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Conventional or greenhouse cultivation of flax: What influence on the number and quality of flax fibers?

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ABSTRACT

Flax fibers (*Linum usitatissimum* L.) are of great interest for textile and composite applications. Thus, their use for industrial purposes requires increasing quantities and constant quality. In general, plants can change their morphology and mechanical properties when submitted to stress, particularly in the case of the reaction of plants to wind, a phenomenon known as seismomorphogenesis. In this paper, the influence of greenhouse or field cultivation on plant architecture and anatomy as well as the fiber yield and mechanical performances of flax fibers are investigated. The results highlight the development of much taller plants under greenhouse conditions, but similar fiber length and number of fibers per plant with both types of cultivation. Finally, the bending stiffness of stems is estimated by three-point bending tests and fiber performances are measured by tensile tests; in terms of mechanical properties at the stem level but also at the fiber scale, there are no statistically significant differences between greenhouse and field cultivated plants. In conclusion, despite the increased plant height under greenhouse conditions (44% increase in total height), fiber yield and properties are unchanged compared to field cultivation. Hence, the greenhouse cultivation of flax does not appear to favor higher fiber yields or quality, but nevertheless maintains compliance with these essential criteria.

1. Introduction

Among industrial crops, flax (*Linum usitatissimum* L.) is probably one of the most ancient plants cultivated for either its seeds or fibers (Deyholos, 2006). Depending on the purpose of its cultivation, flax can be separated in two types, i) oleaginous flax, for the production of linseed oil and ii) fiber (or textile) flax (Goudenhooft et al., 2017). In the case of fiber flax (referred to as “flax” hereafter), the fibers have always been intended for textile manufacturing. Besides clothing and upholstery, a more recent technical application has been intensively developed over the past few decades, involving the use of flax fibers as reinforcement for composite materials (Le Duigou et al., 2016). Within the stem, flax fibers also play a key role as reinforcement, by supporting the plant tissues (Baley et al., 2018; Réquilé et al., 2018) or can even act as ‘plant muscles’ (Gorshkova et al., 2018).

Due to its industrial importance, flax has been subject to thorough varietal selection for about a century, aimed at increasing the fiber yields and the stability of plants to lodging as well as resistance against diseases (Jankauskiene, 2014). One of the current major concerns is the improvement of fiber mechanical properties, to optimize the mechanical performances of composites. Nevertheless, results from the literature show that, even though varietal selection can improve fiber yield, the fiber mechanical properties are only slightly influenced by flax variety (Goudenhooft et al., 2017).

Studies have also been conducted on the impact of mechanically-induced stress (MIS) on plant properties such as yield or anatomy. MIS can be of natural origin, resulting from the action of wind, rain or animals, but it can also be induced indoors, for example by rubbing or brushing the plants (Biddington, 1986). The plant response is termed thigmomorphogenesis in the case of physical contact (Jaffe, 1973) and seismomorphogenesis when it is due to the action of wind (Mitchell, 1975); these responses can differ dramatically between unstressed and stressed plants.

A first example of such responses is the reduction in plant height often observed on plants exposed to wind or other MIS (Biddington, 1986). For instance, it has been shown that wind-exposed trees are shorter and more tapered, but exhibit an overall lower stiffness, even though their mechanical properties are less affected than their morphology (Brüchert and Gardiner, 2006). On the contrary, wheat plants are stronger and less flexible, but show no significant change in stem height under the influence of wind sway (Crook and Ennos, 1996). Seismomorphogenesis also induces changes in plant characteristics such as stem diameter or chlorophyll content, with different responses being observed between species (Biddington, 1986). Besides causing

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morphological and mechanical changes at the stem scale, seismomorphogenesis often leads to a considerable increase of crop yields when plants are grown under optimal conditions in a greenhouse (Grace and Russell, 1977). Thus, the greenhouse cultivation of flax is of interest for the study of fiber yields; in fact, flax is an industrial crop commonly grown in fields, and we might expect changes in morphology and fiber yield when flax is cultivated under much gentler wind conditions. However, no such study of greenhouse cultivation can be found in the literature. Furthermore, little is known on the effect of seismomorphogenesis on the mechanical properties at the fiber scale, which represent an essential criterion for composite reinforcements.

The present study investigates the impact of seismomorphogenesis on flax stems and fibers in terms of architecture, anatomy and mechanical properties. This approach involves a comparison between field and greenhouse cultivated flax at plant maturity. First, this comparison is based on a morphological analysis of flax stems and an estimation of their fiber content. Then, the changes in mechanical performances of flax stems are evaluated by bending tests. Finally, these tests are used to establish a comparison between the tensile performances of elementary flax fibers.

