

Impact of the seeding rate on flax stem stability and the mechanical properties of elementary fibres



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ABSTRACT

Cultivation of flax fibres (*Linum usitatissimum*) for composite reinforcement must provide fibres with good mechanical properties, but also a high fibre yield and lodging stability in order to ensure a stable and satisfactory income for the farmer. This work proposes a study of the impact of the seeding rate on these key parameters. We studied the Aramis variety with 4 different seeding rates (1200, 1500, 1800 and 2500 seeds/m²). The results indicate the significant impact of the seeding rate on the stem's morphological parameters; its increase induces a progressive decrease of the scutched fibre length and of the stem diameter. At the same time, the higher seeding rates obtained improved the scutched fibre's yield (+11% between 1200 and 2500 seeds/m²) but, conversely, induced a drop in the elementary fibre's tensile properties and in the flax stem's lodging stability, mainly due to the large decrease in the stem's diameter. This work shows that a compromise must be found to optimize the fibre yield, the mechanical performance and the plant's stability; it underlines the relevance of using a conventional seeding rate, close to 1800 seeds/m².

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1. Introduction

Over the last few years, we faced significant developments in biocomposites; manufacturers are now considering semi-structural applications for these materials that require the use of vegetal fibres that have efficient and reproducible mechanical properties (Lefevre et al., 2014a). In a previous work (Baley and Bourmaud, 2014), we showed that flax fibre, in spite of slight differences from one variety to another, exhibit stable mechanical performances and can compete with glass fibres. Nevertheless, mechanically speaking, some differences exist between fibre batches.

Variations into fibre mechanical properties could be explained by the structure of the fibre and the biochemical composition of the cell walls (Alix et al., 2009; Bourmaud et al., 2013; Roach et al., 2011) and could be due to the flax varieties gene pool (Brutch et al., 2011) but they could also be influenced by environmental stimuli mainly induced by rain or wind (Menoux et al., 1982). The most common features of thigmomorphogenesis on plants are a decrease in elongation growth and an increase in radial expansion (Braam, 2005) but it also has an influence on the quantity and stiffness of

strengthening tissues (Biddington, 1986; Telewski, 1995). Furthermore, the stimuli frequency has an impact on the plant acclimation as well as on their specific responses, particularly on the increase of the stem diameter (Martin et al., 2010).

Amongst other indicators, the involvement of calcium in the early events of exterior stimuli sensing and transduction was found (Bush, 1995; Knight et al., 1991). In the case of flax, Verdus et al. (1997) evidenced that the number of meristems produced is strictly dependent on the intensity of the environmental stimuli received; the meristems production being governed by calcium depletion signals. On *Arabidopsis*, Braam et al. (1997) showed that the TCH gene regulation and expression is a response to environmental stimuli and could lead to an increase in xyloglucan crosslinks with cellulose microfibrils and hence cell wall reinforcement of non-growing cells stimulated by touch or wind. In wood cell walls, xyloglucans play a linking role, between the S2 and G layer (Mellerowicz et al., 2008); in flax cell walls, xyloglucans are part of the non-cellulosic polymer matrix and are mainly present in the primary wall (Morvan et al., 2003).

During the flax growing period, environmental stimuli are mainly due to the sun, wind and rain, which can induce plant lodging. The boundary conditions, i.e., the anchorage quality and the soil behaviour are also preponderant parameters for plant stability and the lodging is highly influenced by the stem stiffness, the environmental stimuli and especially the additional water

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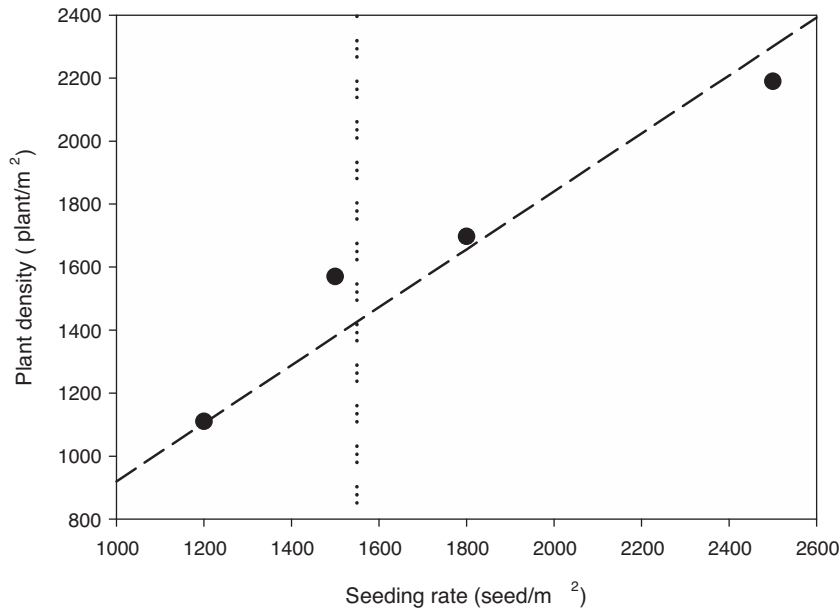


Fig. 1. Relationship between the seeding rate and the plant density. The dashed line represents the case of an emerging plants rate of 92% and the dotted line the recommended plant density (Bert, 2013).

