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Hemp (*Cannabis sativa* L.) for high-value textile applications: The effective long fiber yield and quality of different hemp varieties, processed using industrial flax equipment

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ABSTRACT

Industrial hemp (*Cannabis sativa* L.) has great potential as a sustainable source of textile fiber; yet, to develop a viable European hemp-for-textile chain, agronomic practices and primary processing need optimization to current industrial standards. A straightforward approach is to process hemp using existing, modern equipment for flax (linen). Here we extensively evaluated the quantity and quality of fiber extracted from field-retted hemp stems, scutched on the industrial flax processing line. Varieties from diverse European origin (USO 31, Dacia Secuieni, Bialobrzeskie, Futura 75, Carmagnola Selezionata, Santhica 27 and Santhica 70) were sown in randomized field experiments in Belgium, which has a rich long-standing tradition in high-quality linen production. Biomass yield and the quantity of long fiber processed were assessed across three growing seasons (2017–2019; plot size: 15–45 m^2). In 2018, we also determined the quantity of tow (short fiber) and, the quality of long fiber in terms of fiber tenacity and elongation. The quantity of total fiber extracted (i.e. long fiber plus tow) accounted for 36.2% of the initial straw yield, indicating high processing efficiency. Approximately equal amounts of tow and long fiber were extracted. Mean long fiber yield approximated one ton per hectare; yet yield variation between varieties was considerable (range long fiber yield: 0.6–1.4 ton/hectare). Despite significant variation between harvest years in straw yield, the quantity of long fiber extracted held relatively constant. Fiber tenacity of long hemp was overall high and comparable to flax (range: 37.6–45.3 cN/tex). Results indicate that field-retted hemp has potential to be processed into quality fiber on the industrial flax line and, that fiber yield can likely further be improved by genotype selection. Harvest mechanization, focused on the collection of parallel hemp stem portions of appropriate length for the flax scutching line (ca. 1 m), seems warranted to make this approach economically viable. Additional research on the fiber properties following hackling and wet-spinning will be needed to fully explore the potentiality of long hemp as a flax supplement for textile applications.

1. Introduction

Industrial hemp (*Cannabis sativa* L.) is a high-yielding, environmentally friendly fiber crop (Ranalli and Venturi, 2004; van der Werf, 2004), having great potential as a sustainable source of textile fiber. Unlike cotton, world's most popular natural textile fiber, hemp cultivation requires little water and pesticides (Cherrett et al., 2005), and can positively contribute to crop rotation (Venturi and Amaducci, 1999; Amaducci et al., 2015). Moreover, the current excessive demand for the analogous, long flax fiber (linen; Wolfcarius and Hemmeryck, 2020), which is primarily cultivated and processed in Western Europe, combined with increased customer awareness on the environmental impacts of cotton and synthetic fibers (Ellen MacArthur Foundation, 2017), and an increasing public interest in locally produced goods, foster the prospects of hemp as a local source of textile fiber within the growing European bio-based economy.

Yet, the extant European hemp industry is centered on seed production and so-called 'technical' hemp fiber (Carus et al., 2013). For the latter purpose, hemp stems and their primary bast fiber bundles, which run along the outer length of the stem, are chopped into short fragments

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at harvest and, next, disorderly collected and further processed (Amaducci and Gusovius, 2010). This produces a non-aligned short fiber product, consisting of a mixture of chopped, long primary bundles, in addition to the naturally shorter, secondary bast fibers, which develop when plant stalks attain a larger weight (Westerhuis et al., 2019). Technical fiber is apt for non-woven fabrics among other bulk applications such as the production of paper, composites and building materials (Carus et al., 2013). High-quality yarn spinning, however, requires longitudinal processing lines that keep the long, primary fiber bundles intact and aligned during harvesting and eventual fiber extraction (Ranalli and Venturi, 2004; Amaducci and Gusovius, 2010). This, in addition to agronomic practices targeted at optimizing the yield of primary fiber.

The development of a viable European hemp-for-textile chain therefore demands to adopt a different approach, in terms of both agronomic practices and primary processing, focused on the optimization of 'long' hemp fiber produced at the industrial scale. In flax producing regions, a straightforward approach would be to process hemp using existing, modern equipment for flax ('linen'; Ranalli and Venturi, 2004; Turunen and van der Werf, 2006; Amaducci et al., 2008; Amaducci and Gusovius, 2010). To extract or 'scutch' flax fiber, parallelly oriented stems of about one-meter length are first fed into several pairs of breaking rolls which crush the stems and, break and (partly) remove shives (woody core elements). Next, fiber bundles are passed through scutching turbines, which soften and refine fiber bundles and further remove shives. Final products of industrial flax scutching are a high-value, aligned long flax textile fiber and a non-aligned short fiber, called 'tow', which is similar to technical fiber and could be implemented for non-woven applications and short-staple fiber spinning (Sponner et al., 2005).

