Composites Part C: Open Access 2 (2020) 100010

Contents lists available at ScienceDirect

Composites Part C: Open Access

journal homepage: www.elsevier.com/locate/jcomc

Review

Transdisciplinary top-down review of hemp fibre composites: From an advanced product design to crop variety selection

Jörg Müssig[a,*], Stefano Amaducci[b], Alain Bourmaud[c], Johnny Beaugrand[d], Darshil U. Shah[e]

[a] *The Biological Materials Group, Biomimetics, Hochschule Bremen - City University of Applied Sciences, Neustadtswall 30, 28199 Bremen, Germany*
[b] *Department of Sustainable Crop Production, Università Cattolica del Sacro Cuore, Via Emilia Parmense, 84, 29122 Piacenza, Italy*
[c] *Université Bretagne Sud, UMR CNRS 6027, IRDL, F-56100 Lorient, France*
[d] *INRAE, UR1268 Biopolymères Interactions Assemblages, 44316 Nantes, France*
[e] *Centre for Natural Material Innovation, Department of Architecture, University of Cambridge, Cambridge CB2 1PX, United Kingdom*

ARTICLE INFO

Keywords:
Structural biocomposite design
Structure-property-processing relations
Environmentally friendly crop
Wind turbine blade
Hemp fibre composites

ABSTRACT

Given the vast amount of available research in the area of natural fibre composites, a significant step forward in the development of next-generation plant fibre-based products would be to devise a framework for rational design. The authors use a top-down approach, starting with an example final product to define the product specifications for high-performance hemp fibre-reinforced composites. Thereafter, all process steps are critically analysed: from textile preform and reinforcement yarn production, to fibre extraction and the agricultural process chain, to the microbiology of field retting, to cultivation and selection of crop variety. The aim of the analysis is to determine how far the current state of knowledge and process technologies are in order to use hemp fibres in high-performance composites. Based on this critical evaluation of the state-of-the-art, it can be stated that hemp will be found in high-performance composites in the short-to-medium term. There is, however, a need for performance optimisation especially through the selection of crop variety, best practices in retting, and effective fibre extraction methods to obtain more consistent fibre qualities suitable for reinforcement spinning and composite preform manufacturing processes.

1. Introduction

Fibre renewable resources are being increasingly explored and utilised in engineering polymers and composites due to their combination of environmental and technical performance. The development of publications and the increase in international conferences on the subject of natural fibre-reinforced composites shows the timeliness of the topic. The increasing importance of sustainable - social, ecological and economic - development of materials and products is also contributing to the growing importance of composites made of natural fibres. Our review is not only intended to present the developments in this area in recent years. Rather, by analysing the research, we want to show ways and identify research needs that make it possible to use bast fibres like hemp in high-performance composites. This review follows the approach of developing a framework for rational design, which is in contrast to arbitrary choices commonly made in product design. Our objective is to support the potential use of hemp fibres for high-performance composites based on bottom-up and top-down approaches.

Here, the authors will use a top-down approach, starting with the final product to define the product specifications for high-performance hemp fibre-reinforced composites. The work of Potter is helpful in this context, as it attempts to create a picture of an ideal design cycle for composite materials that deals with all the complexities of this group of materials [1]. We will start with the definition of a product specification in which we list all requirements of the rotor of a wind turbine (see Fig. 1). Using this list of requirements, we will evaluate the entire process chain from product to the best choice of hemp variety to meet the composite specifications. In this transdisciplinary approach, we will review what is known and what has already integrated appropriately in the production chain. Our research will be used to discover what is still unknown and will help to open up new fields of research. Based on this approach, we will generate basic knowledge that will help map pathways to new practical applications.

We will divide the entire process chain shown in Fig. 1 into the following areas:

---

[*] Corresponding author.
E-mail address: jmuessig@bionik.hs-bremen.de (J. Müssig).

https://doi.org/10.1016/j.jcomc.2020.100010
Received 9 June 2020; Received in revised form 18 July 2020; Accepted 20 July 2020
2666-6820/© 2020 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license.
(http://creativecommons.org/licenses/by-nc-nd/4.0/)

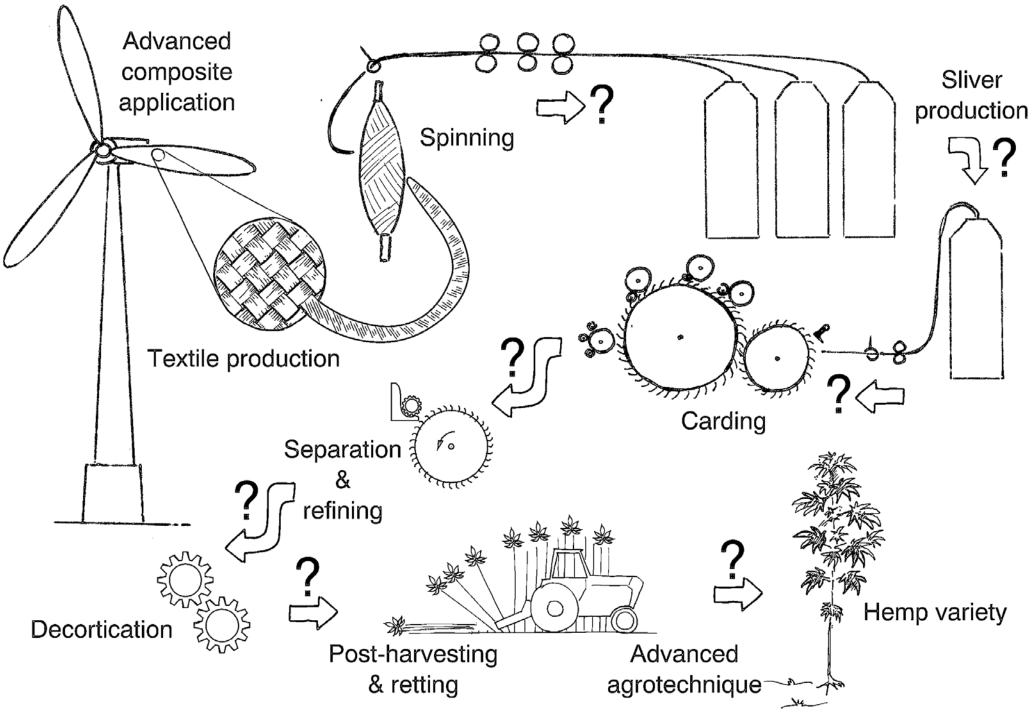
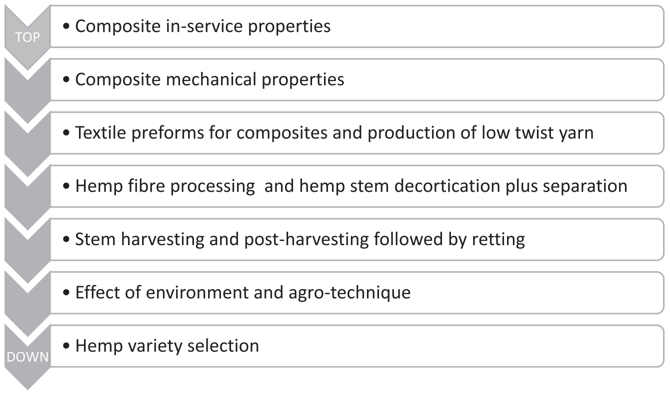


Fig. 1. The entire process chain as a top-down approach from product to the best hemp variety choice for reaching the composite specifications for a high-tech application like the rotor blade of a wind turbine.



- Composite in-service properties
- Composite mechanical properties
- Textile preforms for composites and production of low twist yarn
- Hemp fibre processing and hemp stem decortication plus separation
- Stem harvesting and post-harvesting followed by retting
- Effect of environment and agro-technique
- Hemp variety selection

2. Composite in-service properties

Twenty-five thousand tonnes of hemp fibre were produced in the EU in 2013, around 3500 tonnes (14%) of which went into the production of bio-based composites, primarily compression-moulded fleeces and needle-felt textile materials for the automotive sector [2]. Speciality pulp and paper (57%), and insulation (26%) were more likely end-uses for hemp fibre [2]. Nonetheless, the use of short (hemp) bast fibres in non-structural composites have been state-of-the-art for several years, if not decades. For instance, in the 1990s, >95% of hemp was directed to speciality paper production. As industrial hemp cultivation in Europe has increased almost three-fold from under 16,000 hectares in 2013 to over 45,000 hectares in 2017 [3], hemp fibre production and their application in biobased composites has also increased (at least in absolute volume), particularly noting that Europe accounts for around a quarter of global industrial hemp cultivation [3].

Today, there is a significant voice, at least in the scientific community that acknowledges that the real challenges and associated opportunities for market penetration and capture lie in the development of aligned hemp fibre composites for performance-demanding applications. Two concept cars – Henry Ford's hemp car of the 1940s [4] and Lotus's latest Eco Elise – demonstrate that hemp bio-based composites are potentially applicable for structural body panels, and not just interior trims, for example. We particularly note that such concept product development and full-scale case studies are paramount and much-needed in advancing future applications of hemp bio-based composites by tackling technical, economical, socio-cultural challenges.

2.1. *Specifications for a hemp fibre-reinforced composite rotor blade for a small wind turbine (<100 kW)*

Of the various engineering components and structures we come across in daily life, the rotor blades of a small wind turbine are challenging, exemplar structural components due to the variety of failure criteria they have to be designed and tested against for certification [5, 6]. To give an idea of size and scale, a small wind turbine is classed as one with a rotor diameter < 16 m or rated capacity < 100 kW. Rotor blades are critical components of a turbine from both technical and economic perspectives. At the mercy of the wind, rotor blades need to function within specified limits during normal operation conditions (design wind speeds of 11.9 ms^{-1}), as well as severe conditions (extreme hurricane-like gust wind speeds of 59.5 ms^{-1}). Moreover, rotor blades have a typical design life of 20 years and cycling at over 100 rpm, and they can accumulate in excess of 10^9 fatigue cycles.

