluloses than hemp stems, and less hemicelluloses but more lignins than flax stems. Significant amounts of pectins (about 3% of stem dry mass) were present in the cortex, around the fiber bundles (Figure 3b), and in the pith.

Table 1. Main chemical components of the stems of white and yellow sweet clovers, as compared with the stems of flax and hemp (% dry mass).

			Hemp *stem*		Flax *stem*
	White sweet clover *stem*	Yellow sweet clover *stem*	in-house analyses	Struik et al. (2000)	Dambroth and Seehuber (1988)
Ash	3.2% ± 0.2%	2.8% ± 0.1%	3.2%		
NDF residue	83.9% ± 3.0%	83.4% ± 0.6%	86.2%		94%
ADF residue	66.1% ± 1.7%	66.7% ± 1.6%	71.4%		
ADL residue	11.8% ± 4.4%	13.6% ± 3.4%	60.2%		
Cellulose	54.3%	53.1%	60.2%	59–67%	60%
Lignins	11.8%	13.6%	11.2%	4–6%	7%
Hemicelluloses	17.7%	16.7%	14.8%		27%
Proteins	3.6% ± 0.0%	5.0% ± 0.2%			
Fat and wax	0.8% ± 0.1%	0.7% ± 0.1%			
Pectins	3.6% ± 0.1%	2.9% ± 0.3%			3.0%

Table 2. Cell wall components of cortical fibres and shives of white and yellow sweet clovers, as compared with the stems of flax and hemp (% dry mass).

	White sweet clover	Yellow sweet clover	Hemp	Flax
	Cortical fibres	*Cortical fibres*	Dittenber and GangaRao (2012); Kymäläinen and Sjöberg (2008)	Kymäläinen and Sjöberg (2008); Xie et al. (2011); Yan et al. (2014)
Ash	5.1% ± 0.2%	4.2% ± 0.1%		
NDF residue	73.4% ± 0.5%	70.0% ± 0.5%		
ADF residue	61.2% ± 0.5%	59.7% ± 0.3%		
ADL residue	8.8% ± 1.6%	5.4% ± 0.1%		
Cellulose	52.4%	54.3%	60–75%	57–81%
Lignins	8.8%	5.4%	3–14%	2–10%
Hemicelluloses	12.2%	10.3%	11–21%	9–21%
	Shives fibres	*Shives fibres*	Kymäläinen and Sjöberg (2008); Popa et al. (2013); Stevulova et al. (2012); Williams and Wool 2000)	Kymäläinen and Sjöberg (2008); Ross and Mazza (2010); Williams and Wool (2000)
Ash	1.6% ± 0.1%	2.4% ± 0.1%		
NDF residue	89.8% ± 0.1%	84.6% ± 0.3%		
ADF residue	70.9% ± 0.2%	66.1% ± 0.2%		
ADL residue	24.5% ± 0.1%	24.0% ± 1.0%		
Cellulose	46.4%	42.1%	40–52%	36–47%
Lignins	24.5%	24.0%	22–30%	23–30%
Hemicelluloses	18.9%	18.4%	27–30%	25–26%

The chemical composition of the cell walls of the two fibrous fractions was similar to that reported for other French fiber crops. The cortical fibers contained large amounts of non-fibrous material (<26%), but the cellulose/hemicelluloses/lignins ratio was very similar to those of flax and hemp fibres. Sweet clover shives had a lower hemicelluloses content than the shives of flax and hemp. As hemicelluloses are responsible for fiber elasticity (Köhler and Spatz 2002), this finding provides a chemical basis of the rigid and brittle behavior of this material.

Tapped densities

The two fibrous materials had different apparent densities. The finely ground (less than 1% retained on a sieve with 500 μm mesh) samples of cortical fibers of yellow and white sweet clovers had tapped densities of 0.150 ± 0.008 g/cm^3 and 0.160 ± 0.009 g/cm^3, respectively. The finely ground samples of shives fibers from yellow and white sweet clovers had tapped densities of 0.269 ± 0.013 g/cm^3 and 0.288 ± 0.009 g/cm^3, respectively.