The efficiency of this industrial extraction process entails the retting of stems (i.e. the removal of pectines). After retting, stems are easier to decorticate, and fiber bundles are cleaner than those obtained from non-retted stems (Sponner et al., 2005; Paridah et al., 2011; Réquilé et al., 2018). Field retting is currently the common practice for flax in Europe and seems also applicable to hemp (Liu et al., 2015; Mazian et al., 2018; Bleuze et al., 2020). For field retting, stems are spread evenly out after harvest and, next, left in the field for a couple of weeks. The combined action of dew, rain, sun and colonization by soil microbiota then facilitates the natural degradation of the pectin-rich middle lamella, thereby loosening bast fibers from the stem and advancing the partial dissociation of fiber bundles. This strictly natural process has a low economic and environmental impact but requires sufficient field knowledge and favorable climatic conditions. Over- and under-retting may affect fiber quality (Müssig and Martens, 2003; Liu et al., 2015; Placet et al., 2017; Mazian et al., 2019).

To date, little work has been done to quantify the effective yield and quality of field-retted hemp extracted on an industrial flax line (Sponner et al., 2005; but see Musio et al., 2018 for an evaluation of long fiber yield in two genotypes). This is probably because the quantity of stems needed to feed an industrial system is not compatible with the dimensions of most field plot experiments. Therefore, estimates thus far are largely based on indirect and/or small-scale approaches (e.g. Sankari, 2000; Bennett et al., 2006; Amaducci et al., 2008; Westerhuis, 2016). Furthermore, biomass and fiber yield are known to vary widely between hemp varieties, agronomic practices and environmental conditions (Bennett et al., 2006; Tang et al., 2016). And, the content and biochemical quality of primary fiber bundles (the source of valuable 'long' hemp fiber) and, stem processability may do so as well (Sankari et al., 2000; Toonen et al., 2004; Eder and Burgert, 2010; Petit et al., 2019; Westerhuis et al., 2019). The yield and quality of hemp fiber, suitable for high-value textile destinations, can therefore be expected to depend upon the genotype(s) and field (retting) conditions investigated. However, data thus far are largely circumstantial.

Here we present a comprehensive evaluation of the scutched fiber quantity and quality of a diverse set of industrial hemp varieties, registered within the EU (USO 31, Dacia Secuieni, Bialobrzeskie, Futura 75, Carmagnola S., Santhica 27 and Santhica 70). We evaluated the influence of genotype and year-by-year variation on biomass accumulation and long fiber yield during three consecutive harvest years (2017–2019). In addition, 'green' bast yield, 'tow' yield and, the quality of long hemp fiber for textile destinations, were assessed for a single harvest year (2018). The research presented was conducted within the framework of the 'Own Grown Hemp' project, which aims at optimizing sustainable hemp cultivation and its processing into high-quality textile fibers for the region of Flanders (Belgium), having a rich and long-standing tradition in flax cultivation and textile production. The project was initiated based on an explicit request from local flax processers and weavers to extend their portfolio with high-quality hemp fiber of local origin.

2. Materials and methods

2.1. Field trial set-up

Field trials were carried out during three consecutive growing seasons 2017–2019 at the experimental farm of HOGENT and UGENT, located in Bottelare (50.96 °NB, 3.75°EL, Belgium). The soil type prevailing at the experimental farm is sandy loam. Different hemp varieties were sown in a randomized complete block design with four replicates ('plots') per genotype at a density of 240 viable seeds per m^2 (~300 seeds per m^2). Seed viability was determined under laboratory conditions prior to sowing (~80%). Sowing was carried out at the beginning of May by drilling seeds at 2−3 cm depth in a rototilled seedbed using an experimental plot sowing machine. The distance between seeding rows was 12.5 cm. Nitrogen fertilization, applied prior to sowing, was estimated at 100 kg N ha^{-1}. Mean monthly temperature and precipitation for the three consecutive growing seasons are presented in Table 1.

Seven fiber hemp varieties, registered within the European Union, were evaluated (i.e., USO 31, Dacia Secuieni, Bialobrzeskie, Futura 75, Carmagnola Selezionata, Santhica 27 and Santhica 70; Table 2). For the growing seasons 2017 and 2019, the effective long fiber yield of field-retted hemp was quantified based on a plot size of 15 m^2 (in four replicates; hence, 60 m^2 per variety). In 2018, an in-depth evaluation was based on a larger plot size of 45 m^2, with each plot being subdivided into three subplots of 15 m^2. One subplot was used to assess a varieties potential fiber yield, based on 'green', non-retted hemp stems ('bast yield' as in Tang et al., 2016; Y_{BAST}). The remaining two subplots (accounting for 120 m^2 per hemp variety) were field-retted and later on used to determine effective long fiber and tow yield following processing on a modern flax line (see below).