While the design of structural components from hemp has been rare even in scientific literature, a number of studies have explored the potential of flax composites for small wind turbine blades that range in length from 0.6 m [7, 8] to 1.2 m [9] to 3.5 m [10]. Shah et al. [10, 11], following IEC 61,400 standards [5, 6], demonstrated the efficacy of a flax blade through load analysis, fatigue life prediction and full-scale structural testing. Notably, the recent Green2Green Austrian research project has concluded similar capabilities of fully hemp-based green composites – hemp woven textiles reinforcing an epoxidised hemp oil resin – for a developmental wind blade in terms of meeting strength requirements

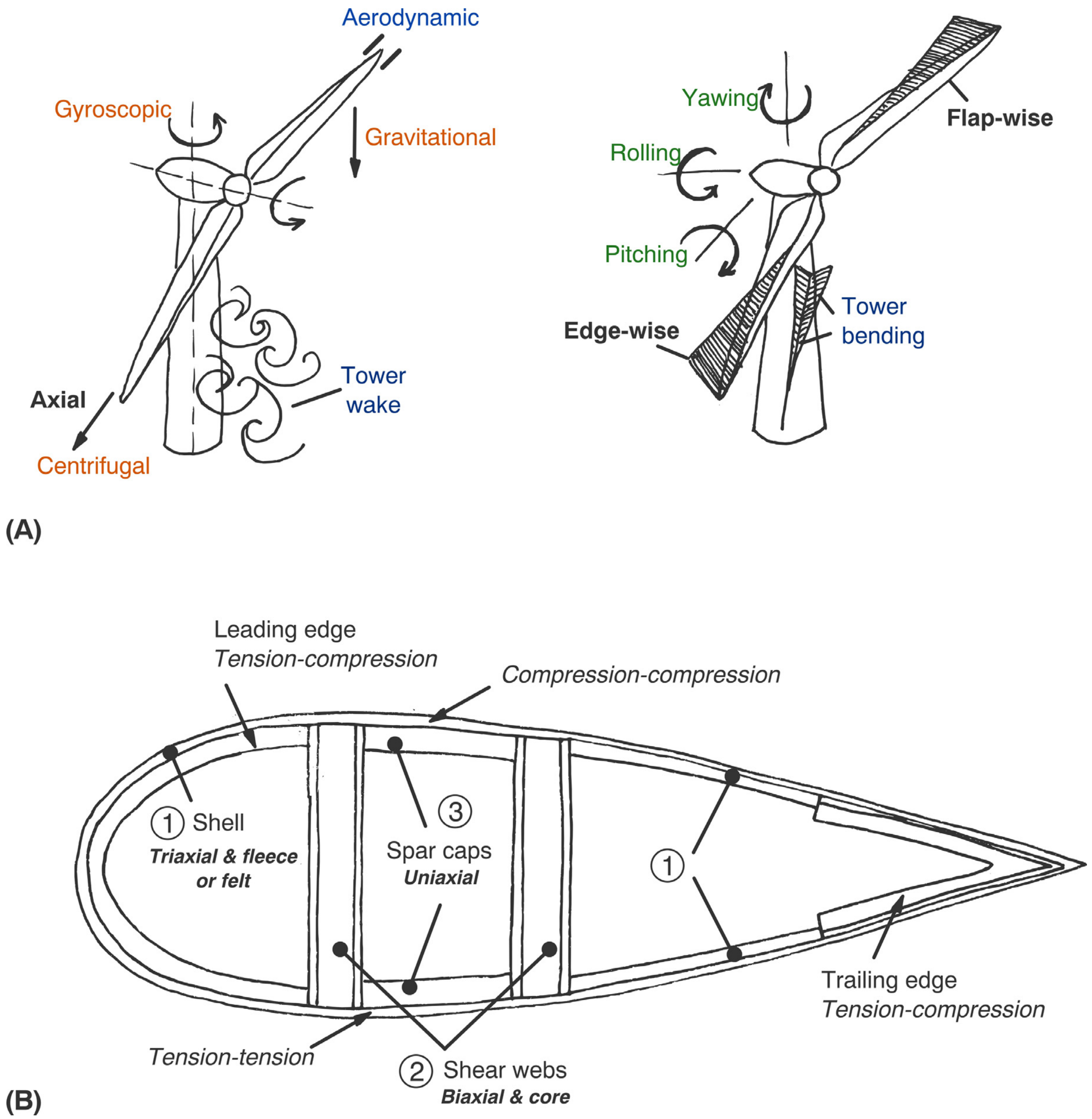


Fig. 2. (A) Loads on a rotor blade. The loads on small rotor blades can be categorised as aerodynamic loads (in blue, such as drag, lift and shear), inertial loads (in orange, such as gravitational, gyroscopic, and centrifugal) and operational loads (in green, resulting from turbine control such as yawing, pitching). Of these, aerodynamic loads are most important. These loads can be divided into flap-wise (bending the blade downwind), edge-wise (bending the blade in the rotational direction) and axial (along the blade length) directions. Of these, flap-wise loads are most significant. These loads can be further expressed as tension/compression fatigue loads (see b). (B) Design of a rotor blade. Typical small rotor blades have a shell-spar composite structure, with a combination of aligned laminates to achieve the desired structural performance. The multi-axial fibre reinforcement in the shell and shear webs provide resistance against torsion-related shear loads, the unidirectional fibre reinforced spar caps provide axial (tensile) and bending (flexural) stiffness and strength, and the core in the shear webs provides resistance against buckling. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

[12]. For reference, the relevant properties of aligned flax and glass composites in the design of a turbine blade are presented in Table 2.

To tackle the various loads a rotor blade experiences (Fig. 2a), blades are typically designed to have a complex composite structure (Fig. 2b). They comprise of a shell, a central spar/shear webs, and possibly details for the leading and trailing edge. A combination of core and laminate materials are employed, with the composite laminates typically being reinforced by a triaxial [0,±45] fabric for the shell (with nonwoven material for thickness/bulking), biaxial (±45) fabric for the shear webs and unidirectional (0) fabric for the spar caps. Non-crimped fabrics (e.g. stitched multiaxials) are preferred over woven fabrics to avoid loss in property from fibre misorientation, which can be substantial for plant fibre reinforcements, and better impregnation [13, 14]. Glass fibre reinforcements are most commonly used for small rotor blades, with core materials being low-density polymer foams or wood (e.g. balsa) [15]. As resin systems, while liquid thermoset resins are commonly used for processing via hand lay-up or vacuum infusion, thermoset prepregs for autoclave moulding and even thermoplastics for liquid infusion or autoclave moulding are increasingly being adopted.

Hemp rotor blade materials would need to possess a diverse property profile, including, stiffness, yield and ultimate strengths, and fatigue endurance. Table 1 outlines this property profile, with supporting discussion henceforth.

Table 1
A hemp fibre composite wind turbine blade is required to meet a number of selection criteria. Material properties of interest and routes to achieve these are outlined.

Property of interest	Corresponding failure criteria (from IEC 61400[5, 6])	Pointers for hemp bio-based composite material and blade design
Stiffness	The analysis shows possibility of *blade tower collision* a rotor blade hitting the tower due to substantial tip deflection from wind loads	*High stiffness is required.* Stiffness can be optimised by increasing fibre content thanks to process evolution, like using more aligned (unidirectional vs multi-axial) reinforcement preforms or prepregs with low-twist yarns/rovings and non-crimp fabric, produced from minimally-processed (low defect) fibres. Other promising process techniques include automated fibre placement (AFP).
	Full-scale testing shows *functional failure* [b] – stiffness degradation of the blade – below worst case loads significant (of the order of 5–10%) and irreversible reduction in stiffness upon loading	*Evolution of stiffness as a function of applied load (and time/damage accumulation) is relevant here.* Hemp biobased composites show (partly-irreversible) non-linear stress-strain response. As the initial stiffness (typically measured at below 0.15% applied strain) may not be an appropriate indicator of the practical stiffness of the composites, use the fairly stabilised residual stiffness (above 0.4% applied strain) as a suitable design value. Use of twisted yarns may aggravate non-linear response.
Strength	The analysis shows that stresses experienced by the blade are above material failure stresses along the blade cross-section Full-scale testing shows *superficial failure* [a] below normal operation loads (at design wind speeds of 11.9 ms^{-1}) Full-scale testing shows *functional failure* [b] – substantial permanent deformation upon unloading – *or catastrophic failure* [c] below worst case load (typically at extreme wind speeds of 59.5 ms^{-1})	*High yield and ultimate strengths are required.* Both can be optimised by increasing fibre content, using more aligned (unidirectional vs multi-axial) reinforcement preforms with low-twist yarns/rovings and non-crimp fabric, produced from minimally-processed (low defect) fibres. Process techniques, such as automated fibre placement (AFP). Reducing porosity is also recommended. Plant fibre composites naturally have a low elastic limit (of around 0.15% applied strain), and therefore high stiffness is desired to ensure high yield strength. Observation of damage accumulation behaviour of plant fibre composites and their structure is of interest.
Fatigue endurance	The analysis shows inability to survive design *fatigue cycles* at the normal operation loads (at design wind speeds of 11.9 ms^{-1})	*Fatigue strength at 10^6 or 10^9 cycles is relevant here.* Fatigue strength is known to be proportional to static ultimate tensile strength. Fatigue life design using a fully-constructed empirical constant life diagram is important.

Desirable objectives
low density – lighter blades are easier to transport, have reduced centrifugal loads, and reduce loads on the tower structure (and consequently the amount of material used in its design).
cost-effectiveness – through optimal material and manufacturing costs
environmental durability – vis. effects from UV-light, moisture, lightning – to ensure 20–30 year design life
low embodied carbon materials and safe end-of-life disposal – to minimise ‘waste’, and have opportunities to re-use, recycle, or recover (including energy through incineration), and to avoid land-filling of material/product

[a] Superficial failure has no immediate structural consequences. This includes the formation of cracks, fibre buckling or delamination even if there is no strength degradation.

[b] Functional failure is when there is a substantial loss in functionality of the blade through substantial permanent deformation or stiffness reduction.

[c] Catastrophic failure is when there is complete disintegration, collapse or failure of the blade.

The requirement of high stiffness can be catered for by optimising composite parameters, such as fibre content, textile architecture, and fibre and matrix properties [16]. The fibre properties, themselves are influenced by biochemical and structural properties, as well as fibre processing steps (including retting and extraction).

Hemp fibres and their composites [17, 18, 19] – and plant fibres and their composites in general [20, 21] – exhibit a characteristic non-linear stress-strain response. While traditional fibre-reinforced composites have a linear stress-strain response showing constant stiffness for over 0.5% applied strain, the stiffness (measured through secant or tangent modulus) of hemp fibre composites can drop by over 30%, even up to 50%, in the strain range of 0–0.4%, due to a low elastic limit of *ca*. 0.15% [14, 20]. While, most studies calculate and report initial stiffness in the strain range of 0–0.1% (below the elastic limit) for hemp fibre composites, for design purposes, it may be more appropriate to use the fairly stabilised residual stiffness above 0.4% applied strain as a practical design value. Consequently, designing a rotor blade with hemp composites – and plant fibre composites in general - is more complicated. This is particularly because, as per IEC 61,400–23 [5], a blade functional failure is judged to have occurred when there is a significant – of the order of 5–10% – and/or irreversible reduction in blade stiffness.

Furthermore, Shah et al. have shown that the stiffness profile along the blade is different for a similarly constructed flax and E-glass blade, with the latter being double over much of the blade length [10]. The stiffness profile and consequently, the deflection profile of the blade during wind loading will inadvertently influence the power characteristics of the turbine. This would be important to characterise and design for a hemp bio-based composite blade.

