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Comparing flax and hemp fibres yield and mechanical properties after scutching/hackling processing

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ABSTRACT

Increasing the production of high-performance natural fibres that minimise their impact on the environment is a challenge that flax (*Linum usitatissinum L.*) cannot address alone. In flax traditional production territories, hemp (*Cannabis sativa L.*) can be a complementary source of high added value fibres if their yield of long line fibres can be maximised to levels equivalent to the one of flax. The objective of the present work was to establish process parameters maximising the long line fibre yield using flax dedicated scutching and hackling devices. A lab-scale scutching/hackling device was used to establish sets of process parameters which best improve the long fibre scutching yield and as a consequence minimise the production of tow fibres. Decreases in straw processing transfer and beating speeds during scutching were necessary so that to be less aggressive on the straw and fibres. Very high long fibre yields were obtained after scutching and hackling at the laboratory scale (18 % of the hemp straw mass). These very high results, combined to high straw yield production in the field indicate that hemp can be a very productive source of high-performance fibres as these ones showed tensile properties completely suitable for a textile use as well as for load bearing composite materials. If the potential of high production yields and high mechanical and morphological properties was demonstrated at the lab-scale, this one should be improved at the industrial scale. Suggestions to reach this goal are provided to prevent too high transformation of long fibres into tows and to keep the mechanical potential maximum. When using optimised parameters and a lab-scale scutching/hackling device, it was demonstrated that hemp has the potential for providing equivalent amounts of long fibres per hectare than flax with tensile properties about 20 % lower than the ones of flax.

1. Introduction

In recent years there has been a development in many areas of plant fibre-based materials (Bono et al., 2015), which has led to an ever-increasing demand for flax scutched fibres, particularly in Europe, which produces 80 % of the world production of flax and hemp. A study conducted by ADEME, the French environment agency, in 2015 (Gabenisch and Maës, 2015) predicted that it would be necessary to sow 145,951 ha (ha) of fibre crops in France by 2030 in order to meet the demand. This would represent about 1,000,000 tons of straw (Bono et al., 2015).

In 2018, a total area of only 107,000 ha of textile flax was cultivated in Europe, including 89,000 ha in France (Mahieu et al., 2019). Due to the need for a mild and humid climate (especially to permit good dew retting levels) and long crop rotations with flax cultivation being repeated on the same land only once every six to seven years to avoid soil depletion and the proliferation of diseases (Heller et al., 2014), the traditional flax production areas (France, the Netherlands and Belgium) are at their maximum production capacity and cannot satisfy an ever-increasing demand for flax fibres. It is therefore necessary to find an additional crop to increase the production of high added value fibres for textile and technical applications to reach the targeted surface of 145 000 ha suggested (Gabenisch and Maës, 2015).

In the past, hemp was cultivated for such applications (Clarke, 2010; Fike, 2016), in particular for the rigging of sailing ships. Hemp fibres were used for manufacturing sails and ropes (Bouloc, 2013). A decline in its use during the 20th century led to a sharp decrease in its cultivation worldwide. Hemp cultivation in Europe rose from 15,000 ha in 2013

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(Carus et al., 2017) to 47,000 ha in 2016, of which 16,400 ha in France (Carus et al., 2017). A study conducted by FRD (Fibres Recherche Development) and whose results were published in an ADEME report (Meirhaeghe, 2011) showed that 200,000 ha of hemp is likely to be cultivated in France in the future for different end uses such as fibre, cannabidiol (CBD), shives for building, but this work only investigates the production of long line fibres. Indeed, unlike flax, hemp is adapted to the climatic and soil conditions of most areas of France and Europe, which allows its establishment over a large geographical area (Meirhaeghe, 2011; Müssig, 2010) in Europe or in many places in the world such as China (Amaducci et al., 2015). However, the possibility to perform dew retting advantageously is more favourably conducted in mild and humid areas even though it was shown it can be conducted in many different European climates with increased durations for example (Réquilé et al., 2021). The textile flax production zones in Europe where the extraction capacity by scutching/hackling is already present corresponds to the most favourable zone for dew retting of flax and also for hemp. Hemp could also be favourably inserted within flax crop rotations due to its limited fertilizer and pesticide requirements and for its competition against weeds (Horne, 2020; Piotrowski and Carus, 2011).

In the 19th century, harvesting was performed mainly by hand in Europe and in China (Pari et al., 2015). In Europe, the first machines to perform fibre extraction using breaking rollers and beaters appeared in 1820 (Clarke, 1995; Pari et al., 2015). In Eastern Europe, hemp was mainly cultivated for textiles for its long line fibres and countries such as Hungary and Romania developed specific scutching and hackling devices to extract the fibres. These machines, however, required as input, well-retted stems. Water retting was traditionally performed prior to fibre extraction (Karus and Vogt, 2004). These processing lines could process whole hemp stalks (Müssig, 2010) and very long line scutched fibres (up to 2 m) could be obtained. However, the resulting fibres were subsequently cut into sections of about 70 cm to be hackled on flax machines. These devices are now very old and have been decommissioned for their dependency on water retting that has been banned in most countries due to its high environmental impact (water pollution) and the risk for humans and animals health (Jarrige, 2018). Moreover, the hemp industry in Eastern Europe was labour-intensive, particularly for the harvesting stages and this negatively affects the economic sustainability of traditional value chains.

Indeed, the hemp sector has not been able to draw inspiration from the mechanisation of the flax sector (Bertucelli, 2015) and there is currently no complete mechanised hemp harvesting chain for long line hemp fibre production.

China, for its part, has invested considerable resources to modernise and recreate an economic sector entirely based (in north-east China) on the flax value chain and field retting. This means using flax machinery for the management of the harvesting and fibre extraction. However, this requires that the stem length is shorter than 1 m. In the field a hemp mower, a swath turning machine to homogenise the field retting and an adapted baling system are necessary. A similar production system proved to be technically feasible in the early years 2000 with the "baby hemp" cultivation in Italy (not performed anymore because the system was not economically viable and the farmers were not adequately paid), where stems were kept short by applying an herbicide when the plant was approximately 120 cm high (Amaducci, 2005). In China, manual labour is still used to perform dew retting management and cutting hemp stems in 1 m pieces. If in the past, the numerous attempts to develop hemp harvesters were not completely satisfactory (Gusovius et al., 2016), suitable hemp mowers are now on the market (Chinese and Italian Brands). However, a machine to cut on the field the mown stems is still not available but this is necessary if flax turning and bailing machinery is to be used. This type of machine is under study and advanced prototypes were tested in summer 2021 with a global success even though improvements need to be completed. With the success of such a prototype, a complete value chain could be created using flax processing lines.