2.2. Estimation of fiber yield

Hemp for textile use is preferably harvested around the time of flowering, when primary fiber content is high and lignification is low (Mediavilla et al. 2001, Westerhuis et al., 2019). Flowering state was therefore recorded weekly on 10 representative plants. When 50% of plants of a given variety were flowering, stems were harvested using a double sickle bar mower of 1.5 m width, mounted on a small tractor (see Fig. 1A). The day before harvest, the length and diameter of 10 plants per plot was determined. Diameter was measured at stubble height (10 cm above ground level).

At harvest the above-ground biomass per plot was measured and stems were spread evenly out in the field for dew-retting. Stems were left in the field for five to seven weeks, and turned manually every two weeks, as is recommended for hemp (Mazian et al., 2019; Bleuze et al., 2020). At the end of retting, the straw was greyish-brown and fibers did easily peel off the stem (Fig. 1B). Next, all straw per plot was air-dried and stored in a barn for three to four months. In January-February, parallel stem bundles, cut at a maximal length of 1 m, were decorticated and processed in a nearby industrial flax plant (Van de Bilt zaden

Table 1
Monthly mean maximum temperature, minimum temperature and total precipitation (TP) during the growing seasons at Bottelare (Belgium).

	2017			2018			2019		
	Tmax (°C)	Tmin (°C)	TP (mm)	Tmax (°C)	Tmin (°C)	TP (mm)	Tmax (°C)	Tmin (°C)	TP (mm)
May	21.4	8.9	16.6	**22.2**	8.2	34.4	18.1	**6.9**	43.8
June	**25.8**	13.1	24.4	**24.2**	14.3	**5.0**	**25.8**	12.3	98.8
July	24.9	12.6	69.4	**29.8**	14.1	**12.4**	26.8	13.0	36.0
August	24.5	12.2	82.2	25.4	13.5	76.4	26.7	12.8	36.4

Source: Metinet, meteo-station Bottelare. Values in bold deviate from the long term-average for Belgium (Ukkel).

Table 2
List of origin, sexual type and earliness of tested hemp varieties. Varieties are ordered by earliness (time to flowering).

Genotype	Code	Origin	Sexual type	Earliness
USO 31	USO	Ukraine	Monoecious	Early
Bialobrzeskie	BIA	Poland	Monoecious	Mid-late
Santhica 27	S27	France	Monoecious	Mid-late
Santhica 70	S70	France	Monoecious	Late
Futura 75	FUT	France	Monoecious	Late
Dacia Sequieni	DAC	Romania	Monoecious	Late
Carmagnola S.	CS	Italy	Dioecious	Late

NV; manufacturer: De Poortere; see Fig. 1C). Apart from a reduction in turbine speed from 200 to 120 rotations per minute, no modifications were made to the standard processing settings for flax scutching. Per experimental plot harvested, the initial straw weight, and the weight of long fiber extracted on the flax line were measured. Means per variety were extrapolated to tons per hectare (Mg. ha^{-1}), rendering estimates of 'straw' and 'long fiber' yield, henceforth abbreviated as Y_{STRAW} and Y_{LF} respectively.

The larger experimental plot sizes harvested in 2018 (30 m^2) allowed us to measure the quantity of short fiber (Y_{SF}; see below) at the plot level in addition to the quantity of long fiber processed. To evaluate the effectiveness of processing hemp stems on the flax scutching line, the effective total fiber yield ($Y_{TF} = Y_{SF} + Y_{LF}$), was compared to 'bast yield' (Y_{BAST}), as a proxy of the potential fiber yield. The latter was calculated per hemp variety as the product of the dry-matter yield (Y_{DM}) and the bast fiber content (BFC) of non-retted 'green' hemp stems, determined by decorticating a subsample of dried, green hemp stems between breaking rolls as in Tang et al. (2016; $Y_{BAST} = Y_{DM} * BFC$). Y_{DM} was the product of the fresh weight of above-ground green biomass per plot and its dry-matter content, assessed by oven-drying a subsample of five harvested stems.

The overall influence of harvest year on biomass (plant height, diameter and straw weight) and, long fiber yield (Y_{LF}) was evaluated by a two-way ANOVA, with 'year' and 'genotype' as fixed effects. In 2019, several CS and Santhica 70 plots were insufficiently dry before storage and turned out rotten. These were therefore excluded from further investigation. In addition, in 2017, the two newly bred varieties Santhica 27 and Santhica 70 were not included in our field trial yet. The comparison of biomass and long fiber yield between harvest years was therefore restricted to the subset of four hemp varieties successfully

Fig. 1. Pictures of harvesting (A), retted hemp fiber (B), the flax scutching line (C), scutched long fiber hemp (D) and tow (E).

quantified throughout all three harvest years (i.e., USO 31, Dacia Secuieni, Bialobrzeskie and Futura 75). The influence of genotype on diverse yield performance parameters (Y_{DM}, Y_{BAST}, Y_{STRAW}, Y_{LF}, Y_{SF}) was thoroughly evaluated by one-way ANOVA analyses followed by Tukey post-hoc testing for the harvest year 2018. The latter analysis was based on all seven hemp varieties. All statistical tests were conducted in SPSS 20.0 (IBM SPSS Statistics 20). Yield variables followed or approached the normal distribution.