Like stiffness, the ultimate strength of hemp fibre composites can also be enhanced through optimisation of composite parameters [16]. A notable advantage of hemp fibre composites, in comparison to a fibreglass blade, is the opportunity to substantially reduce mass and therefore the magnitude of centrifugal/axial loads, provided the need for increased laminate thickness (and therefore material mass), to achieve the desired stiffness and strength, is limited. Most loads on a blade can be

Table 2
Tensile, compressive and fatigue properties of unidirectional [0] and biaxial [±45] flax/polyester and E-glass/polyester composites. Material performance indices are shaded. Data from [23].

			Unidirectional composites			Biaxial composites		
Property			Flax	E-glass	Flax/E-glass	Flax	E-glass	Flax/E-glass
Tensile	Fibre volume fraction	%	30.9	42.8	–	29.2	28.0	–
	Composite density	gcm^{-3}	1.31	1.79	0.732	1.30	1.61	0.807
	Composite stiffness	GPa	23.4	36.9	0.634	5.70	8.77	0.650
	Composite specific stiffness	GPa/gcm^{-3}	17.9	20.6	0.869	4.38	5.45	0.804
	Effective fibre stiffness[a]	GPa	67.6	81.6	0.828	–	–	–
	Composite strength	MPa	277	826	0.335	51.4	139	0.370
	Composite specific strength	MPa/gcm^{-3}	213	461	0.462	39.5	86.3	0.458
	Effective fibre strength[†]	MPa	883	1920	0.460	–	–	–
	Composite failure strain	%	1.70	1.90	0.895	3.76	4.12	0.913
Compressive	Fibre volume fraction	%	32.5	30.0	–	N/A[b]	N/A[b]	N/A[b]
	Density	gcm^{-3}	1.30	1.64	0.793	N/A[b]	N/A[b]	N/A[b]
	Composite stiffness	GPa	11.3	21.0	0.538	N/A[b]	N/A[b]	N/A[b]
	Composite specific stiffness	GPa$^{1/3}$/gcm^{-3}	1.73	1.68	1.03	N/A[b]	N/A[b]	N/A[b]
	Composite strength	MPa	101	313	0.323	N/A[b]	N/A[b]	N/A[b]
	Composite specific strength	MPa$^{1/2}$/gcm^{-3}	7.73	10.8	0.717	N/A[b]	N/A[b]	N/A[b]
	Composite failure strain	%	3.44	3.70	0.930	N/A[b]	N/A[b]	N/A[b]
Fatigue ($R = 0.1$)	Fibre volume fraction	%	26.9	30.0	–	29.2	28.0	–
	Density	gcm^{-3}	1.29	1.64	0.787	1.30	1.61	0.807
	Single cycle strength	MPa	236	567	0.416	51.4	139	0.370
	Fatigue strength at 10^6 cycles	MPa	115	204	0.564	22.1	57.3	0.386

[a] The effective fibre properties are ‘back-calculated’ using the rule of mixtures.
[b] N/A = not measured.

expressed as tensile or compressive loads along the blade length. It is evident from literature that there is a gap in characterisation and understanding of compressive behaviour of hemp (and other plants) fibre composites, which can be a limiting design case, given the low compressive strength reported for plant fibre composites [22, 23]. Yield strength of the blade also needs to be optimised as a functional failure is deemed if there is substantial permanent deformation (e.g. tip deflection) upon unloading. As it is known that the characteristic yield point of plant fibre composites is around 0.15% applied strain, to maximise yield strength, initial stiffness needs to be maximised [14, 20].

It is observed that fatigue strength is proportional to static ultimate tensile strength, as the rate of strength loss per decade of cycles is fairly constant – this is true for a range of plant fibre types, fibre contents, and textile architectures [24, 25, 26]. However, designing against fatigue requires extensive material characterisation in terms of obtaining stress-life curves for a range of stress ratios to construct a constant-life diagram. For hemp composites, only limited data exist in literature on fatigue behaviour [24, 25, 26].

In light of the above discussion, three key future research directions are envisaged at the product scale.

Firstly, full-scale and multi-scale studies on hemp fibre composites and their products are needed. There are only limited full-scale comparative case studies showing the potential of plant fibre composites. While it is interesting and expected that a hemp composite turbine blade, like a hemp fibre and its composite, have a non-linear stress–strain behaviour, it is interesting and unexpected that a hemp or flax composite blade can meet strength requirements, but underperform with regards to stiffness in comparison to a fibreglass blade [10]. More full-scale and multi-scale studies, across labs, will enable better understanding of the behaviour and performance of hemp fibre composites, to facilitate better design of products.

Secondly, materials development of hemp bio-based composite needs to be more combined with product design. In engineering design, material selection and design embodiment go hand-in-hand. How can we better design with hemp fibre composites? For example, by altering turbine design and having higher tip clearance (to avoid tower collision), we can design around the lower stiffness of hemp fibre composites. We can also have a graded and stepped spar (e.g. varying thickness along the blade length) to produce a blade stiffness and deflection profile that would yield better turbine power characteristics. Similarly, towards the development of high-performance bio-based composites, exploring avenues such as hybridisation strategies (e.g. with carbon or basalt fibres [27], for stiffness or fire performance), routes to produce cost-viable aligned hemp fibre reinforcements (non-crimped vs woven, rovings vs twisted yarns) and generating end-of-life re/down-cycling options (e.g. using blade materials for nacelle cases) is of interest.

Thirdly, extensive materials characterisation of hemp bio-based composites is needed. There is limited data on hemp bio-based composite properties necessary for the detailed design of products. Compressive, fatigue and creep behaviour of hemp fibre composites need better evaluation [22, 13, 24, 25, 26]. Besides, development of numerical/computational analysis of bio-based composite components (e.g. with finite element methods) for design purposes is a necessary step forward, particularly noting the multi-scale nuances of hemp bast fibres. For instance, the non-circular, non-uniform cross-section of the coarse hemp fibres [28], and their prevalence as bundles as opposed to single fibres, stands in contrast to uniform synthetic fibres.

3. Composite mechanical properties

In Asia, North America and Europe, the hemp industry primarily produces short fibre bundles in a disordered line, in contrast to the streamlined flax industry producing wet-spun yarns in a longitudinal line. In Europe, hemp fibre bundles are mainly used in the paper industry, for regular or specialized products such as bill paper money, thanks to an efficient industrial sector. However, this plant, whose fibres are structure-supporting tissues, can also provide long fibre bundles with a high potential for the textile and composites industry. In this section, we will first present the particularities of this fibre in terms of growth, morphology and mechanical performance. The link between fibre ultrastructure and mechanical properties will also be discussed. Second, we will review the state-of-the-art performance of two mains subfamilies of hemp-reinforced composites. We will explore unidirectional (UD) composites for high-performance applications, but start with injection-moulded composites as mid- or low-performance composites, due to the

Table 3
Main properties of hemp fibres. Mechanical properties, diameter and length are given for single hemps fibres. Density is given for cell wall and not apparent fibre.

Biochemical Composition in% of dry matter[a]					
Cellulose	Hemicellulose	Lignin	Pectin	Fat and Wax	References
55–90 *(70)*	12 *(16)*	2–5 *(6)*	3 *(2)*	1.7 *(0.7)*	[29, 37, 192, 193, 47, 194, 113, 195]
Structural properties[a]					
Length in mm	Diameter in µm	MFA in °	Density in g/cm^3	Cristallinity index in%	References
5–55	10.9–42.0	2–11	1.4–1.6	55	[29, 47, 33, 31, 196, 138, 197, 198, 199, 200, 201, 202, 203]
Mechanical properties (single fibre)[a] [b]					
Young's Modulus in GPa			Strength at break in MPa	Strain at break in%	References
14.4–90 (65)			285–1110 (800)	0.8–3.3 (3))	[47, 138, 200, 196, 204] [205] [206]
Mechanical properties (fibre bundle)					
Young's Modulus in GPa			Strength at break in MPa	Strain at break in%	References
17.2–40			315–1011	2.1–6.5	[207] [208] [209] [142]]
Behaviour towards moisture					
Absorption regain in% at 65% relative humidity. 20 °C			Water retention in%		References
6–12			50–55		[210, 211, 212, 205, 213, 214, 215, 216, 217, 218]

[a] Most frequent published in brackets according to [33].

[b] To illustrate the possible differences between the strength of a single fibre and a single fibre bundle, it is worth referring to the work of Bos et al. [102]. The authors describe for flax that for a clamping length between 100 and 25 mm the strength of a single flax fibre bundle is about 500 MPa. At clamping lengths smaller than 25 mm, the strength increased and reached a value of about 850 MPa (clamping length 3 mm). Single fibres prepared from the fibre bundles achieved strengths of 1522 MPa to 1834 MPa, depending on the pre-treatment condition.

limited literature on the former (hemp UD composites). Finally, we will identify the barriers that need to be broken down to optimise the performance of hemp fibres and their composites, especially in link with retting, separation of fibre bundles and quality of fibre extraction.

3.1. Hemp fibre properties

3.1.1. Growth and structural properties of hemp fibres

Among fibre plant crops, hemp is one of those whose fibres impart bending stiffness to the plant. Primary hemp fibres develop in an intrusive way, which gives them a significant length. After a stage of phloem cell division at the apex of the plant [29], coordinated growth begins, during which the cell develops at the same rate as the surrounding tissues to reach a few hundred microns [30]. Then begins the intrusive growth phase, which lasts only a few days but during which the fibres lengthen by several mm per day [31]; thanks to their pointed ends and the multiplication of the nuclei, they can reach extraordinary lengths, up to several tens of mm. In the case of hemp, the average length of the primary fibres is around 15 mm [32], but there is scatter in generally reported values [33], from a few mm to more than 50 mm [34] (see Table 3). When intrusive growth is complete, the filling of the fibres' cell walls with cellulose and encrusting polymers begins and continues through the growth life of the plant, which gives the fibres their high mechanical properties, particularly stiffness. In hemp, there is also a network of secondary fibres that can form in the vascular cambium, depending on both the harvest time and the plant section (basal internode) [35]. These secondary fibres develop intrusively about 600–700 mm from the apex of the plant [31]. These fibres grow in already formed tissues, and for this reason, they do not reach the lengths of the primary fibres and rarely exceed 2 mm in length [36, 37]. These secondary fibres have smaller diameters than the primary fibres [34, 38]. However, after extraction of the secondary fibres, it may be challenging to distinguish them from primary fibres because a bundle of secondary fibres can have morphological characteristics very similar to those of a bundle of primary fibres [39]. Depending on several factors, notably the cultivar, it is known that the fibre yield may also vary considerably [40]. In terms of biochemical composition, hemp fibres, like flax fibres, can be classified into the family of gelatinous cell walls [41], with a high content of cellulose and non-xylan hemicellulose [42] (see Table 3). Within the cell walls, the cellulose microfibrils are embedded in a matrix of non-cellulosic polymers and oriented with the axis of the fibre at an angle of about 11° [43], though some authors report smaller angles; see Table 3. Hemp fibres have a moderate lignin content, not exceeding 5% [37]. The hydric expansion of the hemp bundles under hygro- and hygro-thermal conditions is notable (about 0.9) [44]. Indeed, there can be wide variation in cell dimensions due to swelling mechanisms which induce notable anisotropic deformation of the hemp bundles between 'dry' and 'wet' states. Recent investigations of the nanomechanical properties of hemp bast fibres confirmed the multi-physical implications of the moisture level within the cell wall matrix polymers, reporting that indentation modulus decreased with increasing moisture content [45].

