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Varietal selection of flax over time: Evolution of plant architecture related to influence on the mechanical properties of fibers

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ABSTRACT

The varietal selection of flax (*Linum Usitatissimum* L.) has always focused on specific criteria fulfilling requirements of farmers and textile workers. Thus, the current development of composites using flax as reinforcement presents new challenges for flax breeders in terms of fiber quantities and quality. However, the impact of the varietal selection on the mechanical properties of resulting fibers is yet to be determined. In the present study, several architectural characteristics of flax stems are defined. Stem transverse sections from four varieties selected from the 1940s to 2011 are compared. Anatomical changes over time are highlighted. The most important ones involve the gap between fiber bundles and the amount of fibers which can be improved with the selection (from 7.8% to 13.4% of the tissue area per section). This trend coincides with the increase in biomass production over time expected from the selection work. Moreover, this study demonstrates that flax fibers preserve their good mechanical performances in spite of the anatomical differences. Thus, through varietal selection, it is possible to increase the biomass yield while preserving the excellent specific mechanical properties of flax fibers. Finally, flax fibers can compete with glass fibers to reinforce composite materials.

1. Introduction

1.1. Composites reinforced by flax fibers

Owing to their high-performance mechanical properties, low density and natural origin, flax (*Linum Usitatissimum* L.) fibers are being increasingly used as reinforcement of composite materials to reduce environmental impacts (Le Duigou et al., 2011). The good properties of adherence with polymer matrices (Bourmaud et al., 2012) and recycling possibilities (Bourmaud et al., 2016a; Dickson et al., 2014) make flax fibers even more interesting. Indeed, it is currently possible to guarantee specific mechanical properties able to compete and substitute glass fibers in composite parts (Baley and Bourmaud, 2014).

The use of flax fibers as reinforcement is not a recent innovation. Indeed, in 1937, de Bruyne developed Gordon Aerolite, a composite made of flax rovings impregnated with a phenolic resin matrix (Bakelite). This material was used for aircraft applications during the Second World War (Cotterell, 2010; de Bruyne, 1939). Based on an inverse method, a Young's modulus of about 60 GPa can be estimated for the flax fibers used in Bakelite, which already show good mechanical performances for the period in question.

However, little attention has been focused on the selection of flax varieties producing fibers with high mechanical performances. Recent studies have demonstrated that the performances of final composites could be linked to the mechanical properties of the fibers (Lefeuvre et al., 2015; Martin et al., 2013). Moreover, mechanical studies combined with biochemical analyses have shown that the performances of flax fibers could be related to their composition (Lefeuvre et al., 2014a). Additionally, since these same authors showed that varieties could lead to different fiber compositions, the flax variety could play a key role in affecting the performances of both flax fibers and their composites. From now on, breeders need to pay attention to the criteria of mechanical properties, especially if, as predicted, the use of scutched flax fibers continues to expand for the industrialization of composites.

1.2. History of the varietal selection of flax

Two types of flax have been cultivated for several centuries: oleaginous flax (yielding linseed oil) and fiber flax (also called textile flax). In the case of fiber flax, the plant was originally harvested to extract fibers used to produce clothing or domestic textiles. New varieties have been developed and selected by breeders during the last century. For instance, in Eastern Europe, fiber flax breeding started in 1922 in Lithuania with two varieties, namely 'Dotnuvos pluotiniai' and 'Dotnuvos ilguneliai I' (Jankauskiene, 2014). Meanwhile, in Western Europe, the flax variety 'Concurrent' was selected

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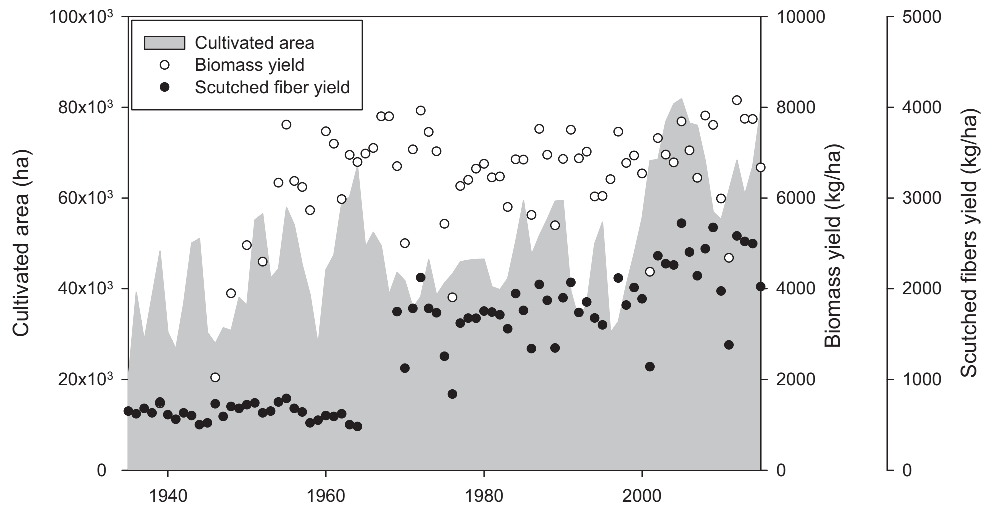