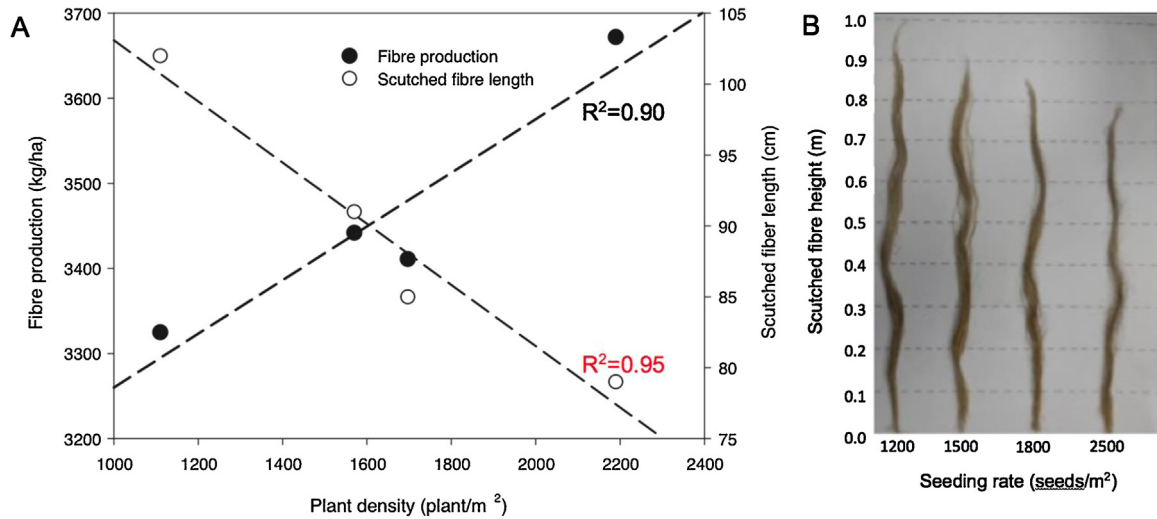


Fig. 2. Impact of the plant density on the scutched fibres yield and stem height (A) and illustration of the scutched fibre length evolution (B).

Table 1
ANOVA one way parameters *P* values indicating the statistical differences between each plant density for elementary fibres Young’s modulus, strength and elongation at break. Bold values are significantly different ($P < 0.005$).

Compared plant densities	Young’s modulus Tukey prob value	Strength at break Tukey prob value	Elongation at break Tukey prob value
1570-1110	2.54×10^{-1}	9.63×10^{-1}	9.68×10^{-1}
1697-1110	7.81×10^{-1}	4.27×10^{-1}	2.35×10^{-1}
1697-1570	8.44×10^{-1}	1.86×10^{-1}	4.48×10^{-1}
2190-1110	3.34×10^{-3}	2.54×10^{-3}	3.60×10^{-1}
2190-1570	3.48×10^{-1}	1.03×10^{-2}	1.43×10^{-1}
2190-1697	8.14×10^{-2}	7.57×10^{-6}	2.99×10^{-3}

weight. Consequently, the distribution of water drops on the plant increases its mass and, with windy conditions, the risk of instability becomes even more significant. The work of varietal selection aims to develop new varieties to increase the production of fibres or seeds but also concerns the behaviour of lodging or disease resistance, which are primordial parameters in order to ensure a

sufficient income for the farmers. In a previous work (Bourmaud et al., 2015), we evidenced that the lodging stability of flax was correlated to the supporting tissues mechanical properties. The lodging stability criteria, which could be optimized during the work of varietal selection, could be assimilated to an indicator of the flax fibre’s mechanical performances. Furthermore, the varieties hav-

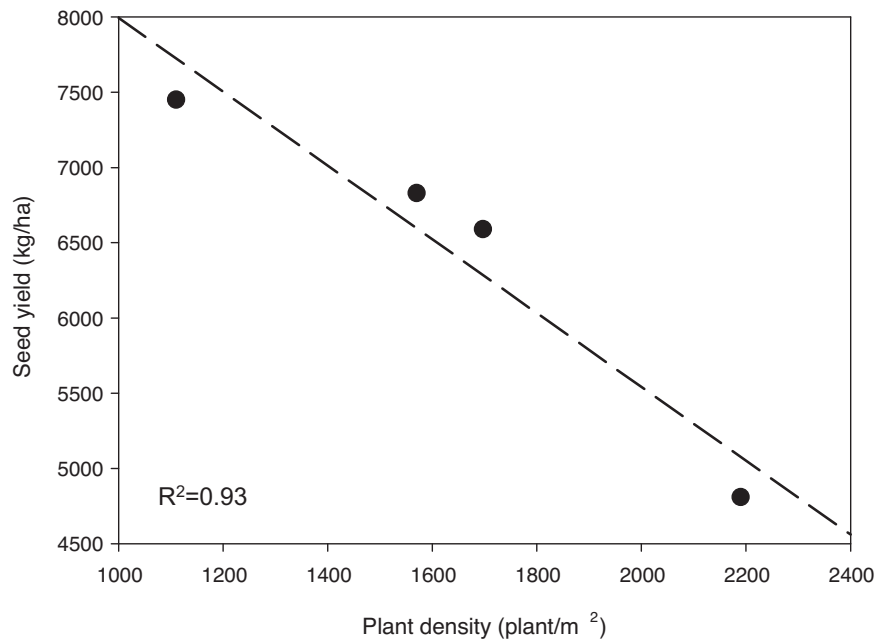


Fig. 3. Impact of the plant density on seed yield.