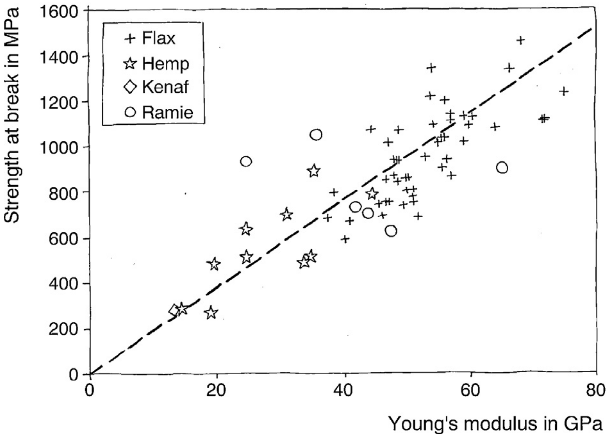


Fig. 3. Literature review of single plant fibres tensile performances[46]..

3.1.2. Mechanical performance of hemp fibres

Due to their short length, the mechanical characterisation of secondary hemp fibres is difficult. However, a comparative study by Bourmaud et al. showed that the indentation moduli of the cell walls of secondary fibres was close to those of the primary fibres. This is reassuring from the point of view of reinforcement development for the composites industry as the separation of primary and secondary fibres is practically impossible during the extraction process [38]. In this section, we will focus mainly on the mechanical performance of primary hemp fibres.

Fig. 3 shows the mechanical properties of different plant fibres from the literature [46]. All these values were obtained by tensile tests on single fibres. Table 3 gives an overview of important properties of hemp fibres; mechanical properties from literature are given for both single fibres or fibre bundles. When a bundle is considered, the reader must keep in mind that the gauge length and therefore the loaded volume is a crucial parameter that can make comparisons between published works difficult.

There is a marked hierarchy in fibre performance between plant species, with hemp fibres generally performing less well than flax or ramie, both in terms of modulus and strength at break. Indeed, considering their microfibrillar angle, their biochemical composition and their crystallinity rate [47], the plant cell walls of hemp display characteristics very similar to those of flax and the differences in terms of mechanical performance cannot be explained by these endogenous parameters alone. As mentioned above, the presence of secondary fibre bundles may be responsible for the lower average properties. However, one of the key reasons is related to the size of the lumens [48, 49]. Comparative studies have highlighted that size of the lumen is more pronounced in hemp [47] and which, assuming equal wall stiffness, leads to a decrease in the apparent properties of the fibres. This hypothesis is further supported by low mechanical properties of kenaf fibres which exhibit even larger lumen size [50]. In the 1950s, Hayward reported that at fibre maturity, the lumens occupied as much as 30% of a hemp fibre cross-section area [48], which is in stark contrast to recent reports stating the value to be a few per cent to up to 10%; perhaps, a consequence of agro-breeding studies and cultivar development and selection over the decades [49]. The extraction methods, which we will discuss in one of the following sections, may also be responsible for this difference. The widespread use of hammer mills is particularly detrimental to plant cell walls [51] and can lead to the creation of defects, leading to reduced mechanical properties in the extracted hemp fibre [52, 47].

The middle lamella binds adjacent fibres together in a fibre bundle. Melelli et al. employed peak-force quantitative nanomechanical property mapping (PF-QNM) give an indication as to measure the indentation modulus of the middle lamella and examine why hemp fibre bundles were more difficult to individualise than flax fibre bundles [53]. They show that the mean indentation modulus of the middle lamellae of field-retted hemp is in the range of 16 GPa, whereas in flax bundles a value of only 10 GPa was found. Thus, in line with the higher lignin content and cohesive performance of its middle lamellae, the processing of hemp fibres is more challenging [54]; this will be discussed in detail in later sections.

3.2. Hemp fibre composites

The performance specifications of a reinforcement are dependent on the application of the composite produced. Injection moulded short-fibre reinforced parts are generally described as low- or mid-performance composites. Composite performance is highly dependent on the orientation of the reinforcements, and it has been shown that this parameter is of major importance in relation to the intrinsic properties of plant cell walls [55]. For such injection moulded parts, intended for high-volume markets, price is also an important factor. In this context, hemp fibres are of great interest. In addition, according to Melelli et al., hemp fibre bundles are more lignified than flax in most commercial batches [53]. Due to the increased stiffness of the hemp fibre bundles, they orient themselves in the flow direction during plastic processing and facilitate higher anisotropy of properties in the component. Fig. 4.a shows the stiffness values for parts injected with a range of plant fibres and with a similar polypropylene matrix; all samples have the same fibre fraction (30%-mass) [46]. Recently, a comparison of mid-performance hemp-based composites was published, illustrating how hemp has been researched for such applications in recent years [56]. Hemp fibre properties also allow their use in the field of thermo-compressed nonwovens (like fleeces or needle felts) widely used in the automotive sector [57]. Alone, or in combination with flax or kenaf, the fibres guarantee a low price and sufficient mechanical performance for these non-structural interior automotive parts. In addition, the heterogeneity of their morphologies, particularly in terms of diameter, is an advantage for the acoustic performance of these parts [58].

For structural applications, composites with continuous fibres or staple fibres in the form of yarns are preferred. These composites are generally assimilated as high-performance composites. While hemp can be converted into reinforcements for such applications, as we will discuss in later sections, the industrial sectors currently in place do not provide access to the same consistent quality of hemp fibres as those provided, for example, by the flax industry. Fig. 4.b compares the maximum strength of epoxy matrix unidirectional composites reinforced with hemp fibres with similar materials made from other plant fibres [46]. For unidirectional composites, the tensile modulus is directly correlated with fibre volume fraction [21]. In addition to fibre content, the strength is strongly influenced by the aspect ratio of fibres or fibre bundles, and by the quality of the interface between the fibres and the matrix [59, 60, 61], as well as by the degree of individualisation of the bundles [62]. In the case of hemp, the intrinsic properties of the fibre penalise the strength at break, because they are shorter and possess a smaller aspect ratio, compared to flax, for example [63].

Moreover, the quality of retting and fibre extraction is also a major parameter. These processes have a major impact on the individualisation [64] and surface quality of the fibre bundles [65], and it is important to control them to guarantee long fibre bundles without cortical, woody core or middle lamellae residues. These non-structural elements penalise the interface with the resin [66], significantly reducing interfacial strength and promoting the presence of fibre bundles, which are preferred fracture zones within a composite. Hemp exhibits more lignified bundles than flax, so their individualisation is more difficult, and only a near-perfect control of retting can promote optimal fibre division. Unfortunately, this is still poorly controlled by hemp fibre producers [67]. Furthermore, as mechanical processing may have a negative impact on the fibre quality [68, 65, 54], this should be carefully decided in order to ensure that the fibres have the mechanical properties, morphology and surface characteristics required for the production of high-performance composites. For hot-melted quasi-isotropic short fibre thermoplastic composites, typically made by extrusion and injection, the mechanical extraction of the fibre must be optimised for the same reasons as expressed above. Even though these composites are dedicated to non-structural applications, the higher individualisation rate can be a challenge. The aspect ratio of the reinforcing elements is also known to be an influencing factor impacting composites properties, like the strength at break or the Young's modulus [69]. The tensile properties increase with aspect ratio up to a maximum value, and decrease thereafter, leading to a well-known bell-shaped curve [70, 71, 72].

4. Textile preforms & low-twist reinforcements for composites

Reinforcement form has a property-governing effect on the resulting composites (see Fig. 5 [16]. Pellets used for injection moulding produce hemp fibre composites with very short fibres/fibre bundles (sub-mm) and nominally random orientation in 3D (with some local orientations due to shear effects at the boundaries and edges). The low reinforcement efficiency factors relating to length and orientation [73, 74, 16] result in low mechanical properties, comparable to that of the unreinforced polymer, which is suitable for non-structural, aesthetic applications. Semi-finished textile products like fleeces and needle-felts as reinforcements have fibre bundles of moderate length, but nominally random 2D orientation, leading to composites with good properties suitable for semi-structural (self-mass supporting) applications only. For structural applications, long fibre bundles, aligned reinforcements, in the form of woven, non-crimped, stitched or unidirectional fabrics, are more appropriate, as high length efficiency factors, and optimised orientation efficiency factors are obtained. However, the production of such aligned textiles requires specific processing of hemp into intermediate products such as yarns and rovings. The use of aligned carded slivers as quasi-UD layers is also possible, which can additionally have a lower environmental impact as the energy-intensive spinning process is omit-

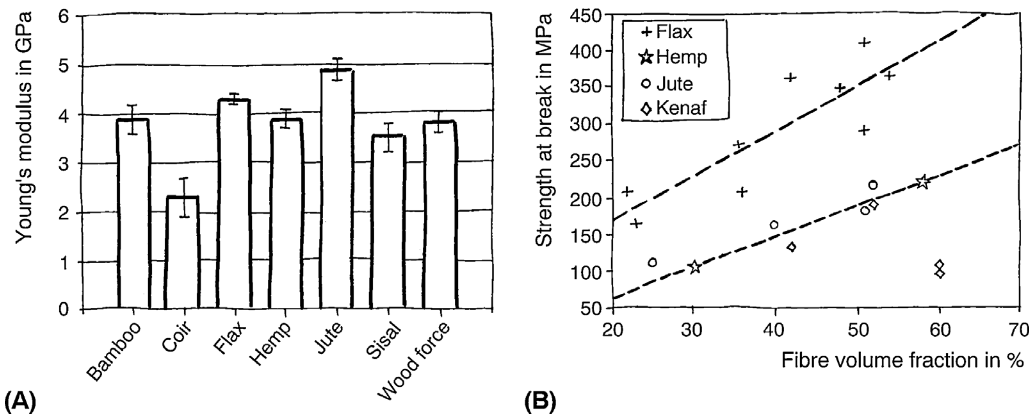


Fig. 4. Comparison of tensile modulus of injection moulded (30 mass%) fibre-reinforced PP composites (A) and strength at break of epoxy-hemp UD composites (B) with literature data[46].