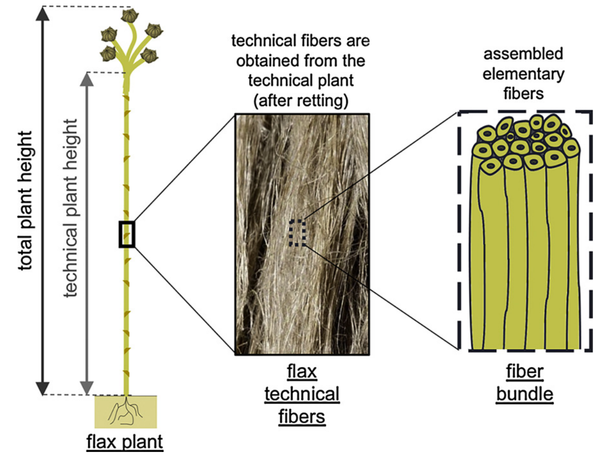

Fig. 1. Schematic diagram defining the different plant heights measured in the present study, illustrating the origin of elementary flax fibers. The elementary fibers are assembled in bundles, forming technical fibers. These latter are extracted, after retting, from the technical part of the stem.

2. Material and methods

2.1. Plant material

Flax plants of the variety Bolchoï (selected by Terre de Lin in 2014 for its high fiber yield, its resistance toward lodging, its ease of cultivation and its triple resistance to diseases (*i.e.* against fusarium wilt (*Fusarium oxysporum*), powdery mildew (*Oidium lini*) and scorch (*Phytium megalacanthum*)) (ARVALIS - Institut du végétal, 2016) were provided by Terre de Lin, an agricultural cooperative based in Normandy (France). All plant batches were cultivated in 2016 at Saint-Pierre le Viger in Normandy (France) without diseases nor pests. A first batch of plants, corresponding to field trials, was grown in fields under normal conditions (*i.e.* without any climatic perturbation such as drought or severe rainfalls (Lefeuvre et al., 2013). Table 1 gives the meteorological parameters recorded in fields in 2016 by the nearby station, as well as average values for the past period ranging from 1981 to 2010 for comparison.

The second batch was cultivated in a greenhouse to restrict the impact of the wind, and the authors assumed that the major differences between both batches result from the seismomorphogenesis. The greenhouse is commonly used by the breeder for the flax varietal selection. Thus, the composition of the soil and nitrogen fertilization used in the greenhouse were similar as the outside. Field cultivated plants were only submitted to natural watering provided by rainfalls, whereas the plants cultivated in the greenhouse were submitted to an artificial watering as well as gentle heating or airing to keep a temperate atmosphere. If the moisture and temperature were not similar as the outside ones, the conditions in the greenhouse were kept as mild as possible, *i.e.* as suitable as possible for the cultivation of flax.

Both batches of plants were pulled out at maturity, *i.e.* attainment of yellow ripeness (Robinson, 1931). Plants were sampled and dried (at 23 ± 2 °C and 50 ± 4% of relative humidity until stabilization of the stem weight) at this step for both architectural and mechanical analysis of the stems.

2.2. Structural analysis of the plants

The total and technical heights of the plants were determined using a measuring tape from 15 specimens per batch. The “technical height” extends from the bottom of the plant to the beginning of the inflorescence, being that part of the plant giving rise to flax fibers, as schematized in Fig. 1.

Basal diameters of each stem were measured at 10 cm height, and the technical diameters were measured at mid-height of the technical stem, from 3 measurements at mid-sample using a caliper. The mid-height of flax stems is a location of interest, since it is known to yield the greatest number of fibers (Tiver, 1942). The “total height-to-basal diameter ratio” is calculated as the total height (in mm) divided by the basal diameter (in mm), used here to estimate the slenderness of the whole plant. However, the “technical height-to-diameter ratio” is calculated as the technical height (in mm) divided by the technical diameter (in mm), used here to illustrate the technical characteristics of flax stems. Finally, total and technical stem weights were measured to allow determination of the total and technical linear weights, respectively.

2.3. Anatomical analysis of stems

Samples of 1 cm length were cut from the middle height of the

Table 1
Meteorological conditions in 2016 and from 1981 to 2010 (when available) corresponding to field trials. Data collected from the nearby meteorological station (Dieppe, France).

	Rainfall (mm)		Mean maximum temperature (°C)		Mean minimum temperature (°C)		Mean wind speed (km/h)	Maximum wind gust (km/h)
	2016	1981–2010	2016	1981–2010	2016	1981–2010	2016	2016
January	117.6	65.8	8.8	7.5	4.4	2.8	22	58
February	107.9	51.5	8.7	7.6	4.1	2.6	23	54
March	57.3	56.7	9.4	10.3	4	4.5	19	65
April	59.8	56.6	12.3	12.3	5.9	5.8	17	40
May	125.8	60.6	21.8	15.4	10	9	16	47
June	51.7	58.6	17.5	17.9	13.3	11.8	15	43
July	7.8	54.7	20.4	20.1	14.6	13.9	15	32