Nowadays, hemp fibres for paper pulp, or insulation materials are extracted using hammer mills (Carus and Sarmento, 2017). This process is very efficient but it damages the fibre and reduces its length. Hemp fibre price, used for technical non-structural automotive applications, is generally much lower (0.75–0.80 €/kg in Carus, 2018) than the price of scutched textile flax. However, the mechanical properties of hemp fibres extracted using a hammer mill remain generally low (Placet, 2009; Placet et al., 2012) (285 MPa and 14 GPa for strength and modulus respectively). These fibres cannot be used for load-bearing applications. The possibility to obtain load-bearing grade fibres from hemp would open a complementary market to the one of flax fibres, which is globally saturated and guarantee a higher price than that for the fibres extracted using hammer mills. Ideally, this price should be lower than that of flax long line textile fibres (2–3 €/kg are values given by flax cooperatives such as "Terre de Lin" and are reported in: "Union Agricole" Website (Hennebert, 2019)), too expensive for numerous applications in the automotive or other industries.

As mentioned above, the old East European hemp scutching and hackling lines are no longer operating, and only flax dedicated equipment are available industrially to extract long line fibres. Preliminary scutching and hackling trials of hemp stems on industrial flax lines were performed by (Musio et al., 2018) with low scutching yields of long line fibres and high amounts of scutching tows. Vandepitte et al. also used industrial scutching facilities with some of the process parameters changed for hemp extraction purposes with a wide range of European hemp varieties (Vandepitte et al., 2020). Higher levels of long fibre scutching yields were globally obtained but this one was dependant on the batches/varieties/levels of dew retting. Following scutching, hackling is generally performed to start the division of technical fibres. During this process tows may also be generated. In hemp stems, the mass of fibres represents, depending on the varieties, about 30–35 % of the mass of the stem. To value the hemp straw and particularly its fibres in the most advantageous way, it is essential to maximise the amount of long line fibres obtained at the end of the extraction process.

Main objective of this work is to investigate if hemp could become a source of long line fibre for load bearing composites in complement to the flax ones. To reach this objective, this study proposes to study the long fibre yields obtained at the end of the scutching/hackling process and the quality of fibres (mechanical and morphological properties) that can be obtained. A first set of trials are performed at the industrial scale first, using flax dedicated machines and their associated settings to establish a reference. Then, a laboratory scale scutching and hackling equipment was used to investigate/optimise the scutching and hackling process parameters (settings) to improve the quantities of fibres and maximise their performances. Projections of long fibre yields in conjunction to dew-retted dry hemp stem yields are also given and permit to discuss the future of a complementary value chain in flax territories.

2. Materials and methods

2.1. Plant material

Hemp stems were obtained from a field trial carried out in Italy within the framework of the European project SSUCHY and supplied by the "Universita Cattolica del Sacro Cuore" (UCSC, Piacenza, Italy). The field trial was sown on 2nd April 2019 with the cultivar Futura 75 with a seed rate of 50 kg/ha. Stems were harvested in August (19th), at the end of flowering, and were separated into two batches. The first batch consisted of green stems, i.e., stems that were harvested dried and immediately packaged in bundles. This will be referred to as un-retted material. The second batch consists of stems harvested at the same time as the previous batch and then dew-retted for 3 weeks which was judged as appropriate for a good retting level according to the colour of the stems. All stems were cut into 1 m sections. The total dry biomass (10.6 ton/ha) as well as the biomass that can be used for fibre extraction (first m: 4.7 ton/ha and second m: 2.3 ton/ha of the hemp plant) were measured after drying the stems. Another variety, Fibror 79 (sown on the same date as FUTURA 75) was harvested at full flowering on 26th August. It was only considered as a matter of comparison for some of the measured parameters. The total biomass represents 14.8 ton/ha with 6.3 ton/ha for first m and 3.5 ton/ha for second m. It was cultivated in the same location just near the Futura 75 plot. Textile flax straw yield (Kozasowski et al., 2012) (5−7 ton/ha) is given as a comparison purpose.

2.2. Fibre extraction device

A lab scale scutching/hackling extraction device was used (Taproot Fibre Lab company, Port Williams, Nova Scotia, Canada). It, was used to separate the different plant fractions contained in the hemp stems (fibres, shives and dusts) with the main objective to obtain the long line fibres analysed in this study. The hemp stems are stabilised before testing at 65 % relative humidity and 23 °C (room atmosphere).

This lab-scale scutching/hackling device is composed of three distinct modules. The first one has the function of breaking the wooden part of the stems and allowing a first extraction of the shives and the dust. It is composed of a set of three pairs of corrugated rollers with adjustable distance between centres and speed of rotation. The material obtained is then automatically transported to a scutching system. It consists of two rotating turbines, which rotate in opposite direction to each other. Their role is to beat the fibres and to remove the shives still tied to the fibres. The residence time in the scutching module and the turbine speed are adjustable. Finally, the fibres are subjected to a progressive hackling (combing) stage (with a progressive refinement of the combs) to align the fibres and reduce technical fibre diameter. The hackles or combs are mounted on two rotating belts that can be adjusted in speed. The translation speed of the fibre is also adjustable. Stems from the retted and un-retted batches are subjected to extraction by scutching and hackling using the lab scale device.

An additional part of the fibres from the dew retted stems were extracted using an industrial scale Depoortere (Waregem, Belgium) scutching device and a Linimpianti (Linificio, Villa d'Almè, Italy) hackling machine located at the "Terre de Lin" company (Normandy, France). Fig. 1 shows the different steps of the industrial scutching and hackling of hemp stems. This scutching machine is composed of two distinct devices: a breaking system composed of a succession of horizontal fluted rollers and a beating stage which consists of successive pairs of rotating turbines, with each turbine rotating in opposite direction. The scutching machines are designed to process more than one ton of flax straw per h and globally deliver 250 kg of long line fibres. The hackling machine is a Linimpianti type equipment that was designed to process about 80 kg/h of scutched fibres. It is a fast and high production rate if one compares to traditional Mackie type machines which process globally up to 40 kg/h. For hemp, different settings were specifically applied to the scutching breaking and beating steps, but still with a high extraction speed, close to the one used for flax straw.

The extraction parameters chosen for our device (transfer speed and rotation speed of the scutching turbines and hackle belts) were optimised so that to obtain large quantities in mass of hackled long line fibres. Gentle extraction conditions have been applied by the lab-scale device with a low transfer speed during breaking and a low turbine rotation speed during scutching. Globally, a reduction of the transfer speed by 300 % and the turbine rotation speed by 400 % is applied in comparison to what is classically used in industrial scutching facilities for flax. The actual values used in the industrial flax facilities (Terre de Lin) are confidential and cannot be given here.