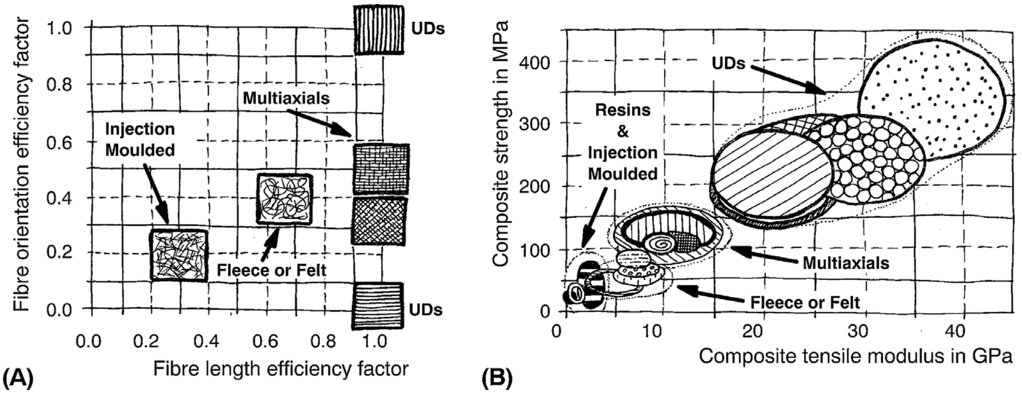


Fig. 5. (A) The length and orientation of the reinforcement, in the various textile architectures, lead to a range of composite property-governing reinforcement efficiency factors. (B) Consequently, composite mechanical properties are strongly influenced by the textile architecture and reinforcement form. Unidirectionals (UDs) have long and aligned fibres and consequently highest efficiency factors and mechanical properties (when loaded in the fibre direction). Multiaxials, such as woven textiles and non-crimped/stitched fabrics, have long fibres but oriented in specific multiple directions, and therefore intermediate properties. Nonwovens and injection moulding compounds have (very) short fibres that are randomly oriented (in 2D or 3D) and consequently lowest mechanical properties. Data and figure inspired from [16].

ted. Dissanayake et al. reported that by using a carded sliver, energy consumption can be reduced by 28% compared to a spun yarn [75].

The traditional textile uses of hemp fibre have been for twine, rope, nets, webbing, sacking, rugs, tarpaulins, heavy industrial canvas, and fabrics for clothing [76]. Clarke and Merlin traced the widespread introduction of hemp fibre use for textiles in Asia, Egypt, the Mediterranean region and northern Europe. They report that the archaeological, as well as historical records, are rich in evidence supporting the ancient importance of hemp fibre as a textile resource to humans [76].

Yarns are the most prevalent intermediate product, and can be processed into different textile products. Fig. 6 gives an overview of yarn (or thread) based textile structures, based on the textile classification from Schnegelsberg [77, 78]. Product examples for hemp textile are given for water-retted, wet-spun hemp.

The braided and woven textile products shown in Fig. 6 are based on wet-spun yarns, which are very compact. The yarns are generally highly-twisted, and for the given fabric (bottom-right photo in Fig. 6) the weft thread is composed of several twisted threads. The poor impregnability of such twisted spun yarns, and resulting intra-yarn impregnation porosity and reduction in composite mechanical properties, is well-documented [14, 23, 79].

Furthermore, it is expected and observed that the fibre misorientation inherent in a twisted yarn has substantially detrimental effects on the mechanical properties of their aligned composites [13, 14]. Based on a $\cos^2(2\alpha)$ effect on reinforcing potential [13], where α is the surface twist angle, while a zero-twist roving would enable 100% of the reinforcing potential of the fibre bundles in the roving, yarns with 10°, 20°, and 30° would receive 88%, 59% and 25% of the reinforcing potential of the fibres. Indeed, most commercially available hemp yarns and their comprising fabrics have surface twist angle above 20° It is therefore strongly recommended that low-twist rovings are essential to take advantage of the full fibre properties. However, low-twist rovings in hemp are not currently produced, although such reinforcement forms do now exist at a commercial scale for flax. A moot, but meanwhile useful, recommendation is that fine hemp yarns with small diameters should be used [14, 13]. This is because even if a hemp yarn is twisted to the same level (in revolutions per metre), a smaller diameter hemp yarn has a notably lower surface twist angle, and consequently the fibres are misoriented by a lesser degree. In addition, dry-spinning (rotor/ring spinning) produces more twisted yarns than wet-spinning [14, 23], as wet-spinning, through the benefit of stronger threads in wet, swollen conditions and increased inter-fibre friction, is less reliant on twisting to form a continuous product. Progress in wet-spinning and exploring possibilities of using binders, as has been done for some flax-based unidirectional products, such as by Lineo(now EcoTechnilin Ltd) (France) with the commercialized FlaxTape© or FlaxPreg©, are important areas of development of future low-twist hemp reinforcements.

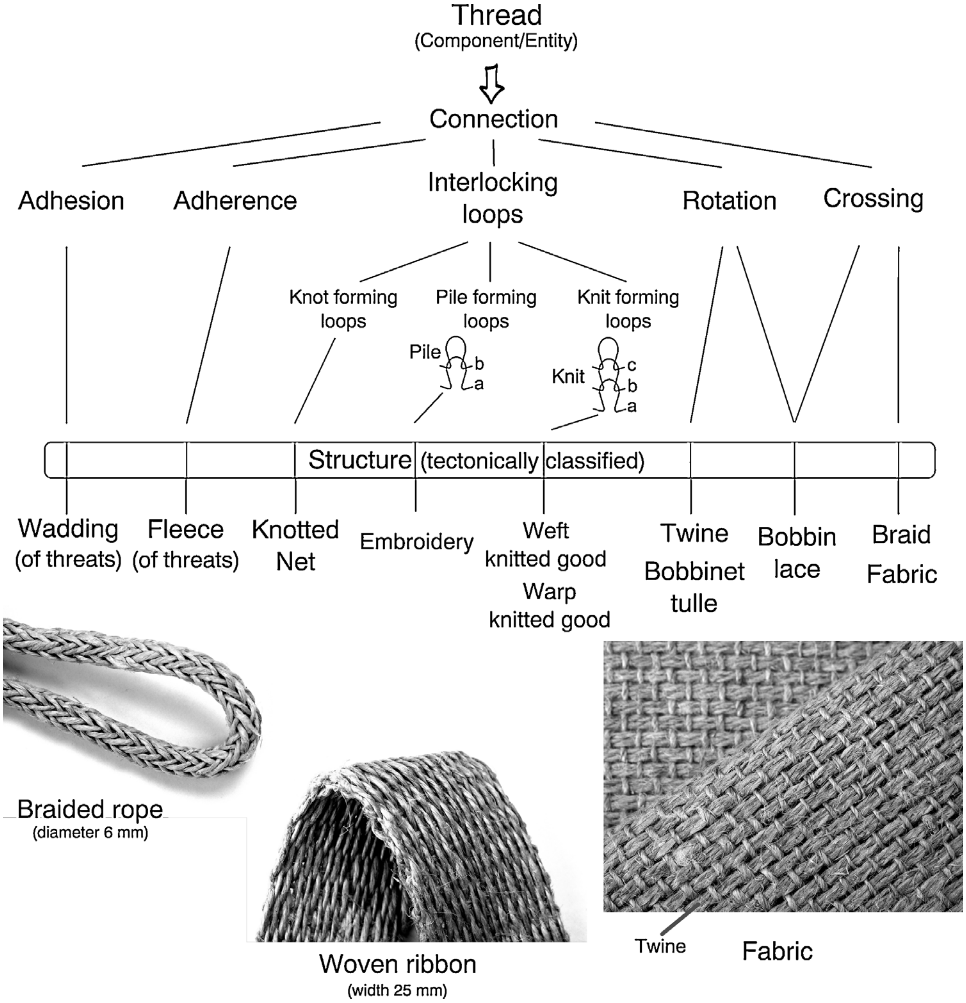


Fig. 6. Traditional thread-based hemp textile structures (based on the textile classification from Schnegelsberg)[77, 78]). Product examples are given. Hemp braids and fabrics produced from traditionally produced wet spun hemp yarns are shown.

While yarn twist is a source of misorientation at the fibre scale, conversion of yarns into specific textile preforms can also lead to further misorientation. For instance, woven fabrics require interlacing yarns/tows over and under adjacent yarns/tows, and braided materials require further interlacing, twisting and coiling. This also results in crimping. Indeed, higher levels of yarn twist, and coarser yarn diameters, can exacerbate issues of such misorientation at the textile preform scale resulting in up to 5–10% further drop in mechanical properties [14, 23]. Avoiding out-of-plane misorientation (e.g. from crimp) is critical in further improving composite mechanical properties. For this, considering non-crimped fabrics and stitched multiaxials, wherein layers of specifically oriented unidirectional textiles are stitched together, is important [10].

Special textiles developed for composites require low twist rovings and yarns. Fig. 7 shows the visualized result of a review of different techniques to produce hemp yarns. The overview lists process lines which are no longer in use, some which are in use or under development, and others which are future developments. For each of the listed process lines, we will provide a critical evaluation of the possible advantages and disadvantages to produce hemp yarns and textile semi-finished products to manufacture components for structural composite applications.

4.1. Traditional method

According to Clarke and Merlin, hemp fibres were used across all of Europe and Asia for millennia to manufacture cordage and textiles [76]. Historically, two types of hemp fibre processing are to be distinguished to manufacture yarn suitable for weaving fabrics [76]. In China and other Asian countries, hemp bark was split into narrow strips (see Fig. 7– strip hemp) and was tied together to form a yarn, while in Europe the bark strip (strip hemp) was combed to refine the fibre bundles before spinning [76, 80]. For a better understanding of traditional hemp yarn production in Europe, it is worth to take a closer look at Hungary. Sponner et al. provide insights into the traditional production method, from water-retted hemp stalks to wet-spun yarns [81]. In Hungary scutched hemp and tow (see Fig. 7) used to be spun to yarns with different techniques, but some traditional hemp processing techniques and types of machinery like water-retting and wet-spinning disappeared, because of changes in demand, high production costs, unfavourable working conditions, as well as environmental regulations [81]. The traditional process line can be optimized by replacing the water retting process by osmotic degumming [82]. Konczewicz et al. showed that osmotic degumming improves the quality of the extracted fibre bundles significantly in terms of colour, odour, aspect ratio, as well as emissions of volatile organic compounds compared to field-retted hemp [82].