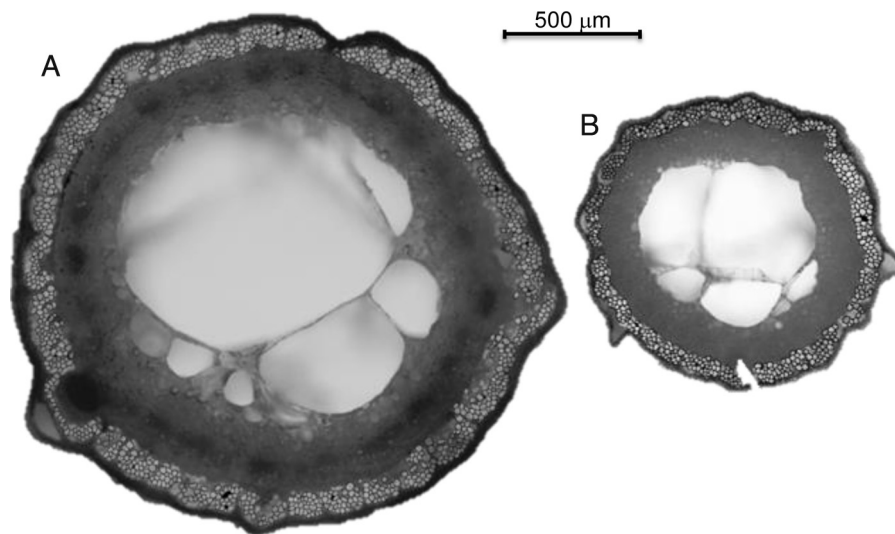


Fig. 4. Aramis stems sections (middle height) for 1110 (A) (diameter = 1.87 ± 0.34 mm) and 2190 (B) (diameter = 0.91 ± 0.22 mm) plants/m².

ing a high lodging resistance generally exhibit a high fibre yield (Bourmaud et al., 2015; Ilea et al., 2001). According to Menoux et al. (1982) the fibre aspect ratio (length divided by diameter) is also a good indicator of the plant's lodging tolerance, underlining the fibre's role as supporting tissue.

The stem and fibre morphology, and consequently the plant's stability are strongly linked to the seeding rate. Indeed, the number of ramifications, leaves, the quality of rooting, as well as the nutrients or water availability are key parameters for the stem's stability and development. For flax, in order to reduce the lodging risk and maximize the fibre yield, the recommended number of plants is approximately 1500/m² (Bert, 2013). In general, an increase in the seeding rate induces a decrease of the stem or fibre length (Easson and Long, 1992) and diameter. The number of ramifications (Agegnehu and Honermeier, 1997; Couture et al., 2004; Gubbels

and Kenaschuk, 1989; Stevenson and Wright, 1996) or capsules (Casa et al., 1999) is reduced, whereas the straw yield increased (Couture et al., 2004; Easson and Long, 1992; Stevenson and Wright, 1996). The increase in the plant's density generally induces a yellowing and a decrease in the number of fibres, especially at the bottom of the stem. In this case, the risk of lodging is increased (Easson and Long, 1992; Gubbels and Kenaschuk, 1989) due to the lower cell wall thickening and to the poor rotting quality. Nevertheless, in the cases of poor or dry soil, a high seeding rate could be a solution to facilitate the plantlet emerging due to its collateral helps.

The aim of this work is to study, for the Aramis flax variety, the influence of the seeding rate on the fibre's mechanical performances and on plant stability. Four seeding rate values were chosen between 1200 and 2400 seeds/m². Firstly, we carried out a detailed

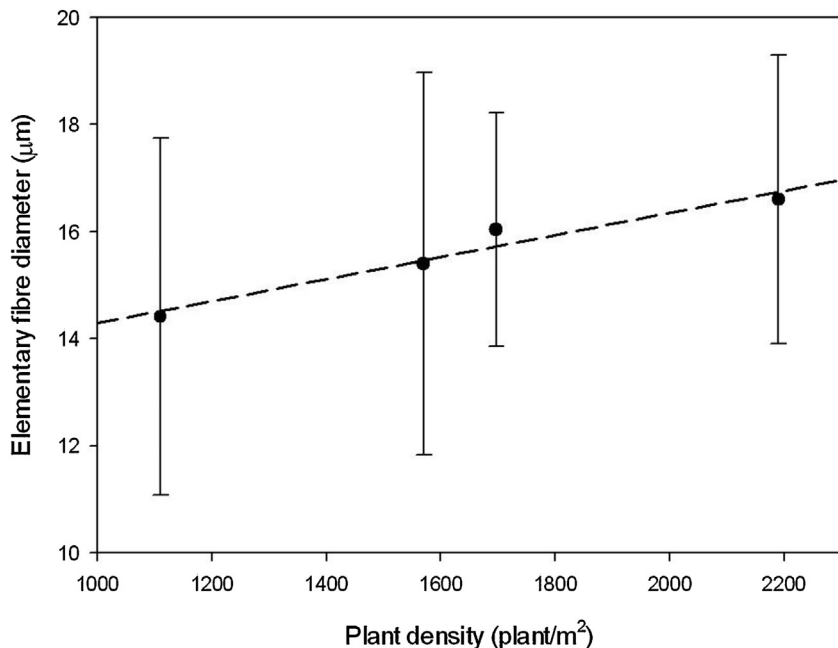


Fig. 5. Relationship between the seeding rate and the elementary fibre diameter (measured from stem cross sections at the middle height of the plant).