As a result, some of the shives remain after the scutching stage, on the contrary to what is observed during industrial scutching. The type of combs and the hackling machine design offers the possibility to remove this wood without difficulty and to obtain clean long line fibres at the end of extraction.

2.3. Lab scale drawing device

Following the stage of hackling and the realisation of a continuous sliver at the end of this process, the large count sliver (high linear mass of about 15,000 tex (g/km)) is submitted to six drawing stages where the linear mass of the sliver decreases in our case up to a linear mass of about 150 tex depending on the settings. The used apparatus is a lab scale drawing system (Linimpianti company, Villa d'Alme, Italy). This device mimics, at a reduced scale, the six drawing/doubling stages used in the flax spinning industry to prepare the slivers into rovings that will be used at the spinning stage. During the different stages of this process, six parallel flax dedicated systems using pin drive devices to bring the slivers and a wooden wheel to perform the drawing ("Gill type") were used. This type of drawing system is also called "gill drawing system". perform the different drawing operations. During this stage, the sliver mass is reduced but it is also homogenised as between each drawing stage, six drawn slivers are each time grouped together before the

Fig. 1. Scutching and hackling principle.
Pictograms rearranged from Müssig and Haag (2015).

following drawing. During these operations, the technical fibre diameter is also reduced when the technical fibres are pulled from the Gill system pins. The fibre diameter obtained at the end of the extraction and preparation processes was therefore investigated and compared for different batches at this stage.

2.4. *Plant fractions*

After processing the hemp stems through the various modules of the lab scale scutching hackling extraction device, several plant fractions are obtained. The shives, which are the woody part of the stems, can be separated from the dust generated during the extraction process and from the long line fibres and shorter fibres, also called tows. Thus, the by-products obtained at the output of each module (breaking, scutching and hackling) are manually separated and weighed in order to determine the impact of the different extraction steps on each of the plant fractions as well as the yields. The study of the impact of the modules on the losses of the plant fractions is important in order to know which elements should be improved to increase the quantity and quality of the fibres. Fibre yield (mass of fibre/mass of straw) is computed at the end of the industrial scutching and hackling equipment.

2.5. *Mechanical and physical properties of the fibres*

In order to investigate the impact of the different extraction steps (breaking, scutching and hackling) on the mechanical and physical properties of the long line fibre, single elementary fibres are extracted after each module. Fibres are tested in tension and the evolution of fibre surface defect is investigated. The results obtained are compared to the initial potential of the material prior to any mechanical extraction.

In the study of the industrial extraction of hemp fibres, fibres could only be collected after the scutching and hackling modules.

2.6. *Extraction of elementary fibres*

To determine the initial mechanical potential of the elementary hemp fibres, prior to any mechanical extraction, fibres are manually extracted. To reach this objective, sections of stems are randomly taken and the bast peeled by hand. The elementary fibres are then carefully separated from the bast after soaking them in distilled water for about 10 s as specified in the NF 25-501-2 standard (NF T25-501-2, 2015).

Fibre samples were also taken after each extraction module of the lab scale scutching/hackling device. Thirty elementary fibres were then extracted from each batch to determine the impact of the various stages of the process on the mechanical properties of the fibres. The number of defects, as well as the morphological and mechanical properties of the fibres were evaluated.

2.7. *Fibre quality measurements*

2.7.1. *Determination of the number of kink-band defects*

The main defects that can be observed on the surface of the fibres are kink bands which can be examined under polarized light as shown, for example, by Baley or Thygesen (Baley, 2004; Thygesen and Asgharipour, 2008). Kink bands are among the defects that can be visible on the surface of the fibres and are expected to be zones of weakness for the fibres as cracks were shown to preferably initiate from these zones (Guessasma and Beaugrand, 2019). They can come from a disorientation of the cellulose fibrils (Baley, 2004) due to some compression or bending loads. The number of kink bands on the surface of thirty elementary fibres for each batch is counted after observation with an optical microscope under polarized light and over a distance of 330 μm. In addition, the area of each of these kink bands is also determined, using ImageJ software following a manual identification of each kink band. The surface tool permits computing the area of the identified defects.

2.7.2. *Determination of the cross-sectional areas of the elementary fibres prior to tensile test*

The elementary fibres extracted from each batch are glued at each end to plastic tabs with a light-sensitive glue (DYMAX, Wiesbaden, Germany) to prevent the fibre slipping during the tensile test. A gauge length of 12 mm is taken for tensile tests.

The measurement of fibre cross-sections is carried out using a device manufactured by the company Dia-Stron (Dia-Stron Ltd., Hampshire, UK) called the Fibre Dimensional Analysis System (FDAS) and controlled by the UV Win software also developed by the company. This type of device permits to accurately determine the diameters of the fibres using an "automated laser scanning" method based on the light shadow (ombroscopy) technique performed using a high-precision laser source and photodetector (LSM 500S, Mitutoyo, Japan).

The fibres mounted on plastic tabs are positioned in the rotating jaws of the FDAS module and held in position by a pneumatic system. By 360 ° rotation of the jaws, the diameter of the fibre is measured over its entire circumference locally. The fibre is then translated and another part of the fibre is scanned over its whole circumference again. This operation can be repeated over the entire length of the sample. In this study, ten measurements are distributed over the 12 mm length of the gauge. As the fibre is rotating, the projected diameters are recorded and the maximum and minimum diameters are extracted to determine the fibre cross section using an elliptical model as recommended for technical fibres by (Garat et al., 2018) who observed that this approach permits obtaining cross section measurements with a higher accuracy than with other models such as the circular model recommended by the NF 25-501-2 standard (Garat et al., 2018). This is due to the fact that hemp fibres are not circular. The measurements are carried out with an accuracy of 0.01 μm.

A more detailed description of the device is available in Grégoire et al. (2019).

2.7.3. *Tensile testing on elementary hemp fibres*

Tensile tests are carried out on thirty elementary fibres from each batch (raw material and after each extraction stage). The device to apply the tension on the individual fibre was developed by the Dia-Stron, company. This is an automated high-precision extensometer (Lex 820, Dias-Stron Ltd., Hampshire, UK) which is equipped with a ±20 N load cell. Displacement is achieved using a step by step motor which permits to control the displacement with an accuracy of 1 μm. This makes the device suitable for fibre breaks with low levels of deformation.

The tests are carried out using a displacement speed of 0.0167 mm/s and a break threshold value of 5 gmf (gram force) (0.05 N) as recommended by the NF T25-501-2 standard (NF T25-501-2, 2015). The deformation selected for Modulus of elasticity corresponds to the one of the Young’s modulus, at the beginning of the stress-strain curve.