Fig. 1. Evolution of cultivated area, biomass yield and scutched fiber yield of textile flax from 1935 to 2015 (Bert, 2013; Billaux, 1969; Doré and Varoquaux, 2006; Trotel, 2016).

in 1921 by one of the several Dutch agricultural experiment stations (Leeuwarden) (Doré and Varoquaux, 2006). 'Concurrent' was used as a reference until the 1950s (Plonka and Anselme, 1956), when a new selected variety was shown to be superior (Billaux, 1969). The varietal selection, whatever its origin, has always been undertaken to increase the fiber production yield (Jankauskiene, 2014), the resistance against diseases (Spielmeyer et al., 1998) as well as the lodging stability (Gibaud et al., 2015).

In this way, cultivated flax varieties have evolved over time and have been selected, among other purposes, with the aim of increasing the biomass. Fig. 1 gives averages regarding fiber flax culture over the past decades based on several sets of data found in the literature and from personal communication (Trotel, 2016, personal communication). From this figure, it appears that flax culture is on the increase. This is combined with a pronounced rise of fiber yields, while straw yields remain generally stable. Although fluctuations can be seen over time (mostly attributed to severe weather conditions) and a great isolated increase of the scutched fiber yield in the 60 s (attributed to the mechanization of cultural and fiber extraction methods), the tendency toward improved results is very encouraging in terms of quantities required for composite manufacturing.

1.3. Anatomical description of a flax stem

The way of describing the flax section and the vocabulary used to describe its constituents have evolved over time, so the terminology used in this study and the specification of related components are clarified in Fig. 2. Based on this description, it is possible to identify the different tissues forming the stem and fiber bundles at the periphery of the section. Each bundle is itself formed of 15–40 elementary fibers in cross-section. The xylem is located between the cambium and the empty central part referred to as the central lacuna. Thus, the flax stem is a hollow and almost cylindrical component, formed of different successive rings of biological tissues making up the flax biomass. Each of these tissues plays a specific role that remains to be defined. Nevertheless, it is known that fibers are the supporting structure of the stem (Gibaud et al., 2015), making the stem a composite itself.

This study investigates the impact of varietal selection on the properties of the resulting plants and fibers. In this way, an architectural analysis of plants derived from several varieties is first presented. The comparison of four varieties selected over time, between the 1940s and 2011, is performed. Secondly, the mechanical properties of elementary fibers are determined, using conventional tensile tests to evaluate eventual changes in performance between the four studied varieties.

2. Material and methods

2.1. Plant material

Flax samples were provided from Terre De Lin, an agricultural cooperative based in Normandy (France). Four flax varieties were studied: two old varieties that are no longer registered and two currently used varieties. The old varieties chosen here are Liral Prince and Ariane. Liral Prince derives from a selection by the Linen Industry Research Association (L.I.R.A, Ireland) in the 1940s (the exact year is unknown but is assumed to be 1944 (Billaux, 1969)). Ariane was registered in 1978 by the Coopérative Linière de Fontaine Cany (France). These two old varieties were specifically studied as they were largely cultivated with high fiber yields during their respective times (Terre De Lin, personal communication). The recent varieties are Eden (registered since 2009) and Aramis (registered since 2011) selected by Terre De Lin. Eden and Aramis were chosen among others as they give a good compromise regarding productivity, lodging stability and disease resistance. Moreover, they are among the most cultivated varieties during the past few years (Bert, 2013).

Flax plants were all cultivated in France (Saint-Pierre le Viger, Normandy) in 2015. Similar conventional seeding densities were used (Bert, 2013) under identical sowing conditions (same soil and same fertilization treatments). These identical cultivation parameters allow us to draw comparisons in the present study. Moreover, in 2015, the weather conditions could be considered as normal (Lefeuvre et al., 2014b). The plants were pulled out at maturity, when the accumulated temperature received by the plants reaches between 950 and 1100 °C (Bert, 2013). The accumulated temperature has been used for years by farmers to estimate the development and the harvesting time of flax. The formula used to calculate this parameter is:

$$\theta_i = \sum_{i=1}^{n} \left(\frac{\theta max_i + \theta min_i}{2} - 5 \right) \quad (1)$$