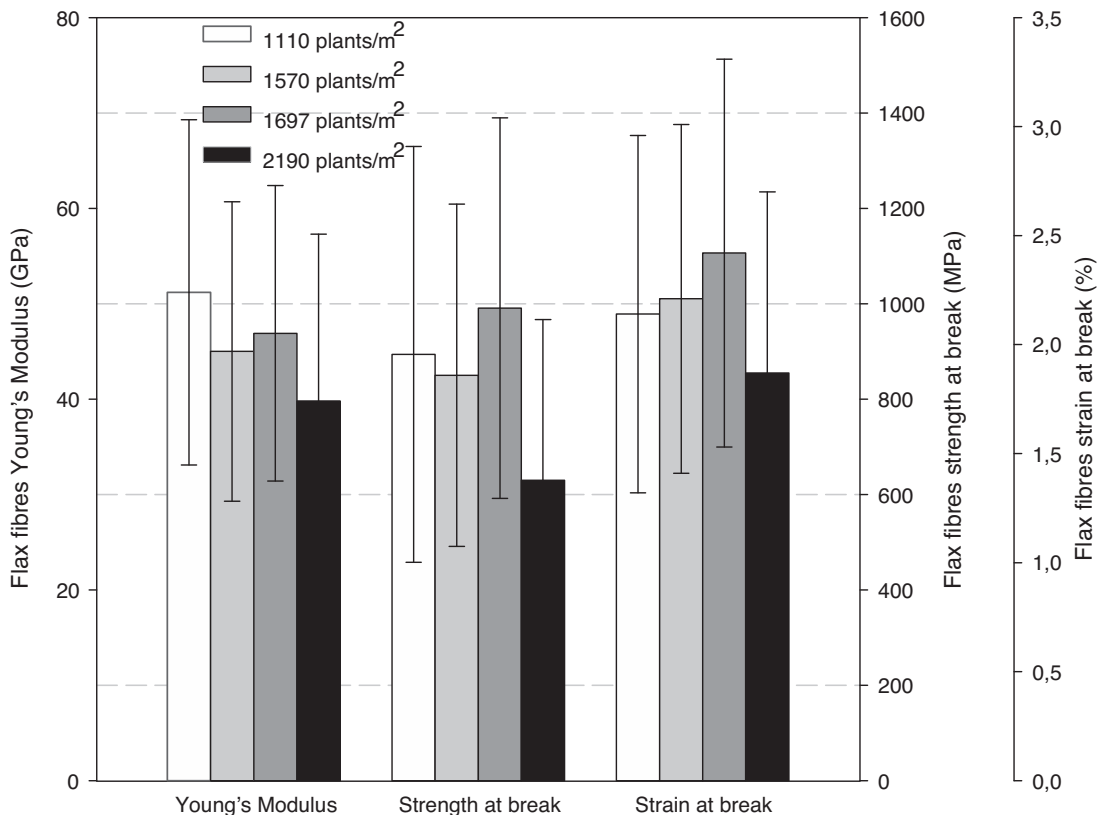


Fig. 6. Impact of the plant density on the elementary fibres' mechanical properties.

morphological and mechanical analysis at the stem and fibre scale. These data were then compared with bending results on stems in order to estimate the lodging stability of the stems; the morphological, mechanical, lodging or yield data were compared to those of other varieties of flax and discussed.

2. Experimental

2.1. Plant material

Eden, TDL 21, TDL 25, Telios and Aramis textile flax varieties, cultivated in 2013 by the agricultural cooperative Terre De Lin

(France), were used for this study. Eden, TDL25, TDL21 and Telios were cultivated with almost the same densities (between 1400 and 1500 plants/m²) which corresponds to the conventional density for flax culture (Bert, 2013). The Aramis variety was cultivated with four different seeding rates: 1200, 1500, 1800 and 2500 seeds/m².

Samples were cultivated on the same plot of land and weather conditions were favourable without any lodging. Before being pulling out, the number of plants per m² was counted. For each sample, dried stems were kept at 23 °C and 50% relative humidity for atmospheric drying; they are named dried stems. The rest of the stems were laid on the soil for dew-retting. After the retting step, plants were scutched to obtain technical fibres used for mechanical characterization; in addition, green stems were pulled out before retting and kept in a freezer (at –18 °C). The long fibres and tows (short fibres) yield after scutching were measured by weight by the cooperative Terre de Lin.

2.2. Tensile tests on elementary fibres

The determination of the tensile properties was made in accordance with the NF T25-501-3 (developed for flax fibres) standard which take into account the compliance of the loading frame. Fibres were manually extracted and they were stuck on a paper frame to have a gauge length of 10 mm. The average apparent diameter (from 6 measurements) was determined under an optical microscope. The frame was then clamped on a universal MTS-type tensile-testing machine equipped with a 2 N capacity load cell, and loaded at a constant crosshead-displacement rate of 1 mm/min up to rupture in a laboratory with a controlled temperature of (23 °C) and relative humidity of (48%). For each sample, at least 50 elementary fibres were tested.