2.7.4. *Determination of fibre bundle diameter distribution*

The “fineness” of the fibre bundles is determined using a lab scale type device (Sirolan-Laserscan) based on a laser scan technology proposed by Itecinnovation company (ITEC Innovation Ltd, Cardiff, UK). It consists in cutting the fibres in short length (2 mm) with a guillotine and dispersing them in an alcoholic liquid to prevent their swelling. Fibres are placed in a fluid flow and they are scanned by a laser: when a laser beam illuminates a fibre, a shadow appears on the photodetector. This area is directly proportional to the fibre diameter if one assumes that the fibres are cylindrical. This device, originally developed for wool fibres was modified by the manufacturer and adapted to bast fibres. This device was available at the Terre de Lin company premises (Normandie, France). The tests were carried out on batches of 1000 fibres and a distribution can be obtained.

2.8. *Statistical analysis*

Student’s statistical tests (t-tests) were carried out on the obtained results in order to detect significantly different (batches) in terms of average values for the mechanical and morphological properties between the different extraction stages. A 95 % confidence interval is taken.

3. Results

The results presented below, both at the industrial scale and laboratory scales, were obtained from the Futura 75 straw. Some results regarding the straw yields are also given for Fibror 79 stems as a matter of comparison and discussion, but the straws of this cultivar were not processed at the Laboratory scale. As mentioned in the introduction part, the industrial results are considered as a reference to establish state of the art property levels and the lab scale campaign propose a full study performed on Futura 75 to demonstrate the possibility to increase the long line fibre yields and their associated mechanical properties.

3.1. Industrial scutching and hackling

At the industrial scale, only dew-retted straws of Futura 75 variety were processed.

3.1.1. Fibre yields

The extraction of dew-retted hemp stems on industrial facilities, with process parameters not optimised for hemp, resulted in fibre yields of 9.15 % after scutching and 5.11 % after hackling. After hackling, the long line fibre mass represents in this case only 17 % of the initial fibre mass in the stem. The feed and beating speeds in the industrial scutching module are the ones generally used on flax. These process parameters appear to be un-adapted as very large quantities of fibres (about 70 % of the total mass of fibres originally in the stems) fall in the tows. After analysis, one can observe that a very large part of the scutching tow fibres are long line fibres (Fig. 2). Scutching tows were taken randomly during the industrial scutching process right below the machines. One can observe in Fig. 2a that a large amount of fibre is present. It contributes to about 50 % of the mixture mass (fibres plus shives). In Fig. 2b, the tows, collected at a different moment contain in a vast majority long line fibre (about 85 % of the mixture mass). A more complete analysis of the tows, with a large number of collected samples would be necessary to characterise the amounts of long line, short fibres and shives contained in the scutching tows. One can, however, observe that the mass of fibre is very large and can be represented by large quantities of long line fibres (more than 1 m long technical fibres) that should not fall in the tows (Fig. 2b). Different hypothesis can be formulated to explain this unwanted phenomenon. The first one is the use of too aggressive process parameters as, on the contrary to what was expected, hemp requires lower compression and beating loads than an equivalent mass of flax. Moreover, a special care in the stem introduction at the entrance of the scutching machine has to be considered so that the stems are well ordered in a homogeneous manner. As the stems were introduced manually, this was not the case during these first industrial scale trials. In next trials, the stems will be baled using the flax machinery and the stems should be un-baled using the dedicated machine homogeneously.

Fig. 2. Scutching tows: (a) mixture of shives, short and average length fibres; (b) Shives and long line fibres.

3.1.2. Tensile properties

Tensile properties of single elementary fibres were determined at the output of the industrial hackling. The strength and elastic modulus are 522 ± 296 MPa and 32 ± 15 GPa respectively.

3.1.3. Fibre diameter distribution after scutching, hackling and drawing

After the three industrial processes, a fibre diameter distribution was performed to serve as a basis for comparison with lab scale results. The detailed distribution is given and commented later, but the mean fibre diameter of the technical hackled fibres is 43.1 ± 1.9 μm.

3.2. Lab scale results

Following the results determined at the industrial scale, lab scale work was performed with the objective to increase the fibre extraction yield and the quality (low fibre diameter and high mechanical properties) of the hackled fibre. The results presented in this Section show the different values of experimental campaigns. The data presented here were obtained at the end of process parameter investigations to maximise hackled fibre yields.

3.2.1. Analysis of the stem fractions after each step of the scutching/hackling process

3.2.1.1. Influence of dew retting on the diameter and external aspect of technical fibres. Fig. 3 shows photographs of technical hemp fibres at the output of the hackling process. The fibres extracted from non-retted stems (left) show a coarse appearance with the persistence of large diameters (a mean diameter of 75.8 μm) and pieces of bark. In the case of fibres extracted following a dew-retting protocol (right), the technical fibres are finer (a mean diameter of 52.4 μm) with no bark remaining on the surface of the fibres.

3.2.1.2. Long line fibre yields. Different stem fractions (long line and tow fibres, shives and dust) are obtained when performing scutching and hackling processes using the lab-scale device.

The stem fractions obtained after the processing of the retted and non-retted material through all the extraction modules are presented in Table 1.

For both retted and un-retted stems, the total fibre content (long line plus tow) in hemp FUTURA 75 stem is equal to about 30 % in mass (Table 1). The results presented in Table 1 indicate that the long line fibre mass (after scutching and hackling) represents about 22 % of the stem mass whereas in the case of dew retted hemp, is about 18 %. As a matter of comparison, the amount of long line fibres obtained with textile flax performed using the same lab-scale equipment is of about 25 % of the stem mass.

For dew-retted materials, a lower quantity (as confirmed by statistical tests) of long line fibres could be extracted from the stems compared to the results obtained for un-retted material. A difference of about 18 % is observed between the non-retted and retted batches.

The results obtained in this study showed that the quantity of fibres obtained at the end of hackling is lower for the field retted fibres compared to what is extracted from the green material. A difference of about 18 % is observed. This is mainly due to the fact that retting

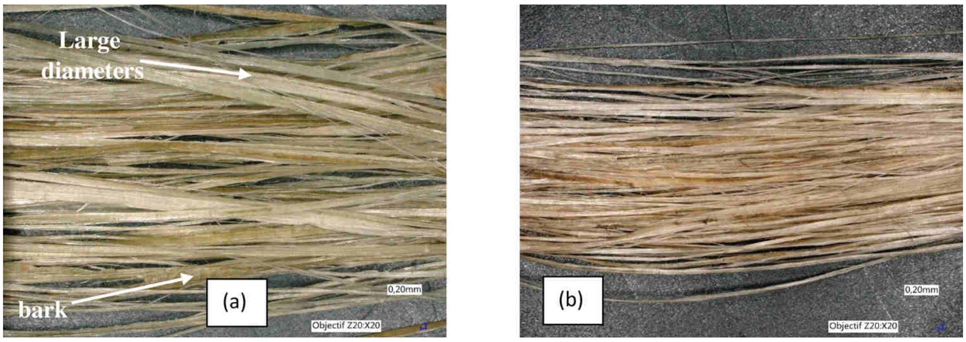

Fig. 3. Example of non-retted fibres (a) and retted fibres (b).