Dynamic vapour sorption (DVS) analysis

Plant cell walls consist mostly of polysaccharides. They therefore naturally contain large numbers of hydroxyl groups, which can bind water molecules. The adsorption and desorption curves (Figure 5) resembled those obtained for other plant fibers (Kohler et al. 2006; Xie et al. 2011). The equilibrium moisture content at 90% relative humidity was 19.2 g of water per 100 g dry weight for cortical fibers and 18.9 g of water per 100 g dry weight for shives. The slightly higher affinity for water of cortical fibers may reflect differences in the chemical composition of the two types of fibers. Shives contain fewer hydrophilic compounds (such as proteins and pectins), and more markedly hydrophobic

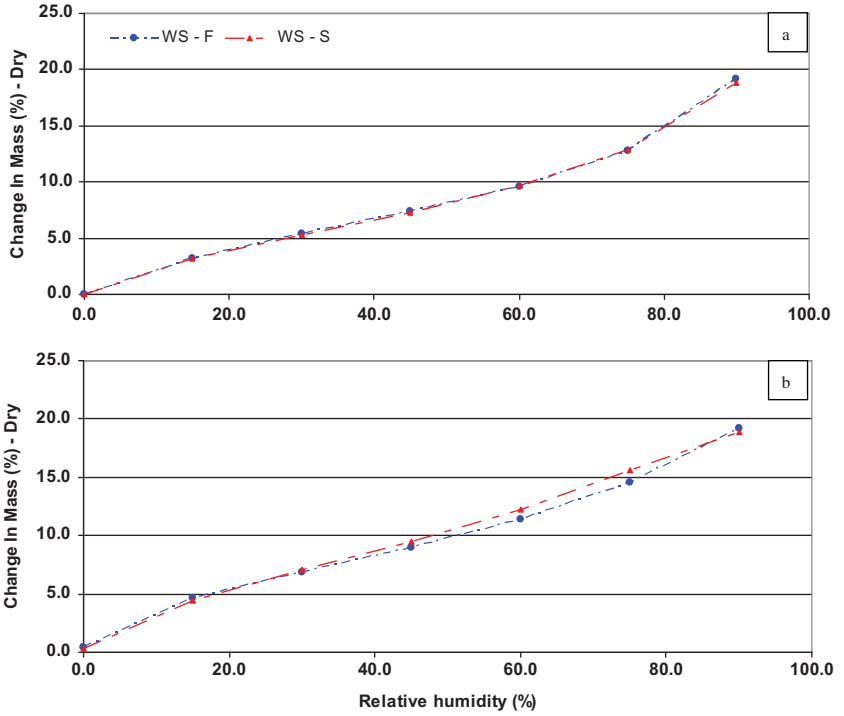

Figure 5. Changes in moisture content as a function of relative humidity during the adsorption (a) and desorption (b) processes, in the isothermal sorption run for fibrous material isolated from sweet clover stems. WS—F: cortical fibres; WS—S: shives.

compounds (such as lignins) (Xie et al. 2011). Hemp and flax bast fibers have equilibrium moisture contents at 90% relative humidity of 25.0 g and 19.0 g of water per 100 g dry weight, respectively (Xie et al. 2011).

The two fractions studied displayed sorption hysteresis. Hysteresis can be influenced by the nature and chemical composition of plant fibers, including their cellulose content and amorphous areas, in particular. Higher levels of hysteresis are associated with stronger interactions between hydroxyl groups and water (Ceylan et al. 2012; Xie et al. 2011). Sweet clover cortical fibers displayed lower levels of hysteresis than shives (1.4–1.7% versus 1.3–2.6%). This difference may be accounted for by the larger specific area on shives (Figure 4e). Hemp bast fibers have a sorption hysteresis of 1.38–1.72% and flax bast fibers have a sorption hysteresis of less than 1.5% (Xie et al. 2011)

Thermogravimetric analysis (TGA)

Yellow sweet clover and white sweet clover displayed similar patterns of thermal behavior. The thermal data obtained with the TGA (Figure 6) indicated that the thermal behavior profiles of the two manually isolated fibrous fractions were very similar to that for the total stem.

The various materials begin to degrade at temperatures higher than 170°C. However, they lost only 1–2% of their dry mass between 170°C and 225°C. These losses can be attributed mostly to the loss of water naturally present in the material (about 9% of the mass), with the remaining 3% of water loss due to the destruction of pectins (which decompose rapidly at temperatures between 180°C and 250°C) and simple sugars. These findings appear to be confirmed by the difference in behavior between the cortical fibers, which are relatively rich in pectin, and the shives, which are relatively poor in pectin (Figure 3b). Between 225°C and 375°C, further degradation was observed, with the stem and the cortical fibers losing 58% of their mass and the shives losing 62%. This further decrease may be due to the destruction of hemicelluloses and some of the cellulose, these compounds being broken down at temperatures of between 200°C and 350°C, and 280°C and 400°C, respectively (Fisher et al. 2002; Yang et al. 2007). Flax and hemp fibers appear to display similar patterns of thermal behavior (Manfredi et al. 2006; Pillin et al. 2011; Yao et al. 2008; Wielage et al. 1999).