2.3. Fiber quality analysis

To evaluate the quality of scutched long hemp, mean tensile load and elongation at break of scutched long hemp were measured for each variety harvested in 2018 (see also Sankari et al. 2000), and fiber tenacity was calculated. For comparison, we also tested a sample of field-retted, scutched flax fiber, processed on the same scutching line (yet at the higher, standard turbine speed of 200 rotations per minute). For this purpose, a flax fiber sample of high yet not superior quality was selected based on expert judgement (pers. comm. Bart De Pourcq; variety unknown). Measurements were made according to ISO 5079 (1995). The atmosphere for preconditioning, conditioning and testing was the standard atmosphere as specified in ISO 139 (2005). Fiber bundles were first made finer by hand manipulation up to the level where they fell apart. All manipulations were performed by the same technician. Per hemp variety, mixed across plots, 150 randomly drawn fiber bundles were then tested. Tests were performed using an Instron tensile tester, model 2519-105. The gauge length was set to 50 mm between the 2 clamping points and the pretension value was 0.05 N, testing rate is 5 mm/min to break. Fiber breaking force N) and elongation at break (measured as a percentage relative to the initial gauge length) were recorded. Fiber tenacity was calculated by dividing the mean tensile load per hemp variety, based on 150 tested fiber bundles, (cN) by mean fiber linear density (tex, i.e. mass per length unit). Linear density (tex) is a standard measure of fiber fineness in textile science (Kozlowski, 2012) and was quantified by determining the mean fiber length (km) and weight (g) per hemp variety. As values of fiber length and strength were pooled by hemp variety, differences in fiber tenacity and fineness between hemp variety could not be statistically evaluated. Mean values by hemp variety were therefore visually compared.

3. Results and discussion

Potential fiber yield (Y_{BAST}), estimated as the quantity of unretted 'green' bast, was just modestly higher than the effective total fiber yield (the sum of long fiber and tow yield; $Y_{TF}= Y_{LF} + Y_{SF}$), which proves the effectiveness of the proposed approach. Y_{BAST} in 2018 was 2.83 tons per hectare (Mg ha^{-1}; Table 3), whereas Y_{TF}, which accounted for 36.2% of the initial straw weight, averaged 1.99 Mg ha^{-1} (Table 4 and Fig. 2). Differences between the estimated potential (Y_{BAST}) and, effective fiber yield (Y_{TF}) probably mainly result from retting losses, in addition to dust produced during scutching. We see no strong indications of differences in stem processability between the seven tested varieties (Fig. 2).

3.1. Effect of hemp variety on fiber yield

Long fiber yield (Y_{LF}), the key variable of our investigation, significantly varied between genotypes (Tables 4 and 5). For the harvest year 2018, there were significant pairwise-differences in Y_{LF} between the early-flowering hemp variety USO 31 (0.6 Mg ha^{-1}) and the newly bred, late-flowering variety Santhica 70 (1.4 Mg ha^{-1}; Table 4). Mid-late and late flowering varieties Dacia Secuieni, Bialobrzeskie, Futura 75, Carmagnola Selezionata and Santhica 27 all scored intermediate (see Table 4 for mean values per variety and Fig. 2). Approximately equal amounts of long fiber (LF) and short fiber (SF) were extracted (see Y_{LF} and Y_{SF} in Table 4); yet, differences between hemp varieties in Y_{SF} were non-significant ($P < 0.05$; Table 4). Y_{BAST} varied from 2.17 to 3.47 Mg ha^{-1} (see Table 3 for values by hemp variety and estimated bast content) and straw yield (Y_{STRAW}) from 3.63 to 7.99 Mg ha^{-1} (Fig. 2). Differences in both Y_{BAST} and Y_{STRAW} were also higher in the late flowering genotype(s) (Table 3).