2.3. Morphological analysis of the flax stem sections

Height and external diameter of the stems were obtained using a tape measure and a calliper. The stem weights were obtained by conventional weighing on a laboratory scale. Internal morphology of the stems and characterization of the fibres were performed by using histological cuts as described a previous work (Bourmaud et al., 2015).

2.4. Three point bending test on green flax stems

For each flax stem, bending tests were performed on 15 cm long segments. These segments were weighted before testing. For bending experiments, we used a MTS Synergy tensile machine with a 50 N load cell, a span length of 120 mm and a crosshead speed of 20 mm min⁻¹. Shears effects were assumed to be negligible due to the high span length/stem diameter ratio.

The bending stiffness EI of the stem, the second axial moment and the Young's modulus of the flax fibres were obtained as described in a previous work (Bourmaud et al., 2015).

By knowing the stem stiffness (at the bottom), height and mass, we can estimate the risk of lodging. We observe that, due to the leaf drop occurring after pulling out, the plant weight takes into account only the stem and seed weight. By a simplified approach, we used the critical buckling load of a vertical beam of constant section and subjected to its own weight (loading uniformly distributed), studied by Timoshenko (1940). This critical load P_{cr} is expressed by:

$$P_{cr} = \frac{7.83 \times EI}{H^2} \quad (1)$$

With EI and H , the flexural stiffness and the height of the flax stem, respectively.

Critical weights of the green stems were calculated for the 5 varieties. We assume that the assumption of a real cantilever beam is questionable and this is a simplified approach. Moreover, the anchorage of the stem in the soil does not have a perfect boundary limit and also depends on the humidity content of the soil.

By knowing the real weight of each stem, one can calculate a factor of safety, expressed as the critical weight/real weight.

2.5. Statistical analysis

We used the OriginPro software (OriginLab Corporation, Inc., Northampton, MA, USA) to perform a one-way analysis of variance (ANOVA with means compared using Tukey post hoc test). Each means was considered to be statistically different if a difference of $P < 0.05$ was noticed.

3. Results

3.1. Impact of the plant density on the biomass yield and stem length

Firstly, Fig. 1 shows the relationship between the seeding rate and the real plant density. As expected, the number of emerging plants is well correlated with the seeding rate, especially for the lower values. The difference between the seeding rate and the number of seedlings is between the range of 4.6 and 7.5% for the lower seeding rate, whereas it is 12.4% for the higher seeding rate (2500 seeds/m²), evidencing an increased competition between the seeds. This gap expresses the difficulty, for each seed, to find enough water or nutrients for satisfactory plant growth. For 2500 seeds/m², the germination rate is equal to 87.6% whereas a 92% value is guaranteed by the flax breeders (Bert, 2013) for a seeding rate of 1800 seeds/m², underlining the competition between the plantlets for a high plant density; for the other seeding densities, this germination rate is always respected. Furthermore, in our case, a drilling machine, with 12.5 mm between each line was used; consequently, the entire available surface is not exploited and the seedling yield would probably be higher by using a specific drilling machine; nevertheless the tool used is multipurpose and could be used for other types of crops (wheat, barley or rape for example). We can add, to conclude on this point, that linear seeding could be useful for case of struggling plant growth (dry ground for example), due to collateral help between the plantlets.

Fig. 2 shows the impact of the plant density on the fibre's (scutched fibres + tows) yield and the scutched fibres height. The total amount of fibres produced is between 3320 and 3670 kg/ha and, at the same time the scutched fibre yield increases from 2060 to 2490 kg/ha. These data are slightly higher than usual data (Bert, 2013) but these varieties are cultivated on experimental plots with optimal conditions; consequently their yields are difficult to compare with those obtained from conventional farming. Nevertheless, we note that the quantity of produced scutched fibres by hectare is today approximately 2–4 times greater than in the beginning of the 20th century or in 1970 (Billaux, 1969), respectively, showing the impact of the work of varietal selection.

We can logically observe a significant decrease (from 102 to 78 cm) in the scutched fibre length with the plant density increase, due to the competition between the plants for the access to the resources. As explained by Braam (2005), the thigmomorphogenesis due to stimuli from neighbouring plants induces a decrease in the stem length. At the same time, plants take up the available space and develop numerous ramifications at low seeding rates (7.2 ± 1.2 capsules for 1110 plants/m² and none for 2190 plants/m²); these branches could also play a role in plant stability by ensuring a collateral support between the flax stems. This point is confirmed by

the seed yield, which is negatively correlated with the evolution of the plant density (Fig. 3).

The same time, as shown in Fig. 4, the morphology of the stem is radically different for the opposite seeding rates. Firstly we observe a drastic drop of the stem diameter for the higher seeding rate, being 1.87 ± 0.34 mm and 0.91 ± 0.20 mm, for 1110 and 2190 plants/m², respectively. Consequently, due to the decrease of the stem perimeter, the number of bundles and elementary fibres is highly reduced when the plant density increases; in the middle stem section, for 1110 and 2190 plants/m², we counted 975 and 532 elementary fibres respectively, or 581 and 291 at the bottom level. Interestingly, we observe that, in spite of this morphological evolution, the surface fibre rate within the plant section remains stable (26.1% and 28.6% for 1110 and 2190 plants/m², respectively), showing the adaptation of the plant in order to ensure its stability. Furthermore, when stem diameters are the smallest, the cell diameter increases (Fig. 5), underlining the strategy developed by the plant to improve its stiffness in order to resist lodging (Bourmaud et al., 2015). This diameter increase is not desirable for composite applications; indeed, the lower the diameter of the fibre, the easier it is to obtain good surface contact and stress transfer between the fibre and the matrix.