Table 1
Mass yields of plant fractions (FUTURA 75) obtained at the output of the hackling device.

	Fibre content (%)			Shives content (%)	Dust content (%)
	Long line	Tows	Total		
Non-retted hemp	21.9 ± 0.9	8.2 ± 0.8	30 ± 2	69 ± 2	0.9 ± 0.7
Retted hemp	18.1 ± 0.8	12 ± 1	30 ± 2	69 ± 1	0.9 ± 0.5
Statistical difference	a	a	b	b	b

Statistical test (Student tests): Letter a indicates a significant difference between the non-retted and retted parameters, letter b indicates no significant difference.

degrades substances such as pectin contained in the middle lamella binding the fibres together (Bleuze et al., 2018; Bourmaud et al., 2019). The retting process has for effect to ease the extraction of tows (short fibres of about 100 mm in length) from long line fibres, mainly during hackling. So, it can be expected that the retted hackled fibres contain fewer short fibres that the un-retted ones. Even if there is a decrease in yield compared to green material due to the fact that the technical fibres are of a smaller diameter and therefore contain fewer middle lamellas in their structure, composites manufactured afterwards will show higher mechanical properties. In the case of un-retted material, the fibres are coarse (large diameter technical fibres including several individual fibres and middle lamellas) and may have pieces of bark on their surface. The presence of this bark is a negative point in the manufacture of composite materials. In fact, the areas where bark is present can be areas of weakness at the composite scale (Derbali et al., 2018). For garment textiles, these fibres cannot be processed as such and require further processing such as degumming. Enzymatic degumming was investigated in the past and the different environmental considerations requiring the treatment of water effluents and cost of enzymes do not permit this process to be industrially and economically competitive (van der Werf and Turunen, 2008). Thus, it is therefore more judicious to favour extraction over retted (dew-retted in our case) material.

3.2.2. *Study of the extraction behaviour of green and field retted hemp*

In this part, the different elements (long line fibres, tows generated during the fibre extraction steps are analysed for both green and field-retted stems.

During breaking, the shives constitute 99 % of the stem mass loss. One percent of the mass is dust and no fibres are lost during this step. Only shives and dust are lost from the stems. During beating, the broken shives fall as well as some tow fibres (7 % of the total mass of the products eliminated from the long line fibres during scutching). This signifies that the amount of scutching tow is relatively low.

The amount of fibre lost from the long line ones during hackling is higher than for the two previous process steps and are presented in

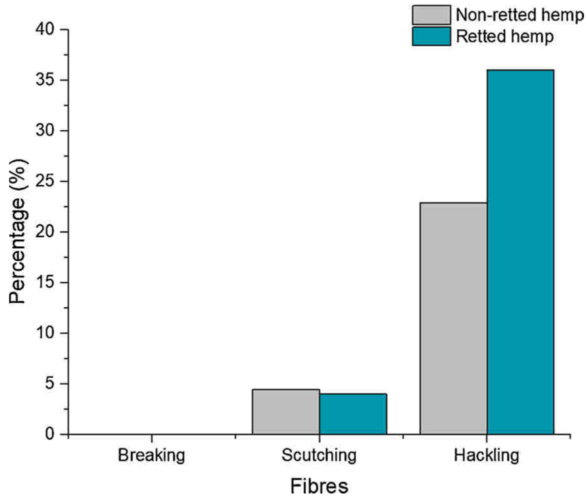

Fig. 4. Fibre losses during the different processing stages for un-retted and dew retted hemp stems.

Fig. 4. The hackling tows constitute in our case of study for dew-retted material 56 % of the fibre mass at the entrance of the hackling device. In addition, it has to be noted that shives are remaining at the end of the scutching device. These shives are eliminated during the hackling step. At the output of the scutching/hackling process, the long line fibre mass from the dew retted stems represents 60 % of the total fibre mass originally contained in the stem. This large proportion of long line fibre is due to the fact that no fibres are lost during breaking and only a small amount of fibres are transformed in tows during beating (4 %). The vast majority of the fibre are lost during hackling as represented in Fig. 2.

Shives, dusts and short fibres are also separated from the long line fibres at different steps of the scutching/hackling process. The shives are lost during the breaking, beating and hackling stages. For retted stems, an equivalent quantity of shives is evacuated during breaking (45 %) and scutching (beating) (43 %). However, there is still a significant amount (12 %) of remaining shives in the long line fibres before hackling, even if it is in smaller quantities compared to the results obtained for un-retted material (20 %). The remaining shives contained in the scutched fibres are eliminated during the hackling stage but the shives are then mixed with the hackling tows that constitute a valuable source of fibres (Müssig et al., 2020). Carding steps can be used to separate the shives from the tows, but damages to the fibres may happen (Ouagne et al., 2017).

In the case of dusts, an equivalent quantity is extracted during the breaking and hackling stages. It seems to come mainly from the breakage of the shives during breaking. In addition, during hackling, the finest fibres break and create a fine dust (Gregoire et al., 2019).

3.3. Comparison of industrial and lab-scale results

The extraction of retted hemp stems on the Terre de Lin's industrial facilities, with process parameters not optimised for hemp, resulted in fibre yields of 9.15 % after scutching and 5.11 % after hackling. The long line fibre mass represents in this case only 17 % of the initial fibre mass in the stem. This is considerably lower than what was obtained with the lab-scale equipment. One can observe in Table 2 that a significant amount of long line fibres is retained after lab scale scutching (28.90 % of the total fibre amount or 96 % of the initial fibre mass in the stem) and after hackling (18.15 % of the total fibre amount or 60.5 % of the initial fibre mass in the stem). This globally corresponds to the values of flax fibre extraction during which about 60 % of the fibre mass is long line fibres and 40 % is tows.

The difference of fibre yields is due to the feed and beating speeds in the industrial scutching module, which are 3 times higher than those used in the laboratory and this leads to long line fibre quantities about 3.5 times lower after hackling. The industrial parameters used at the scutching level are too aggressive and un-appropriate for the fibre extraction of hemp. Softer and probably slower production speeds, as performed at the lab-scale, need to be tested so that to improve the industrial scutching yield and as a consequence the amount of long line fibres obtained after hackling.