As plants were harvested at flowering, late flowering genotypes, which spent a longer time in the field, reasonably tend to produce more stem mass (Struik et al., 2000; Faux et al., 2013, Tang et al., 2016). Differences between genotypes in flowering time were also relatively constant across the three evaluated harvest years (not shown). Our findings therefore confirm the positive relationship between cycle length and stem yield already described by other authors (Struik et al., 2000; Cosentino et al., 2013; Tang et al., 2016). In addition to the effect of biomass accumulation, between-genotype variation in bast content (range 30–39%, see Table 3) possibly further modulates eventual fiber yield. By example, the best-performing variety in our field trial of 2018 (Santhica 70) had the highest green bast content (see Table 3). Furthermore, the mid-late variety Bialobreskie had a high long fiber yield relative to late varieties Dacia and Futura (see Fig. 3). Disentangling the relative contribution of genotype-specific biomass accumulation over fiber content would, however, require the screening of a larger set of subjects (=genotypes), which was beyond the scope of this investigation.

Comparison of effective long fiber yield with literature is jeopardized

Table 3
Flowering time, days to harvest, plant biometrics and above-ground biomass yield of unretted hemp stems. The mean value per hemp variety for the harvest year 2018 is presented (Bottelare, Belgium).

Genotype	Flowering/ harvest (days)	Plant height (cm)	Diameter (mm)	Y_{DM} (Mg. ha-^{1})	Y_{BAST} (Mg.ha-^{1}; BFC%)
USO 31	58/75	180	6.45	6.14	2.33^{a} (38%)
Bialobrzeskie	74/75	154	5.28	7.32	2.45^{ab} (33%)
Santhica 27	87/89	148	6.30	6.66	2.17^{a} (33%)
Santhica 70	94/97	216	6.81	9.06	3.47^{b} (39%)
Dacia Sequieni	96/97	211	6.72	9.44	3.25^{b} (34%)
Futura 75	99/106	202	6.72	9.86	3.08^{b} (31%)
Carmagnola S.	100/106	237	8.04	10.01	3.08^{b} (30%)

Flowering and harvest time represent the number of days between sowing and flowering or harvesting, respectively. Letters denote significant pairwise differences in above-ground dry-matter (Y_{DM}) and bast yield (Y_{BAST}; $P < 0.05$).

Table 4
Variety mean yield performance of field-retted hemp, processed using industrial flax equipment.

Genotype	Y_{STRAW} (Mg. ha^{-1})	Y_{LF} (Mg. ha^{-1})	Y_{SF} (Mg. ha^{-1})	Y_{TF} (Mg. ha^{-1})
USO 31	3.63^{a}	0.64^{a}	1.09	1.73
Bialobrzeskie	4.01^{ab}	0.76^{ab}	0.81	1.56
Santhica 27	4.66^{ab}	0.86^{ab}	0.95	1.81
Santhica 70	7.06^{ab}	1.43^{b}	1.01	2.44
Dacia Sequieni	6.56^{ab}	1.01^{ab}	1.06	2.07
Futura 75	5.88^{ab}	1.03^{ab}	0.94	1.97
Carmagnola S.	7.99^{b}	1.05^{ab}	1.27	2.32
Mean	*5.68*	*0.97*	*1.02*	*1.99*

Letters denote significant pairwise differences between genotypes ($P < 0.05$). Varieties are ordered by earliness (days to flowering; see Table 3). The percentage of fiber relative to straw is given between brackets. LF = long fiber; SF = short fiber and TF = total fiber.

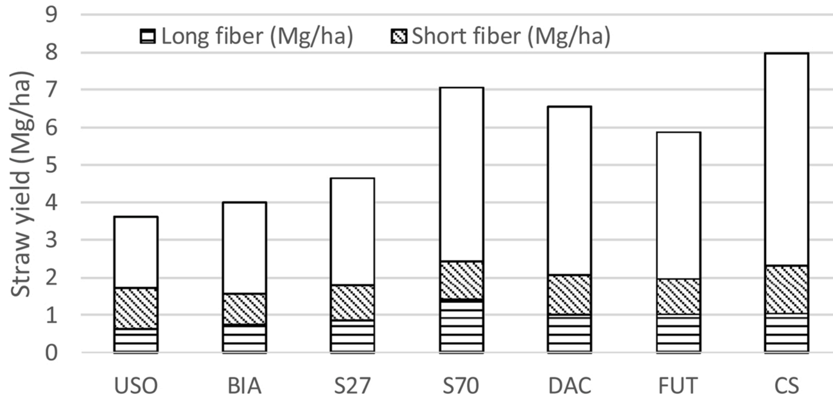

Fig. 2. Fiber yield of seven hemp varieties, grown in 2018. Bars depict the initial straw weight (Y_{STRAW}) by hemp variety; shaded parts show the quantity of long (Y_{LF}) and short fiber (Y_{SF}) extracted following scutching using industrial flax equipment.

Table 5
Summary of two-way ANOVA results. F-statistics of harvest year and genotype on plant biometrics, initial straw weight (Y_{STRAW}) and effective long fiber yield (Y_{LF}).

	Year	Genotype	Year*Genotype
Plant height	134.93***	16.47***	6.57***
Diameter	25.74***	4.47*	5.62***
Y_{STRAW}	26.23***	31.35***	3.16*
Y_{LF}	2.64	7.84***	2.02

* $P < 0.05$; ** $P < 0.01$;
*** $P < 0.001$.