After the disappearance of the wet-spinning process for hemp, both the hackled hemp (see Fig. 7) and the tow were dry spun in Hungary [81]. Depending on the quality of the hackled hemp, spinning techniques can be adopted from the flax sector. For hackled flax, the wet-spinning process with boiling is used to produce fine worsted yarns, while dry-spinning leads to coarser yarns [83]. Hemp yarns from the traditional line are, in general, very compact and are highly-twisted, which does not make them the first choice for high-performance composite applications.

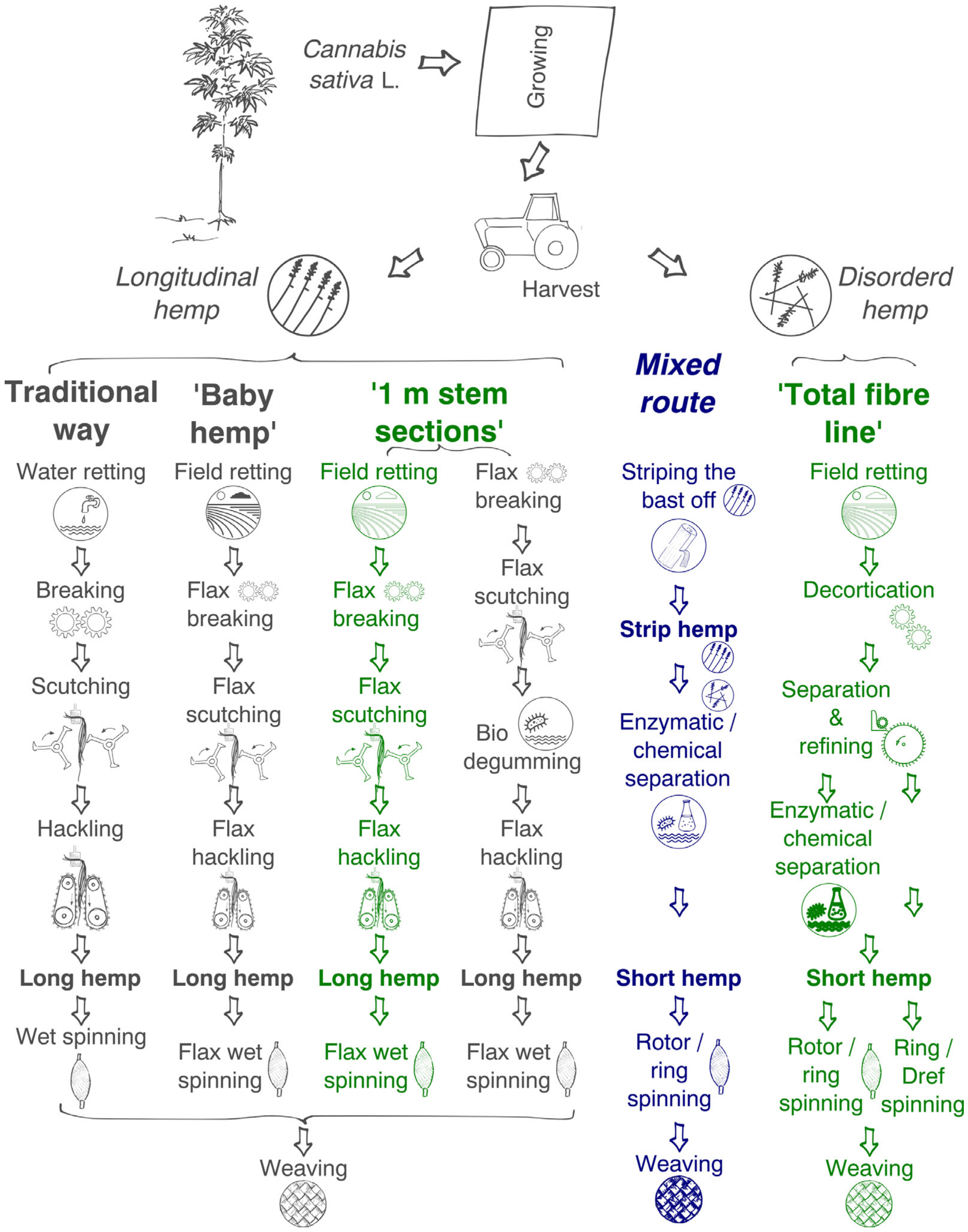


Fig. 7. Historical, current, and future concepts of hemp yarn production (historical and currently no longer pursued processes are in black, current process are in blue, and recent/future developments are in green); "Flax" means that the process has been used to produce and process flax for hemp. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2. Baby hemp production

In the late 1990s and early 2000s, while the traditional processing of hemp into yarns was progressively disappearing throughout the world, increasing demand for sustainable hemp textiles spurred research and entrepreneurial activities to find innovative solutions and/or adapt existing techniques to produce hemp yarns for the clothing industry. In the year 2000, in the north of Italy, in a territory where hemp cultivation had a great tradition, the Consorzio Canapa Italia was funded to reintroduce the production of textile hemp in the region. A complete production chain, from cultivation to the production of hemp yarns, was established to obtain hemp stems of a size similar to those of flax, to process hemp stems through existing flax scutching lines. This was achieved by growing hemp at very high stands (400–500 plants m^{-2}) that were then chemically desiccated when the plants reached 1.2–1.4 m in height. This technique is known as “baby hemp” production [35]. Hemp fibre of acceptable textile quality was produced, but the limited yield, the inconsistent quality, the use of chemical products to stop the plants‘ growth (with its consequent environmental impact) and the low economic turnover for farmers were the main causes for the failure of the enterprise, only 2 years from its start.

4.3. One m stem sectioning and bio-degumming approach

An alternative strategy to adapt hemp for flax scutching lines was studied in the framework of the European Hemp-Sys project (FP5-

LIFE QUALITY; no. QLK5-CT-2002-01363) [84], was further developed within the Multihemp project (European Union's Seventh Framework Programme; no. 311849), and is ongoing currently in the SSUCHY project (The Bio-Based Industries Joint Undertaking - BBI JU). Instead of shortening the height of the crop, as in the 'baby hemp' systems, in this case the hemp crop is harvested at full flowering when the plant reaches maximum height, and subsequently, the stem is cut in two sections of approximately 1 m length, which are kept parallel and baled in the same way as flax. The Hempsys project investigated the processing of non-retted stems, thereby avoiding the difficult step of field-retting, through controlled bio-degumming of the fibre after scutching [84]. This strategy proved feasible at the experimental level both during the Hempsys project [84] and more recently during Multihemp [54]. However, it was never upscaled at an industrial level due to the lack of dedicated harvesting machines that could cut the hemp stem into 1 m sections and lay them in an ordered swath for subsequent baling. The varying stem diameters of the 1 m long sections during processing (scutching and hackling) posed a further problem (in losses and fibre bundle refinement). In addition, there were concerns regarding the environmental impact of the bio-degumming phase due to high water and energy use [85].

4.4. Total fibre line

In the past 30 years, there have been various approaches to separate hemp stems to produce fine fibre bundles for the textile industry. Different separation techniques were developed and evaluated, like chemical separation, steam explosion [86, 87] or enzymatic treatment [88]. An attempt was made to use field-retted or even un-retted hemp from the 'disordered line' (see Fig. 7). Unique concepts for processing these kinds of hemp fibres/fibre bundles on open-end spinning machines were developed. The produced yarns were intended, especially for the clothing industry [89].

Current research and development work reports novel concepts for low twist flax and hemp bast fibre yarns from disordered lines [90]. Corbin et al. report on the development of low-twist hemp rovings [91], their results show that very competitive tensile properties are obtained for fabric-based hemp composites in comparison to flax cross-ply composite laminates. For mid-performance reinforcements, Gregoire et al. recently proposed an alternative process for extracting fibres based on fibre openers [52]. They reported that the length of the fibre bundles was sufficient for textile processing via the carded route, and mechanical investigations provided evidence that a combine machine could provide hemp of quality satisfying the requirements of mid-performance textiles.

4.5. Mixed route

This process chain represents the development of hemp fibre processing for the textile industry in China, which is referred to as "cottonisation of hemp" [83]. Developments in China led to new machine concepts and degumming technologies, which allow producing very fine hemp fibres/fibre bundles to be used on cotton or wool machines, as well to be blended with industrially produced staple fibres [83]. These developments allow the production of hemp fibre bundles, which are processed into yarns in the long-staple range of cotton and wool for clothing and home textile applications. Because of the length of the hemp fibres/fibre bundles, and the twist and the compactness of the yarns, these hemp yarns are less suitable for composite applications.

The fibres/fibre bundles needed for yarn production must be obtained from the hemp plant through decortication and separation processes. In the following section, the methods for hemp fibre processing are presented and critically evaluated.

5. Hemp fibre processing and hemp stem decortication plus separation

We begin with a definition of terms, outline the problem of comparing different processing techniques and provide a concept for precise classification. Fig. 8 expresses the systematic terminology used in traditional hemp processing.

To give a perspective on what has been done for flax, it is useful to cite Akin's work [92]. He points out that while traditional processing of long flax requires the orientation of the stalks and fibre bundles to be maintained throughout the value chain from harvest to final yarn, this strict orientation can be omitted in more modern processing lines. It is not the length of the bundles that is the key issue, but rather the orientation. According to Müssig [93], the following definitions help to distinguish between the processing techniques: (1) longitudinal flax, which is flax with fibres and fibre bundles particularly orientated in only one direction, and (2) disordered flax, which is flax with fibres and fibre bundles having no preferred orientation [92].

Production chain for *longitudinal hemp:* where hemp stems have to be kept parallel until the scutching and hackling phase.

Processing for *disordered hemp:* the most common destination for hemp crops in Europe, and various lines have been developed for this purpose [94].

Regardless of the orientation of the hemp stalks, hemp can be processed in many different ways. With the visualisation in Fig. 9, an attempt is made to systematically structure the different techniques to process hemp from straw to the final fibre bundles, ready for yarn production.

Hemp yarn production is possible for longitudinal and disordered hemp. For the selection of suitable processes (Fig. 9), it is essential to consider the following properties.

5.1. Decortication efficiency

After bale opening (see Fig. 9) the mechanical processing of hemp stems takes place to separate bast fibres from shives. This step is called 'decortication' [95]. To note, there is sometimes confusion or misuse of terms; for instance, some references to decortication can include the cleaning and even refining steps (see Fig. 9). Even some mix-up between defibration and decortication can be found based on the community of end-usage, e.g. pulp & paper [96]. Decortication has an essential position in the entire production chain, and its efficiency is influenced by the mechanical treatment employed [94, 97]. The assessment of decortication is mostly done visual and tactile, but the need for a more objective and reproducible evaluation of decortication efficiency has driven the development of lab-scale assessment machines [95]. With these developments, the energy consumed during decortication is now quantifiable and is paired with the yield content of bast fibres and shives, permitting a systematic comparison for a range of hemp varieties grown under different conditions [98]. This supports both the selection of improved hemp genotypes for dedicated materials applications [99] and the optimisation of agro-techniques [100], with the vision of tailored hemp production for specific end-uses.