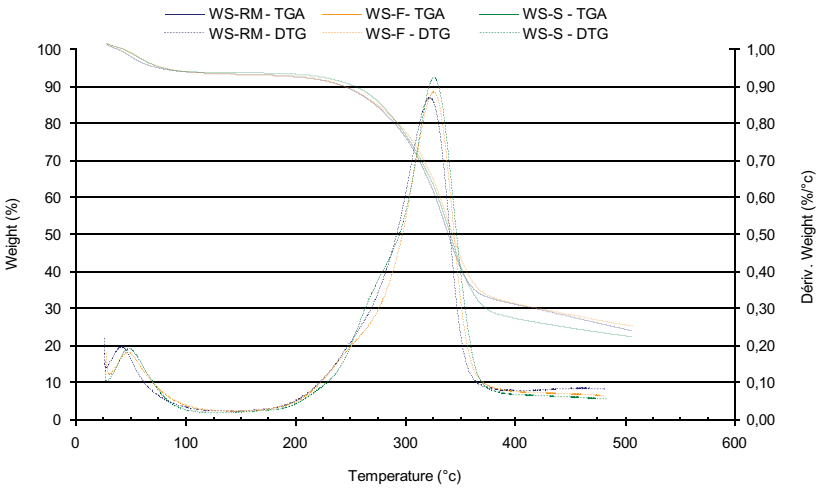

Figure 6. Thermogravimetric data (TGA) and derivatives of the thermogravimetric weight loss data (DTG) curves for fibrous materials from white sweet clover. WS—RM: raw material; WS—F: cortical fibres; WS—S: shives.

Table 3. Agronomic yield—in t/ha.

		Stem (harvested at seed maturity)	Stem (harvested at hay maturity)	Seed
White sweet clover		3.97		0.98
Yellow sweet clover		2.98		0.89
Yellow sweet clover	Frame (2005)		3.25–9.03*	
White sweet clover			5.5–9.4*	
Sweet clover sp.	Baldridge and Lohmiller (1990)			0.78
Sweet clover sp.	Meyer (2005)		2.2–6.7*	0.20–0.67
Flax	*ADEME—Agrice 1998*	7.0		0.9–1.0
Flax	Agreste (2014)	6.68 ± 1.08**		
Hemp		6.10 ± 1.30**		
Hemp	CETIOM (2011)	7.2 à 9.6		0.97–1.43

*Hay: up to 3 harvests/year.
**Yield for seeds and stems.

The thermal behavior and affinity for water of sweet clover fibers are of potential interest for industrial applications. In the plastic industry, the water adsorbed and released by plant fibers leads to changes in size, affecting the linking of the fibers with typical hydrophobic matrix polymers, thereby decreasing the mechanical resistance of composites (Cantero et al. 2003; Kohler et al. 2006). Sweet clover fibers have relatively good water affinity properties and thermal stability at temperatures exceeding 200°C. These two properties suggest that sweet clover fibers may be useful natural fibers for use in composites (cortical fibers), or plastic matrices (shive fibers).

Conclusion

Our findings confirm that white and yellow sweet clovers can grow on estuary soils. Yields were higher for white sweet clover than for yellow sweet clover (Tables 3). Delaying harvest until the seeds had matured resulted in the harvesting of a dry fiber plant that was 160 cm–200 cm tall. Sweet clover stems contain two types of fibers. We assessed the quality of sweet clover fibers in terms of their morphological and chemical characteristics. Histochemical analysis revealed the presence of bast fibers. The morphological structure and chemical composition of sweet clover cortical fibers were similar to those of traditional French fiber crops, such as flax and hemp: the fibers were flexible, light, and essentially cellulosic. Sweet clover shives, resemble the shives of flax and hemp, form a stiff, dense, mesoporous natural material. Sweet clovers are thus a potentially useful new fiber crop suitable for cultivation on wet and saline soils.

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