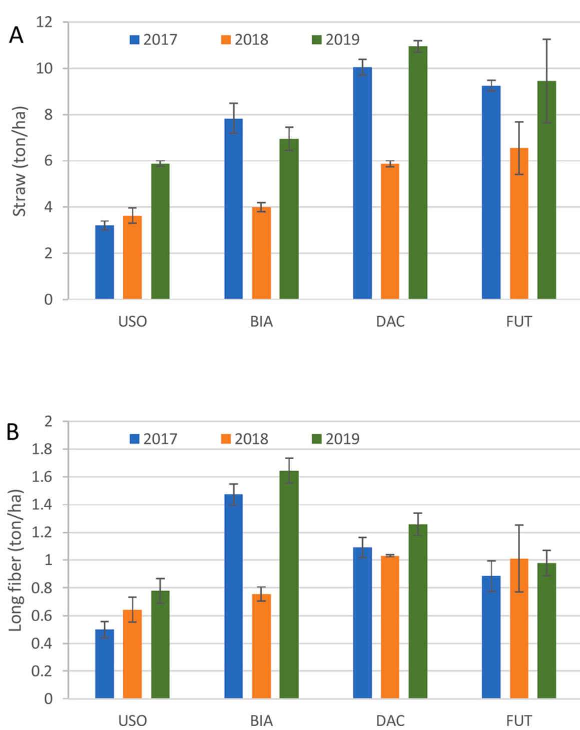

Fig. 3. Between-year variation in mean straw (top; Y_{STRAW}) and long fiber yield (bottom; Y_{LF}). Results shown are based on four hemp varieties (USO 31, Dacia Secuieni, Bialobrzeskie and Futura 75) grown in Bottelare, Belgium during the three consecutive growing seasons 2017-2019. Error bars depict the SEM (standard error of the mean).

by the lack of detailed data for hemp. Musio et al. (2018) found a long fiber percentage of only 2.1% in the hemp variety Futura 75, which was also included in this study. The extremely low scutching yield for Futura 75 was attributed to very moist weathering conditions during field retting, hampering the drying of stems. In Sankari (2000) primary fiber yield estimates were based on lab-scale experiments and did not involve scutching. Estimates ranged from 0.7 to 1.5 Mg ha^{-1}, which is nevertheless highly comparable to the long fiber yield values reported here. Furthermore, our estimates of green bast yield (Y_{BAST}) and, the magnitude of differences between genotypes, are highly comparable to the recently reported values for nearby France but somewhat lower than those reported for Latvia and the Czech Republic (see Tang et al., 2016). Finally, the long fiber yield of our best-performing hemp varieties are somewhat below the values recorded in field trials on the performance of flax cultivars in our study region. The average flax long fiber yield based on 22–24 superior fiber flax varieties, grown in Houtem (Flanders), was 0.7, 2.6, and 2.1 Mg ha^{-1} for the harvest years 2017, 2018 and 2019, respectively (Inagro, 2017, 2018; Inagro, 2019).

3.2. *Yield variability between harvest years*

Analysis of the subset of four hemp cultivars (USO 31, Dacia Secuieni, Bialobrzeskie and Futura 75), evaluated across all three harvest years, showed significant year-by-year variation in Y_{STRAW} and plant characteristics but not in Y_{LF} (Table 5 and Fig. 3). Yearly means of straw mass were 7.58 Mg ha^{-1} in 2017 (tons per hectare; SD: 2.82), 5.02 Mg ha^{-1} in 2018 (SD: 1.67) and 8.64 Mg ha^{-1} in 2019 (SD: 2.69). Pairwise statistical testing showed that Y_{STRAW} was significantly reduced in 2018, which coincided with a reduced plant size at harvest. E.g., mean stem diameter varied much between harvest years (Table 5), ranging from 6.29 mm in 2018 (SD: 0.87), up to 8.44 mm in 2017 (SD: 1.76), and 9.65 mm in 2019 (SD: 2.39). The total mean of Y_{LF} for the four hemp varieties investigated throughout the harvest years 2017–2019 equaled one ton per hectare (0.99 Mg ha^{-1}). Yearly means were 0.99 Mg ha^{-1} in 2017 (or 13.06% of the initial straw weight), 0.86 Mg ha^{-1} in 2018 (17.13%) and 1.13 Mg ha^{-1} in 2019 (13.08%) but did not statistically differ from one another (Table 5). Finally, differences between genotypes in both Y_{STRAW} and Y_{LF} held relatively constant across harvest years, except for the mid-early Polish variety Bialobrzeskie (see Fig. 2 and interaction effects in Table 3), having relatively high but variable long fiber yield. Insert Fig. 3.