Indeed, it is worth mentioning that the less aggressive the decortication step, the better are the mechanical properties of the bast fibres, arguably because of less fibre damage induced during decortication [101, 52]. This becomes evident through the work of Bos et al. [102], who report significantly higher fibre strength for manually decorticated fibres compared to fibres obtained through mechanical decortication. Decortication efficiency is also influenced by stem morphological characteristics [95] and biochemical composition [103]. The latter also impacts mechanical properties, and it is best illustrated through the comparison of decortication efficiency of green stems versus retted stems [104] and assessing the influence of the stem development stage [67]. For retting, to improve the suitability of hemp fibre for current or future intended industrial applications (e.g. structural composites), various bi-

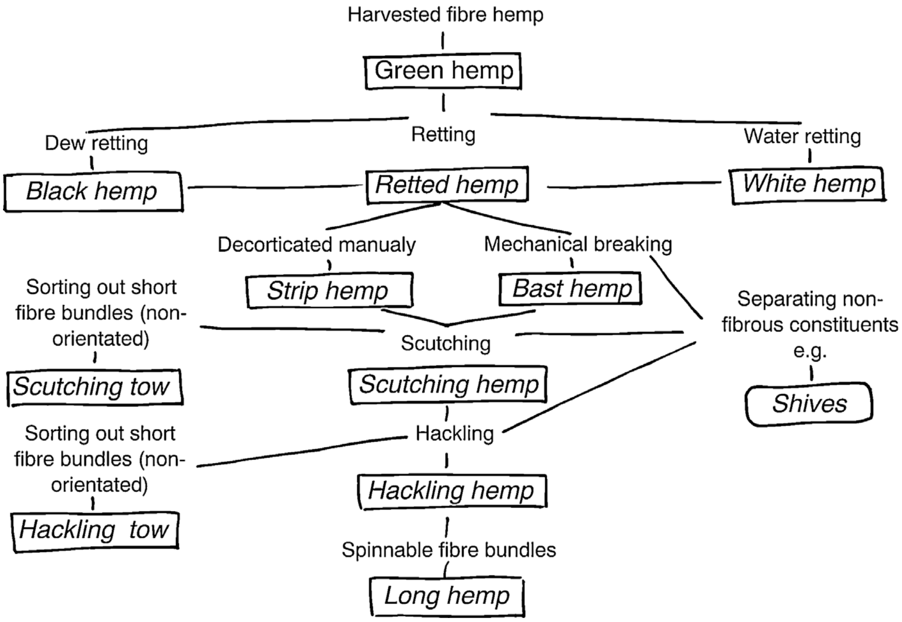


Fig. 8. A schematic overview of the systematic terminology used in traditional hemp processing (adapted from Schnegelsberg [78]).

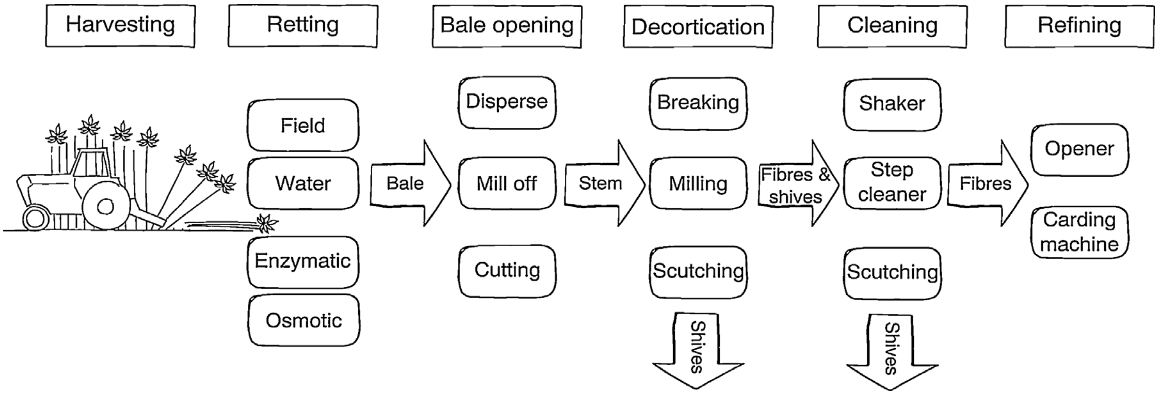


Fig. 9. A schematic overview of hemp fibre processing techniques.

otic or abiotic treatments (sometimes both) have been adopted on the fibres [105] and on the stems [96, 92]. Decortication of stems is made easier following retting – be it water-retting [106] or dew-retting. The underlying mechanism in action here is the decrease in the fracture energy at the interphases of the bast fibres with both shives [107] and the epidermis. Evidence for the latter is provided by imaging the cambium layer being cleaned of its xyloglucan by immunolabeling [108]. A distinct illustration of this assumption is provided by scanning electron microscopy observation (Fig. 10) [109].

Following retting, there is usually no other stem treatment carried out to assist decortication, arguably because of economic reasons, but also because retting is efficient. The steam explosion process must be mentioned in this context to illustrate the convenience of a controlled abiotic treatment. The stems are treated by moist steam (around 200 °C) under pressure (1.5–3 MPa) for a few minutes, followed by rapid explosive decompression [110], boosting the 'cleaning' efficiency. Decortication is facilitated due to the fewer contaminant shives adhering to the fibres. When applied to fibre bundles, steam explosion leads to more single fibres and fewer bundles, with fibre elements of superior length [111] compared to untreated fibre lots [112]. Some other alternatives do exist; for example, microwave-assisted stem decortication is currently being investigated at the laboratory scale. Other abiotic stem treatments that are low cost and industrially up-scalable are desirable to assist the decortication step toward improved fibre/shives fractionation with preserved fibre properties.

5.2. *Cleaning efficiency and contamination with shives*

During the decortication process, the shives are separated from the fibre bundles and are mechanically broken into millimetric particles [51, 94]. As the presence of shives is detrimental to composite properties, cleaning processes free fibre bundles from shives (see Fig. 9). The growth stage of the hemp plant influences the adhesive strength between the histological cell layers. Consequently, it has been shown that higher cleaning efficiency can be obtained by adjusting the harvesting growth stage of stems [113]. A complementary strategy was tested recently by tinkering with the decortication parameters. A large panel of 14 selected varieties were decorticated and the decortication efficiency shown to be dependent on the variety as well as the breaker (decortication) residence time. The retting duration is also shown to influence the decortication and cleaning efficiency by loosening the bond between layers of tissue (see Fig. 10); the longer the retting step (dew retting with a conventional duration), the lower the residual shives content [65].

5.3. *Fibre bundle fineness*

While the decortication step aims to separate the bast from the other cell types, increasing the fineness of the fibre bundles further helps improve composite properties [111]. Various processing techniques influence the fineness of fibre bundles. In practice, enzymatic treatment

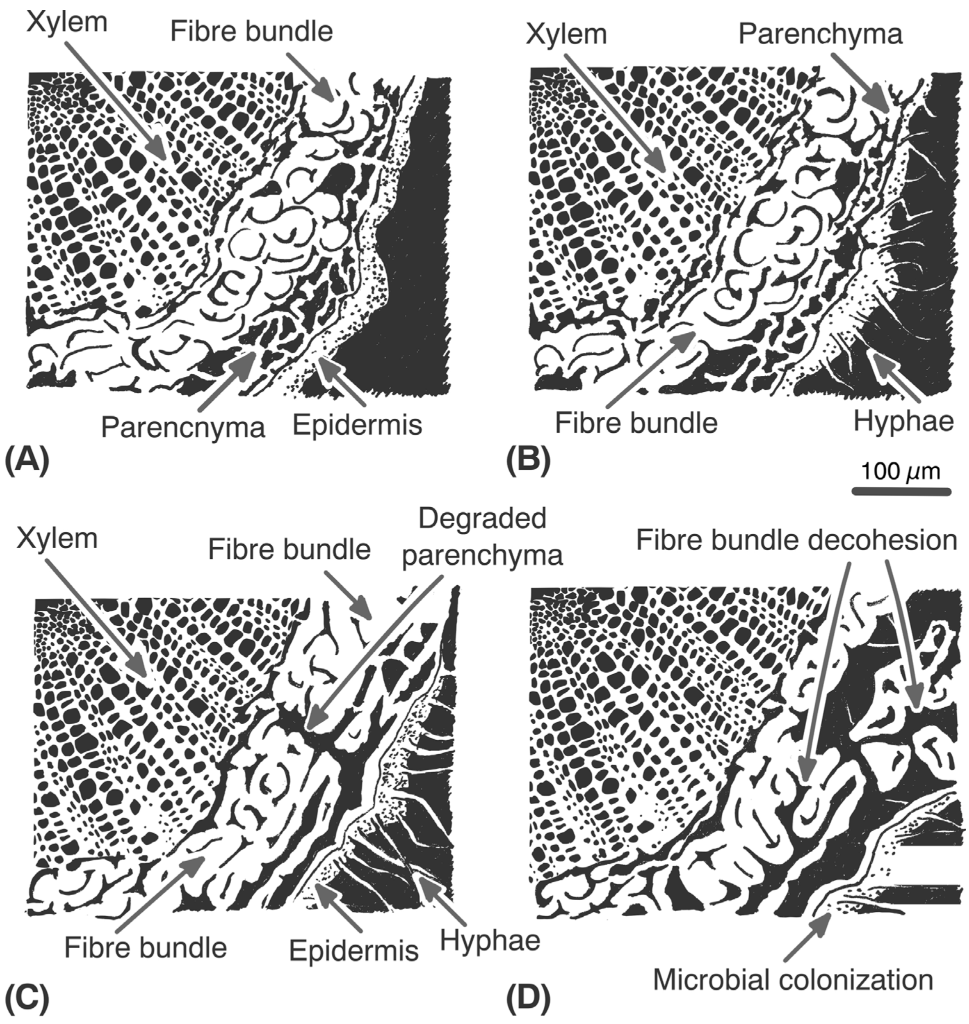


Fig. 10. A schematic illustration of SEM micrographs of cross-sections of hemp stem before and during retting; (A) before retting, after (B) 14, (C) 28 and (D) 42 days of retting. Scale bar=100 μm. (inspired by Bleuze et al.[109].).

of stems (as well as water retting) will result in finer bundles. Therefore retted stems are much preferred over unretted 'green' stems [104]. When a bio-degumming treatment is applied on stems, which is a bioprocess based on hydrolase enzymes, similar effects are observed [54]. In addition, we note that the fineness of the bundles was even better when steam explosion or enzymes were applied on decorticated bundles [111]. Controlled microbial retting has also shown positive results, as has fungi-assisted retting [114]. A mechanical operation like hackling or refining (Fig. 7) helps in getting smaller bundle sizes, and recently [98] the effect of the hemp genotype was illustrated with better bundle fineness obtained with a 'yellow stem' variety (Carmaleonte). The question of the use of intensive processing is always a question of balancing quality and quantity. Lower yields typically accompany intensive refining processes. They, therefore, have a high added value in terms of fineness and low shive content, often at the expense of the yield of long fibre bundles. The result is large quantities of short and low-value fibres.