The increase in the plant's density induces a decrease of the stem length and simultaneously an increase of the scutched fibre yield (+10.4% between the extreme plant densities—Fig. 2). This result is consistent with data obtained by the Flax Technical Institute (ITL) (Bert, 2013); on the Ariane variety flax, they found an improvement of 9.8% in the fibre yield between 1200 and 2200 seeds/m². Thus, interestingly, the fibre quantity drop, due to the stem length evolution and the number of elementary fibres, is positively counterbalanced by the rise in the number of stems and, at a smaller scale, by those of the fibre's diameter.

These various observations confirm that the development of flax plants is very dependent on the environmental context. The selected plants developed a strategy, which results from a complex balance between the height and the diameter of the stems, and supporting tissues (elementary fibres); the final one being to ensure that the stems have a good stability in case of lodging caused by the wind and the rain. The plant elaborates complex structures, as powerful as possible with the space and resources it has.

3.2. Impact of plant density on elementary fibres' mechanical performances

Fig. 6 shows the impact of plant density on the elementary fibres' tensile properties and Table 1 exhibits the Tukey's HSD test by comparing the statistical differences between each plant density for elementary fibres Young's modulus, strength and strain at break. The evolution of tensile stiffness, stress and strain at break follows the same trend for the various sowing densities. A relative stability is observed for the densities of plants ranging between 1110 and 1697 plants/m²; it is followed by a significant decrease for 2190 plants/m².

The Young's moduli range between 46.9 ± 15.7 and 51.2 ± 18.1 GPa, for the three lower densities of plants. These stiffness values are very close and similar to the literature data for elementary flax fibres (Baley and Bourmaud, 2014) and they are not statistically different; the Young modulus presents a significant drop, which is statistically different compared to lower plant densities, for the highest density of plants (39.8 ± 17.5 GPa). Studies have shown that the stiffness values could be impacted by the biochemical composition of the cell walls (Alix et al., 2009; Bourmaud et al., 2013; Lefeuvre et al., 2014b); in our case it is possible that the stress induced by the high density of plants or the low availability of nutrients or water had an impact on the quantity of structuring pectins within the cell walls. In addition, as

highlighted in the first part of this work, the fibres diameters are wider for the highest density of plants (16.6 ± 2.69 mm); literature shows that, in certain cases, the increase in the diameter of the elementary cells causes a decrease in their stiffness (Bourmaud et al., 2010); this point could be a complementary explanation of the decrease in the fibre's mechanical properties.

The same tendency is highlighted for the strain at break of the elementary flax fibres. A significant decrease being observed at a high seeding rate ($1.87 \pm 0.83\%$ against 2.14 ± 0.82 – 2.42 ± 0.99 for the three lower plant densities) evidencing the change in the fibre's mechanical behaviour. Nevertheless, only the comparison between 1697 and 2190 plant/m² is statistically different for the strain. As described for the Young's modulus, modifications to the fibre structure or chemical composition could induce a decrease in the elongation capacity of the cell walls.

The conjugated decrease of the stiffness and strain at break logically has an impact on the stress values. In the same way, the ultimate fibre strength is quite stable and well correlated with literature data (between 850 ± 359 and 991 ± 399 MPa for the three lower plant densities) and exhibits a drop for 2190 plants/m² being 630 ± 337 MPa (–30.9% compared to the average strength of the three lower plant densities). We can notice that this drop is statistically different of the three other plant densities.

Thus, in our case, from a mechanical point of view and as an objective for polymer reinforcement, the sowing density has a low impact on the fibre's mechanical properties until a critical value, which is highlighted in our case, by a significant decrease of the fibre's mechanical properties for 2190 plants/m², especially for the strength at break as underlined by the statistical study. This evolution could be due to a modification of the fibre structure and chemical composition (Bourmaud et al., 2013; Lefeuvre et al., 2014b). Furthermore, it could be induced by a decrease in the nutrients or their low availability because of the competition between the plants or to an adaptation of the fibre properties induced by the decrease in the stem height and diameter; indeed, due to the smaller stem length and diameter, the plant stability could be ensured with less efficient supporting tissues.

3.3. Lodging stability of the flax stems

The lodging stability of the Aramis green stems was investigated; a suitable method to estimate the flax stem stability has been developed in a previous work (Bourmaud et al., 2015). Flexural stiffness was carried out on the bottom part of the stem, this area being preponderant for the plant stability; thus, critical weight and lodging safety factors were calculated for 1110 and 2190 plants/m². The results are detailed in Table 2.