In agreement with our results, between-year variability in hemp biomass yield has regularly been reported (see e.g. Höppner and Menge-Hartmann, 2007; Pahkala et al., 2008; Baldini et al., 2020). In our investigation, a prolonged period of extreme drought in June and July 2018 likely halted stem growth (see precipitation totals in Table 1), which caused the observed reduction in Y_{STRAW} (Fig. 2). Furthermore, the yield of long hemp fiber depends on the proportion of shorter, secondary bast fibers relative to primary fibers (Amaducci et al., 2015). Stem size is known to determine the presence of secondary fibers (Westerhuis et al., 2019), with thinner stems containing relatively more of the desired, primary hemp fiber (Petit et al., 2019). The reduced plant diameter of stems harvested in 2018 thus likely mitigated the impact of reduced straw mass on eventual long fiber yield.

3.3. Long fiber bundle quality

Analyses of long fiber bundle properties, in terms of fiber tenacity and fiber elasticity, demonstrated that field-retted hemp, processed using industrial flax extraction technology, renders high fiber quality. Mean fiber tenacity of the seven hemp varieties evaluated in 2018 was 42.13 cN/tex (SD: 2.97), showing relatively little variability between genotypes (range: 37.64–45.30 cN/tex; Fig. 4). For comparison, the fiber tenacity value of a high-quality, field-retted flax sample, scutched on the same flax line (yet at a higher turbine speed), was 37.56 cN/tex (in line with values reported by Kozlowski, 2012). Fiber elasticity, measured as the percentage of elongation at break, averaged 2.22 % (SD: 0.23) and varied from 1.98 to 2.55% (Fig. 4). Fiber elongation was considerably higher in hemp than the tested flax sample (1.31%; Fig. 4), whereas fiber bundle length was highly comparable between the evaluated hemp and flax samples (see Fig. 4 for fiber length). Tex-values, which are frequently used in textile science to express fiber fineness (Kozlowski, 2012), varied substantially between the tested hemp varieties (note: the lower the value, the finer the fiber). Bialobreskie was the finest hemp variety (7.9 tex) and Santhica 70 the coarsest (13.2 tex). The finesses of the other hemp varieties was comparable, *i.e.* 9.3 tex (USO 31), 10.3 tex (Carmagnola Selezionata), 10.8 tex (Dacia Secuieni), 10.9 tex (Futura 75) and 11.3 tex (Santhica 27). The tex-value of the flax sample was 7.9; hence, identical to the lowest hemp score (Bialobreskie).

A direct comparison of our results on fiber bundle quality with literature is difficulted by the limited number of resources available on the fiber bundle quality of field-retted long hemp fiber undergoing a scutching process. In general, bast fibers, such as flax and hemp, are acknowledged to have high tenacity values and low extension at break relative to cotton (Wallenberger and Weston, 2004; Kozlowski, 2012; Bunsell, 2018). A more detailed analysis by Sankari et al. (2000) found overall higher fiber tenacity and elongation at break in a diverse set of hemp varieties, including the varieties USO31, Futura 77 and Bialobrzeskie, which were also part of this investigation. However, their analyses were based on 'green', non-retted fiber bundles, which likely explains the disparity between our values and those reported by Sankari et al. (2000). Anyhow, fiber tenacity of long hemp in our experiments exceeded the high strength of flax fiber, grown and processed under similar circumstances. Hemp fibers are indeed known to be coarser but stronger than flax (53–62 cN/tex in Grundas and Stepniewski, 2013). Furthermore, as flax is known to exhibit suboptimal fiber elongation properties (Kozlowski, 2012), the higher elongation values of field-retted hemp relative to scutched flax fiber can be considered advantageous. The latter finding seems to contrast the current notion that hemp fiber has a lower elongation at break than flax (Jacob John and Anandjiwala, 2007; Grundas and Stepniewski, 2013). For instance, according to Jacob John and Anandjiwala (2007), hemp fiber (of undefined variety) exhibits a low elongation at break of only 1.6 % as compared with flax (2.7–3.2%) and cotton (7–8%; Jacob John and Anandjiwala, 2007). Nevertheless, high elongation values up to 6 %, depending on the harvesting time, were reported by Liu et al. (2015).