3.4. Hemp fibre production yields perspectives and comparison to flax

The previous part indicates that a very large amount of long line fibres was obtained at the end of hackling at a level that is much higher than was obtained at the industrial scale. If these results (lab-scale) are combined to the ones of straw yields given in Part 2.1, production yields perspectives may be proposed and these ones may be compared to flax lab-scale and average results from the literature at the industrial scale.

18 % of the dew-retted hemp stem mass can be transformed into long line hackled fibres. This corresponds to 60 % of the fibre mass originally contained in FUTURA 75 stems. In textile flax, about 25 % of the stem mass is transformed into long line fibres after lab scale extraction. If the yield of long line fibre is higher for flax than for hemp, it is important also to compare the biomass produced in one hectare. In average, a farmer produces about 5–7 tons (Horne et al., 2010) of retted flax straw/ha, whereas one may produce more hemp straw (about 8–14 tons/ha (Höppner and Menge-Hartmann, 2007)). In the frame of this study, the hemp dry biomass for the Futura 75 that is not a cultivar dedicated to fibre production (dual purpose cultivar for seeds and fibres) is 10.6 tons/ha. If one considers 6 tons/ha of available straw (Part 2.1) with 25 % of long line hackled fibres for flax (Table 2) and 7 tons/ha of straw (Part 2.1) with 18 % of hackled long line fibres for hemp (Table 2) corresponding to the first two m that can really be used during hemp scutching and hackling, it would give about $6 \times 0.25 = 1.5$ tons/ha and $7 \times 0.18 = 1.26$ tons/ha of long line hackled fibres for flax and Futura 75 hemp respectively. Another hemp cultivar more dedicated to fibre production (Fibror 79) gave dry biomass yields of 14.6 tons/ha and stem yields (first two m) of 9.8 tons/ha (Part 2.1). Considering these data, with a hackled fibre yield of 18 %, a mass of $0.18 \times 9.8 = 1.76$ tons/ha would be obtained. This means that the quantity of long line fibres obtainable at the end of the hackling unit could be about comparable or larger for hemp than for flax, at least if one considers the lab scale equipment with their associated settings that lead to 18 % of long line hackled fibres.

The amounts of long line fibres reached at the end of hackling are much higher in this study at the lab scale (18 %) than in Musio et al. (2018) (between 2.1 % and 7.6 %) for the dew-retted material for industrial scutching and hackling using the traditional flax process parameters. Vandepitte et al. (2020) performed industrial scutching following a manual field management including dew retting. Scutching yields of about 17 % were obtained following a procedure using settings adapted to the hemp fibre extraction without communicating them for FUTURA 75 cultivar. If one considers similar hackling yields than in (Musio et al., 2018), or the hackling yields of this study obtained at the industrial scale (50–60 %), they should have obtained hackling fibre yields between 8.5 and 10 % of their stem mass. This is much higher to what was obtained in this work and from (Musio et al., 2018) using industrial equipment. Their good results at the industrial scale show that, as the authors (Vandepitte et al., 2020) indicate, they paid attention to use different process parameters more appropriate than the ones of flax. They however did not indicate them.

If the long line fibre quantity that could be extracted from one hectare of hemp can be higher than the average one of textile flax, this is due to the fact that the scutching step carried out on the lab scale device with "soft" parameters results in almost no long line fibre loss. Gentle extraction conditions have been applied by the lab scale device with a low transfer speed during breaking and a low turbine rotation speed during scutching favours high scutching yields. This is about three times lower in comparison to what is applied in industrial machines set up for flax for the transfer speed and four times lower for the beating speed.

Hemp thus has the potential to give high long hackled fibre yields as demonstrated using the laboratory line. The next step now consists in obtaining such results at the industrial scale with the flax scutching and hackling lines. A complete study should be carried out to evaluate the possibility of obtaining high long line fibre yields at the end of scutching by minimising the long line fibre fall during this process. The main hypothesis for the very high transformation of long line fibres into tows during industrial scutching is the too aggressive process parameters used at the industrial scale. These parameters, adapted and used for flax are not adapted to hemp which is more delicate and requires lower compression and beating loads. This is actually confirmed when the same hemp batches are processed at the lab-scale with "softer" parameters with low processing speed. Of course, a compromise has to be found in a very near future between the amount of long fibre losses (transformed in tows) and the processing speed. During hackling, about 40 % of the scutched fibre mass is transformed into tows. This is also the case for flax depending on the process parameters and quality of the fibrous resource. So, the main difference observed between lab scale and the industrial scale is at the scutching stage and the fibre yield can be much improved. Work on the process parameters is necessary to avoid the very large fibre quantity losses during industrial scutching performed in this work.

3.5. Fibre diameter distribution after scutching/hackling and drawing

An analysis of the distribution of technical fibre (or fibre bundle) diameters was also carried out after six drawing steps using the lab scale drawing equipment on the industrially extracted material and on the one processed at the laboratory to investigate the level of fibre division (Fig. 5). The drawing process has the objective to align the fibres and increase their separation level. First of all, the average fibre diameter obtained at the end of drawing for both types of extraction is relatively close (44.3 ± 2.4 μm for laboratory extraction versus 43.1 ± 1.9 μm for industrial scutching/hackling). Following a statistical test, no significant difference was found between the mean fibre diameter values, for both batches. A large majority of the fibres are small in diameter, even though

Table 2
Comparison of fibre yields after industrial and lab-scale extraction, dew-retted stems: mass of fibres/total mass of stems.

	Fibre yield (%)	
	After scutching	After hackling
Retted hemp Lab-scale extraction	28.90	18.15
Retted hemp Industrial extraction	9.15	5.11
Ratio lab scale/industrial scale	3.2	3.5
Flax labscale (this work)	40	25
Flax industrial scale (Kozasowski et al., 2012)	25	15

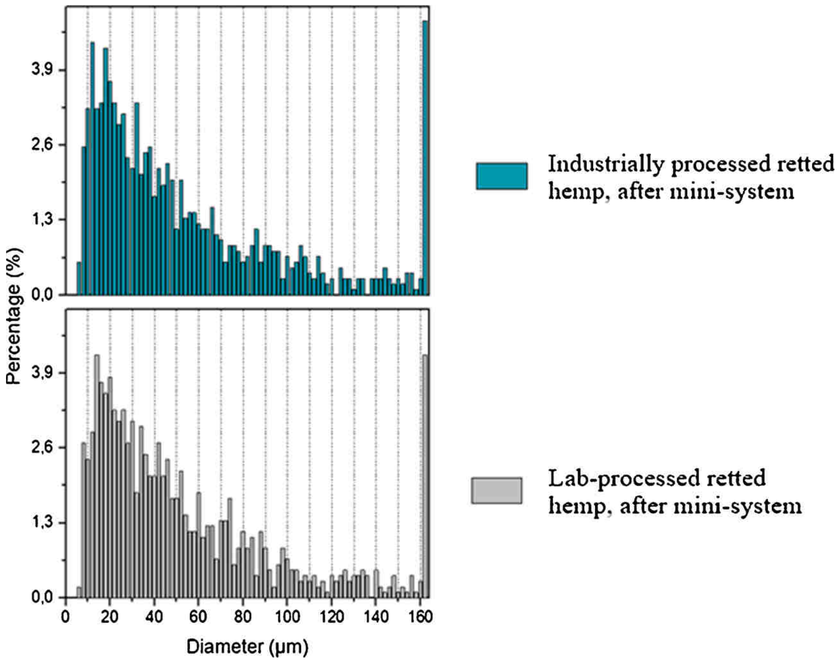

Fig. 5. Technical fibre diameter distribution after drawing after industrial extraction (top graph) and lab scale (bottom graph) extractions.