The average values of lodging safety factors for Aramis 1110 and 2190 are 12.7 ± 1.2 and 7.3 ± 2.6 , respectively. Considering that this safety factor is an indicator of the lodging resistance, these values indicate the plants with better lodging resistance that are cultivated at a low plant density, for the same variety. Thus, in spite of an taller height and a similar surface fibre rate in the stem's sections, the Aramis 1110 appears to be less sensitive to lodging. This increase in stability is due to good mechanical properties of the elementary fibres and almost to the stem diameters. Indeed, the average stem diameter at the bottom of the Aramis 1110 and 2190 are 2.62 mm and 1.33 mm, respectively. Consequently, for these two batches, the ratios between the height and the diameters of the stems are 366 and 571, respectively, ensuring an improved stability for 1110 plants/m². These plant aspect ratios are particularly significant when compared to other vegetal species (Niklas, 1995, 1993) and highlight the remarkable mechanical performances of flax stems.

In addition, it is possible to estimate the critical height of the flax stem, which is the maximum height to which a plant can grow

Table 2
Estimation of the safety factor of the green stems.

	Plant length (cm)	Flexural stiffness EI (N m ²)	Stem weight (g)	Critical weight (g)	Safety factor
ARAMIS	96	0.0245	1.58	20.97	13.3
1110	96	0.0312	1.91	26.49	13.9
plants/m ²	96	0.0386	2.98	32.77	11.0
	96	0.0470	3.20	39.97	12.5
ARAMIS	76	0.0016	0.24	0.24	9.2
2190	76	0.0025	0.56	0.56	6.2
plants/m ²	76	0.0043	0.60	0.60	9.7
	76	0.0006	0.22	0.22	4.0

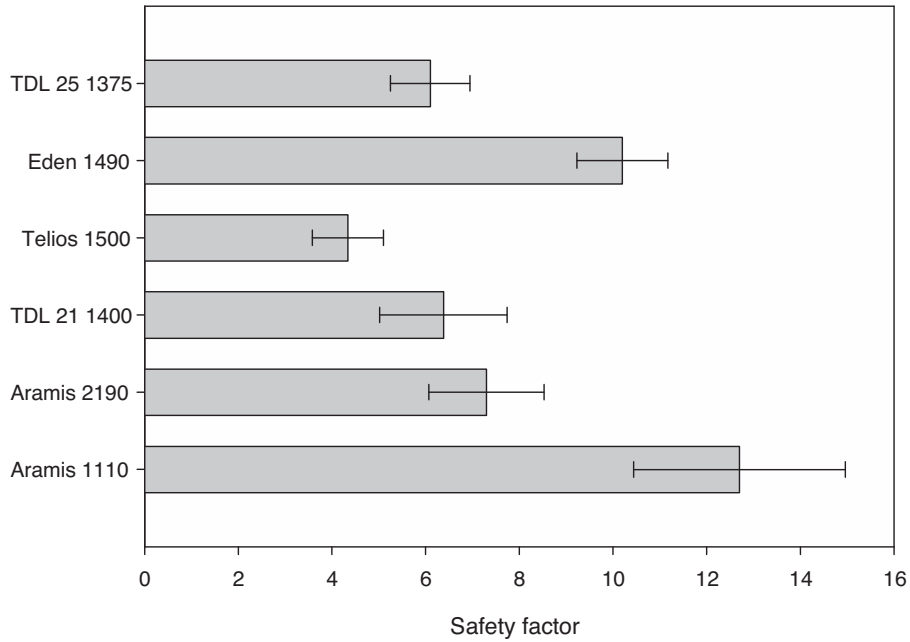


Fig. 7. Lodging safety factors of the green flax stem.

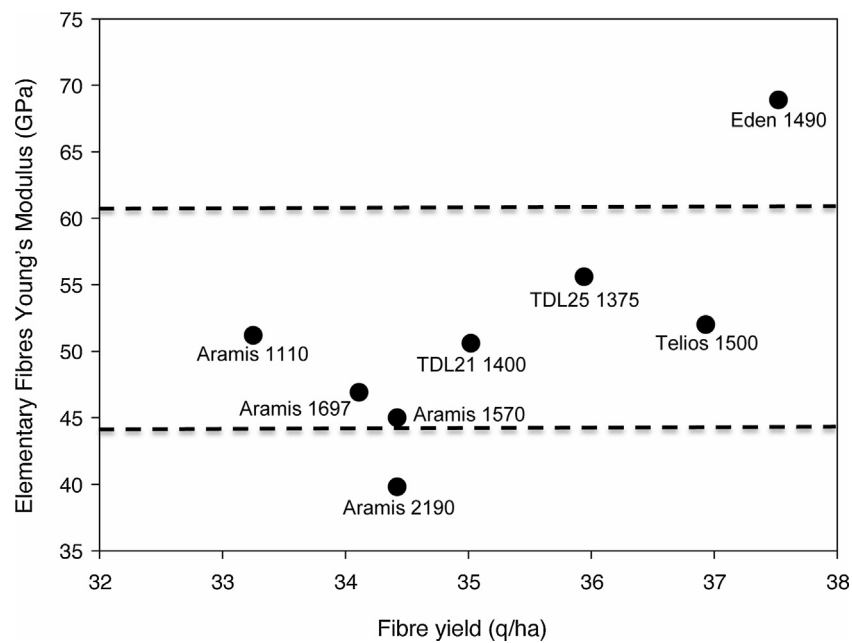


Fig. 8. Fibre yield and elementary fibres Young's modulus of the studied flax varieties. The dashed lines represent the average Young's modulus limits defined by Baley et Bourmaud on 50 flax varieties (Baley and Bourmaud, 2014).

before it elastically wears down under its own weight by using the Greenhill's formula (Greenhill, 1881). This critical height is 0.31 and 0.26 cm for 1110 and 2190 plants/m², respectively. These very low values, compared to the real heights (0.96 and 0.76 cm for 1110 and 2190 plants/m², respectively), evidence the important role of the ramifications and of the neighbouring plants on the flax stems stability. We can observe that some approximations were made for these critical height calculations; the stem diameter is considered to be a cylinder with a homogeneous distribution of biomass all along the stem, which is not the case in reality, the ramifications being mostly present in the top area. Furthermore, the weight of the plants is probably underestimated due to the leaf drop before pulling out; this point induces an overestimation of the critical height and of the safety factor.