4. Conclusions

Results demonstrate that field-retted hemp has potential to be processed into quality textile fiber, analogous to the valuable long flax fiber, using existent flax equipment. Fiber yield appears somewhat lower in hemp than flax; yet, given already considerable variation between the limited number of hemp varieties tested, fiber yield can likely be

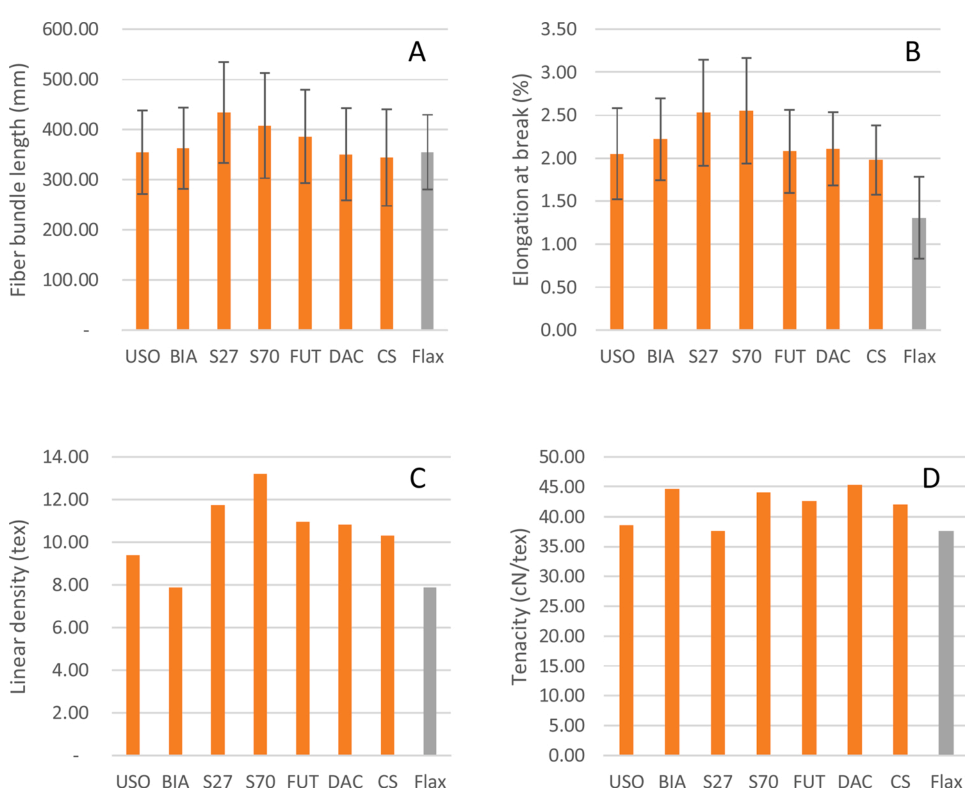

Fig. 4. Fiber bundle quality parameters of the seven hemp varieties investigated (harvest year 2018). The grey bar depicts the mean value of a field-retted flax sample processed on the same flax scutching line. Error bars depict the standard error of the mean for the length (A) and elongation (B) per hemp variety. Mean linear density (fiber fineness) and fiber tenacity values are shown in C and D respectively.

improved by genotype selection. In addition, agronomic practices, targeted at optimizing plant diameter, such as adjusting plant population density, may further advance the primary fiber content and long fiber yield of hemp stems (Tang et al., 2017, Westerhuis et al., 2019). Our findings therefore underscribe the long-standing idea that processing hemp using flax equipment is a straightforward approach to lay out a European hemp-for-textile industry in the short term (Amaducci, 2003). Furthermore, the nowadays very high demand for flax combined with increasing costumer awareness and interest in locally produced goods, may create the momentum for hemp textile fiber produced at the industrial scale.

However, to make this production chain economically viable within industrialized regions, such as the flax-producing countries within Europe, harvest mechanization of hemp stems seems urgently warranted as to reduce labor costs. The automated cutting and collection of parallelly laid hemp stem portions of about one-meter length, which is the appropriate size to feed the current flax line, seems therefore prudent. Furthermore, additional research on the influence of field retting conditions between harvest years and locations on fiber quality, in view of eventual textile destinations, will most probably be needed to minimize variation; and, to provide clear practical field guidelines for farmers. Finally, a thorough evaluation of the quality properties of hemp throughout the next steps of the value chain, i.e. hackling, wet-spinning and weaving, will be needed to fully explore the potentiality of hemp for high-end textile applications, equivalent to flax.

Author contributions

KV wrote the manuscript and performed data analyses. S Vasile assisted in writing and project planning. WV, S Vermeire and MV assisted in practical project planning and conducted most of the field and lab work. AD and JL supervised project funding and, general project management and planning. JL also assisted by managing field work. VT assisted and/or supervised at all stages of the project.

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CRediT authorship contribution statement

Katrien Vandepitte: Writing - original draft, Formal analysis. **Simona Vasile:** Writing - review & editing, Supervision. **Sofie Vermeire:** Investigation, Methodology. **Myréne Vanderhoeven:** Investigation, Methodology, Funding acquisition. **Wouter Van der Borght:** Investigation, Methodology. **Joos Latré:** Supervision, Funding acquisition. **Alexandra De Raeve:** Supervision, Funding acquisition, Conceptualization. **Veronique Troch:** Project administration, Supervision, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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