there is still the presence of medium diameter fibres but in smaller quantities. These results indicate that the fibre morphological properties are globally equivalent following the lab scale or industrial scale extraction process. The average level of division presented in Fig. 5 is a little bit higher than what is generally required for fine garment textiles (25−30 µm). However, in the case of composites, this level of division is sufficient, especially if the fibres keep their mechanical reinforcement potential intact.

3.6. Mechanical properties of hemp fibres impacts of extraction processing steps on the mechanical properties of individual fibres: green and dew-retted material

3.6.1. Laboratory scale scutching/hackling

As far as the un-retted material is concerned, the following steps (scutching and hackling) do not have a significant impact on the mechanical properties in comparison to the reference fibres manually extracted (Fig. 6), either for breaking stresses or modulus. When extraction is performed on retted material, the scutching step has a significant impact on the strength and modulus compared to the breaking step (Fig. 7). However, as a large part of the fibres weakened by the scutching stage are eliminated during hackling and transformed into hackling tows, this explains the slight rise in modulus observed at the hackling stage (Fig. 7). In this case, the modulus and breaking strength after hackling are not significantly different to the ones determined after the breaking step (statistical tests Fig. 7).

The tensile property analysis also shows that dew-retting has no significant impact on the strength and modulus of the fibres after hackling (Fig. 8).

Student's tests have also shown that there is no significant difference between the fibres obtained at the end of hackling and the reference material, both for retted or un-retted stems. The mechanical potential of the elementary hemp fibres is not affected by the scutching/hackling steps and the level of tensile property and modulus of elasticity (875 MPa and 49 GPa respectively). This is globally lower than the potential of flax fibres extracted manually and reported in the literature (Bourmaud et al., 2019) by about 20 %, but highly sufficient for load bearing composite use. The properties obtained in this work cannot be compared directly as very few studies considered the tensile properties of hemp fibres after scutching and hackling extraction. In most of the studies, the fibres were extracted by hand or with more aggressive devices such as hammer mills, (Placet et al., 2012) or (Gregoire et al., 2019) a mechanical fibre opener. The tensile properties obtained in this work are also larger than the ones obtained by Liu et al. (2016) for hemp extracted manually, therefore showing the quality of the fibre extraction. The hackled hemp fibres can be used as a supplementary and complementary

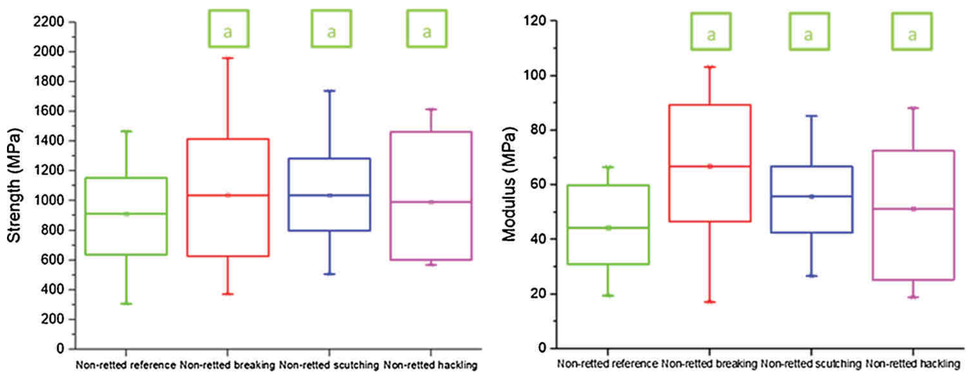

Fig. 6. Mechanical properties of non-retted fibres (a: no significant difference from the reference material; b: significant difference with the reference material).

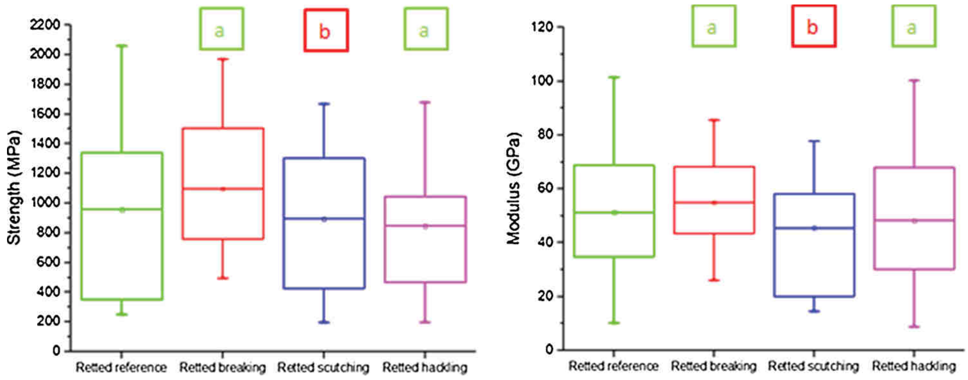

Fig. 7. Mechanical properties of retted fibres (a: no significant difference from the reference material; b: significant difference with the reference material).

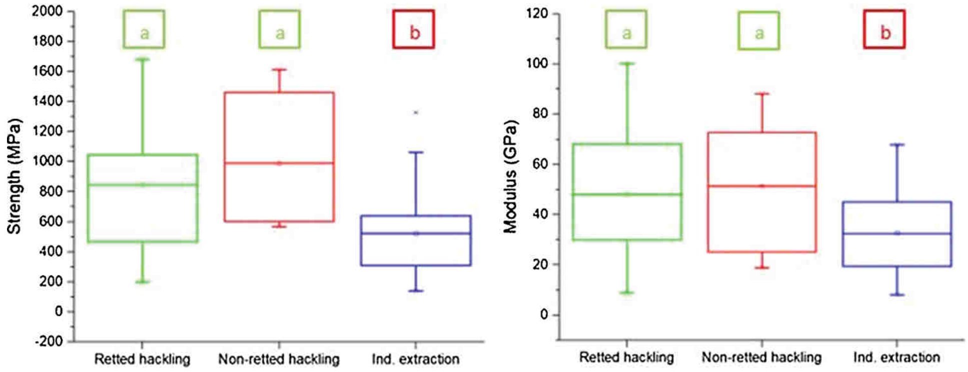

Fig. 8. Comparison of mechanical properties after lab scale hackling (first two boxes) and after industrial hackling: (A: no significant difference from the reference material; B: significant difference from the reference material).

source of reinforcement material.