The lodging stability of Aramis flax could be compared to those of other varieties. Fig. 7 shows the safety factors obtained from carrying out the bending test on Aramis, Telios and TDL21; additionally, bibliographic data from one of our works on Eden and TDL25 were added (Gibaud et al., 2015). We can observe that the Aramis 2190 lodging stability could be compared to those of TDL25, TDL21 and Telios, which are considered to have poor lodging resistance. Conversely, Aramis 1110 exhibits a high safety factor value, which is in the same range as the best varieties such as Eden (Gibaud et al., 2015).

3.4. Choice of an appropriate flax variety for composite application

Nevertheless, the lodging resistance cannot be the only criteria choice for the flax cultivation; in addition, it is necessary to consider the scutched fibre yield as well as the fibre's mechanical performances, especially for composite reinforcement applications. Fig. 8 proposes a schematic representation of the evolution of the rigidity of elementary fibres according to the fibre yield by hectare (scutched fibres + tows). The densities of emerging plants are indicated for each characterized plant. This Figure collates the data discussed at the same time as in the previous sections (Aramis 1110 and 2190 plants/m²) as well as new original data (Telios and TDL 21) or previously published values (Eden and TDL 25).

In order to ensure the development of flax fibres as a composite material reinforcement, several criteria must be guaranteed. Firstly, the farmer must be able to count on a stable and perennial income; for that, the fibre yields must be optimized as well as their lodging stability in order to avoid maximum losses during the growing phase. In addition, the mechanical performances of flax fibres must be as high as possible in order to support their use as a composite and to aim at the broadest applications possible, of being able to be used in semi structural parts.

First of all, we note that, as explained previously, the quantity of plants by square meter has a significant impact both on the fibre yield and the mechanical properties of fibres. If the density of plants is low (Aramis 1110), the fibre yield is low, which is a brake for the cultivation, in spite of a good lodging stability and the good mechanical properties. On the other hand, a high density of plants (Aramis 2190) induces a slight increase in the quantity of fibres but this advantage is counterbalanced by the poor properties of fibres and the resulting poor lodging stability. Furthermore, high seeding rate generates a low rate of seedlings because of the low availability of nutrients and water, as well as competition between the plants. These data on the Aramis variety are compared with other varieties cultivated with conventional densities of plants, close to 1500 plants/m². We observe that these flax varieties, cultivated during the same period and on the same soil (same year and same climatic conditions) always present better fibre quantities by hectare, which is a paramount point for the farmer. In addition the mechanical properties of elementary fibres are also at least equal to that of

the Aramis variety. The Eden variety is especially distinguished in terms of fibre yield and stiffness. Furthermore, this variety exhibits a performing lodging stability; consequently this variety appears to be an excellent choice both from the farmer's income perspective and for the flax to be used as a composite reinforcement. Nevertheless, we have to bear in mind that these different cultivations were performed in optimal soil conditions; results could be different in more difficult conditions, some varieties being more sensitive to the type of soil. Finally, these results underline the relevance of the conventional sowing density (around 1500 seeds/m²) (Bert, 2013), not only for the farmer's income, but also for the quality of the fibres produced.

4. Conclusion

Throughout this work, we studied the impact of the seeding rate on the fibre yield, on the lodging stability and on the elementary fibres mechanical properties of the Aramis flax variety. Indeed, these three parameters could be considered as crucial choice criteria for the development of flax cultivation as an objective for composite materials reinforcement.

Morphologically speaking, the increase in the number of plants/m² induces a significant drop in the diameters of the stems and of the scutched fibre's length and a slight improvement of the elementary fibre's diameter. Despite this, the high plant concentration enables an increase in the scutched fibre yield, which is a key parameter to ensure worthy incomes for the farmers. The elementary fibres obtained for the higher seeding rates exhibit lower mechanical performances, especially for the tensile strength at break. In addition, these plants have a reduced lodging stability, not only due to the poor fibre mechanical performances, but also owing to their small stem diameter and to the absence of branching.

This original work highlighted the importance of the choice of an appropriate seeding rate to ensure stable and substantial incomes to farmers, but also to grow plants, which have fibres with high mechanical performances and a good lodging stability. We shown that a seeding rate of 1800 seeds/m² is the better compromise long fibre yield, fibre mechanical performances as well as stem stability.

In future works, it will be meaningful to know the stem development speed according to the number of plants. This growing rate can have an influence on the on the number of elementary fibres and their mechanical properties; the quality of the cell wall thickening being dependent on the position in the section but also of the timing of this event during the formation stage.

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