3.6.2. *Comparison with industrial scale scutching/hackling*

The results obtained at the end of hackling are also compared to those collected at the end of industrial scutching/hackling devices carried out on retted stems from the same batch as the one extracted on the lab-scale device.

Fig. 8 shows that industrial extraction has a strong and significant impact on both the modulus and the strength with strong decreases (about 35 %) compared to extraction on the lab scale device. At this stage, it has not been possible to identify which process is the most damaging (scutching or hackling) for the fibres in comparison to the lab scale. Both processes are expected to contribute to the fibre property loss in comparison to the lab scale results. In any case, the process parameters used at the industrial scale are expected to be too aggressive and probably damage the fibre by generating defects on their structure.

In order to confirm these observations, an analysis of the kink-band defects observed on the fibres at the end of hackling for the two batches extracted with the lab scale and industrial scale equipment was carried out. The results presented in Table 3 show that the number of kink bands varies little from one batch to the other. When the scutching/hackling of the retted material is carried out industrially, there is still no significant difference in the number of defects in the fibres, but the percentage of the fibre surface occupied by the kink bands has been increased (Fig. 9), but still insignificantly, from 12.2 % to more than 17 % (on average on all the tested fibres). Industrial scutching/hackling therefore probably causes larger defects on the fibres and this may explain the decrease in both modulus and strength for industrially extracted fibres.

To improve both fibre yield and tensile properties after industrial extraction, the authors recommend to reduce the processing speed especially with well-retted stems which are more delicate and to introduce the hemp stems as homogeneously as possible. The magnitude of the processing speed will depend of the hemp level of retting, but a reduction by a factor ranging from 1.5 to 2 (which is a compromise between the lab-scale processing speed and industrial one) is recommended and needs to be tested in next trials. Of course, the reduction in scutching speeds will lead to a reduction in the rate of production. However, it should be considered that the decrease in speed should be accompanied by an increase in the long line fibre yield and the preservation of mechanical properties adapted to load-bearing composite materials, which is not currently the case. With such improved process parameters and way of introduction of the stems it is expected to improve both fibre yields and tensile properties of the fibres to values close to the ones of flax.

Table 3
Impact of treatments on kink-band numbers and areas.

Batch	Number of kink bands (/330 μm)		Surface of kink bands on the fibre (%)	
Non-retted lab-scale extraction	Mean (SD)	11 (± 7)	Mean (SD)	13.6 (± 11.4)
Retted lab-scale extraction	Mean (SD)	10 (± 7)	Mean (SD)	12.2 (± 10.2)
Retted industrial extraction	Mean (SD)	11 (± 5)	Mean (SD)	17.2 (± 7.3)

4. Conclusions

This work demonstrates that long line hemp fibres can be advantageously extracted using laboratory scale flax dedicated scutching and hackling equipment. It also shows that the long line fibre yield is high and as hemp field generally produces more biomass than a flax field, larger quantities of long line fibres could be produced. As the tensile properties and the fibre division of the obtained hemp fibres are

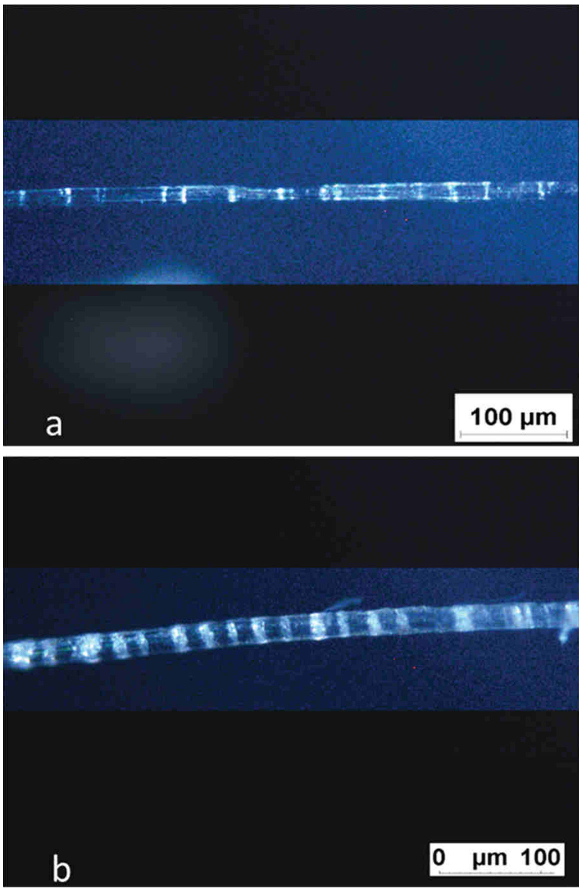

Fig. 9. Example of kink- band area between lab-scale (a) and industrial extraction (b).

completely satisfactory for load-bearing composite materials, they could be considered as a complementary source of fibre for such applications. If the potential of high production yields and high mechanical and morphological properties was demonstrated at the lab-scale, this one should be very much improved at the industrial scale, but this work gives elements and suggestions to reach this goal. With such progresses, hemp crops could be inserted within the flax cultivation rotation in the traditional flax production areas. This would open the possibility to increase the production of high-performance bast fibres to complement the fibre offer of the flax industry. As the long line high mechanical property natural fibres are in very high demand hemp could constitute an income at least equivalent but probably superior to the one of traditional crops such as wheat (Triticum aestivum) or barley (Hordeum vulgare).

CRediT authorship contribution statement

Marie Grégoire: Conceptualization, Data curation, Formal analysis, Investigation, Visualization, Writing - original draft, Writing - review & editing. **Salvatore Musio:** Formal analysis, Investigation, Writing - review & editing. **Vincent Placet:** Funding acquisition, Project administration, Supervision, Writing - review & editing. **Mahadev Bar:** Formal analysis, Investigation, Writing - review & editing. **Emmanuel De Luycker:** Methodology, Supervision. **Stefano Amaducci:** Funding acquisition, Project administration, Supervision, Writing - review & editing. **Pierre Ouagne:** Conceptualization, Project administration, Supervision, Funding acquisition, Visualization, Writing – Original draft, review & editing, paper coordination, Corresponding Author.

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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