5.4. *Fibre bundle length*

Currently, high-quality *long flax* (compare Fig. 7) have mechanical properties suitable for some structural components, though their high price (of fibres, rovings and composites textile) is a major limiting factor. Reinforcement products (non-wovens and aligned textiles) have been specially developed for high-performance flax composite applications in France, Belgium and Switzerland in the past few years [115, 116, 117]. The processing steps correspond to the traditional line (see Fig. 7) for flax in Europe using field retting. The yarns and rovings specially developed for flax composites are generally based on *long flax* (see Fig. 8), which is carded and processed into wet-spun yarns. Realizing a comparable processing technique for hemp in Europe (Traditional Line; Fig. 7) is not currently feasible. Instead, new concepts that use hemp from the disordered lines (total fibre line) need to be materialised. The processing technology has to be adapted in such a way that the hemp fibre bundles have a length spectrum (approx. 5–10 cm) which allow carding and processing into yarns (dry or wet) with a shorter staple length compared to *long hemp*.

Ongoing research aims to process flax and hemp fibre bundles from disordered lines into yarns with nearly unidirectional fibres by an alternative spinning process at lower costs [90]. It has been shown that unidirectional flax yarns produced from this alternative process lead to composites with comparable properties to those constructed with commercial *long-flax* roving. The work on hemp is still in development, with first results that seem promising [90].

5.5. *Fibre bundle damage*

Achieving high decortication yield and cleaning efficiency, alongside well-preserved fibre intrinsic properties (mechanical and morphological) can be challenging, particularly if complementary treatment processes (e.g. retting) are not used. Furthermore, even when the decortication process is optimised, or the crop growth stage is well-adapted to ensure low fibre/shive interface strength, there is a trade-off between limiting fibre damage induced during decortication and the other criteria, such as fibre/shive ratio and degree of individualisation. Fibre damage during decortication manifests as micrometric cell wall structural dislocations, sometimes referred to as defects or kink bands. They form along the length of the fibre spaced tens, hundreds or thousands of micrometres apart [118, 49, 119, 120] depending on dislocation density, harshness of decortication, and severity of composite processing [118, 49, 119, 121]. The tricky point lies in the definition of the length scale of these defects, as the local nanometric dislocation or misalignment of the cellulose microfibrils in a fibre could be considered a damage defect, and/or large micrometric kink bands in a fibre bundle could also be considered a damage defect.

At the outset, it is essential to mention that such damage defects are present, albeit in substantially smaller quantities, in unprocessed, non-decorticated fibres, and are also present in low quantities in hand decorticated fibres [122, 123]. Their multiple origins and descriptions in bast fibres have been widely reviewed [124], alongside their implications on composite properties [16]. Though such defects are detectable in unprocessed stems, for instance, induced by wind [118], they are also generated when hemp stems are processed mechanically [123] and especially in case of under-retting, when extracting conditions must be severe. Indeed, this goes back to the trade-off mentioned earlier about cleaning efficiency and the preservation of the structural properties of the fibre. The impact of all the production process steps on damage evolution in fibres was investigated recently [125]. The results highlight that the decortication stage is the major contributor to damage formation, and subsequent processing steps (see Fig. 9) like carding [52] also add to the total defect count, though to a relatively lesser extent. The selection of process steps and their intensity should be driven by the required fibre quality for its end products; for instance, separation and carding will create additional damage, but also generate finer fibre bundles.

The impact of the fibre extraction process on the morphological and mechanical properties of hemp fibres/fibre bundles has been investigated by researchers using carefully designed experimental setups. Thygesen et al. report a monotonically decreasing relationship between the processing steps and the strength of hemp fibre bundles [118]. They covered retting, scutching, carding, cottonization, and yarn production, and observed a strength reduction of approximately 30% per processing step (on average). Considering that no cellulose modification occurred during any step, they concluded that the strength reduction was driven by fibre ultrastructure damage. In this study, however, fibre morphology was not studied, nor correlated with fibre strength. Note that various hemp processing machines are in use today, and the principal differences in decortication processes, i.e. breaker roller versus hammer mills, will lead to hemp products with contrasting qualities in terms of length, defect count, and shive content [94]. Finally, the extraction process of hemp fibres, alongside crop variety and growth conditions, is an important contributor to the high scatter in its morphological characteristics, which in turn may account for hemp's lower tensile properties, compared to flax [126].

6. Stem harvesting, post-harvesting and retting

The harvesting time and the retting duration of the stems affect the maturity of the fibres, and are not well-controlled by farmers. These parameters also influence the mechanical properties and the degree of individualisation of the fibres, and consequently have a knock-on effect on the performance of the resulting bio-based composites. This section will cover three key points of discussion.

- The morphological properties of hemp, and in particular the degradation mechanisms and structural evolutions at the stem scale during retting will be discussed.
- The influence of retting on the properties of fibres and plant walls will be described, in terms of defects, modifications of the parietal structure, individualisation of the fibres and evolution of their mechanical properties.
- The decortication and separation of fibre bundles and the choice of the harvesting time will be discussed, in relation to the maturity and performance of the fibres. The conditions and monitoring of the retting process will be analysed.

6.1. *Impact of harvesting*

Harvesting is an important step in hemp production. The time and method of harvesting have a significant influence on the quality of the hemp fibres. It dictates the selection of further processing devices for hemp stems, and the economics of hemp fibres production. While the hemp crop can be harvested with a wide variety of prototype and commercial types of machinery [94], all harvesting systems can be grouped in two categories, *longitudinal* and *disordered*, as illustrated in Fig. 7. A comprehensive overview of developments in the field of harvesting and post-harvesting technology can be found in Amaducci and Gusovius [94].

The *disordered* system is the only one used in modern hemp cultivation. It involves standard or modified combine harvesters that, in one or two passages, collect the seeds and leave the stems on the field in a disordered swath. Following this system, the farmer can benefit from the income derived from the sale of seeds, and potentially from the extraction of CBD from the threshing residue [127]. However, in this system, harvesting is carried out considering seed ripening and not fibre quality. Notably, the fibres obtained from stems collected at seed ripening are more suitable for lower value applications, such as the production of paper and pulp [128, 129, 130], short fibre/fibre bundle reinforced thermoplastics [131, 25] or perhaps non-woven textiles (needle felts or fleeces) [130]. Several authors report that fibre quality decreases during seed maturation. Liu et al. have measured that the tensile strength is higher in fibres obtained from stems collected at the beginning of flowering than from stems collected at seed maturation [103]. This is probably due to the accumulation of secondary, short and lignified fibres, and to the reduction of cellulose deposition. Musio et al. measured lower breaking strength values in composites (through the impregnated fibre bundle test) made with fibres obtained from stems collected when the seed matured rather than at full flowering [54].

For the development of new harvesting methods for hemp, possible damage to hemp fibres by the harvesting process has generally not been taken into account. In the literature, there are few studies investigating the damaging influence of the harvesting technique on the fibre properties of hemp [94]. Müssig and Harig report that harvesting methods cause least damage to fibre bundles, if fibres and shives are not separated on fresh green stems during harvesting [132]. Müssig and Martens as well as Gusovius et al. come to the same conclusions [68, 133]. The study also examined a harvesting method that separates fibres and shives from fresh green stems in the field. This harvesting method shows a tremendous damaging effect on the fibre bundles, with a significant reduction in strength [132, 93].

6.2. *Impact of retting at the fibre scale*

During retting, the overall architecture of the plant is impacted. Retting, which lasts several weeks depending on its progress, is a microbiological process during which the stems are colonised by fungi and bacteria. These microorganisms secrete enzymes which induce degradation of the cell walls. Usually, studies focus on plant polysaccharides, although the deconstructing enzyme arsenal is known to be richer. The typical degrading arsenal includes phenol oxidases or proteases and other hydrolases because these polymers are majors constituents of the cell wall. Amongst the polysaccharides, hydrolases and hemicellulases are of major importance. During retting they have, for instance, the ability to degrade the xyloglucan epitopes localized in the cambium layer in flax [108]. This hemicellulose degradation, in turn, facilitates the dissociation of the fibre crown from the xylem part in hemp (see Fig. 10, C) [109]. To note, the most well-known and perhaps most studied hydrolases is the pectinase family [134, 135]. The pectins of the middle lamellae, the cortical parenchyma, the epidermis, the xylem and the bundles of fibres are gradually degraded, which favours the extraction and division of fibre bundles during the mechanical extraction step; an improvement of the separation of fibre bundles from the woody core of the plant is expected. Thus, the retting step induces a significant dissociation of the stem tissues and consequently a drop in fibre bundle interfacial cohesion.

At the scale of the single fibre, it seems evident that multi-scale and multi-feature modifications occur and evolve during the dynamic retting process. This has led to published reports with contrary observations in terms of physical properties (mechanical mostly), biochemical patterns, and fibre cell wall polymers arrangements (cellulose to mention one). The divergent conclusions are argued and even assumed, to be principally explained by the set-point of retting explored. In order to classify the dynamics of the retting process, it is not sufficient to use only the temporal unit (i.e. the retting duration). Rather, the pedoclimatic conditions must always be described, discussed and used for comparison. The effect of soil quality on retting with regards to the consortia of soil microorganisms present is a possible explanation of the different retting dynamics observed. Ribeiro et al. report in their study, which is based on gene sequencing, that the most important fungal and bacterial species are identical in six different hemp retting sites, but they differ significantly in their distribution [136]. This can be interpreted as the field retting process may progress differently according to the richness of its consortia of microorganisms. However, soil that is less rich in microorganisms could be suitable if the retting duration is increased. From a mechanistic point of view, the combination of bacteria and fungi seems very effective for flax [108]. The dynamic response of these microorganisms will probably also increase the efficiency of hemp retting [137].

The action of soil microbiota during retting aids the individualization of larger bundles into smaller bundles, though this can take a few weeks; Mazian et al. monitored this process of separation into smaller bundles after five weeks of field retting [67]. Alongside the changes at the bundle scale, it is clear that not only the middle lamellae between bundles but also the middle lamellae between fibres faces enzymatic degradation [42, 67]. The following sections will explore this further, with the mechanical properties and biochemical aspects as the focus.

6.3. *Impact of retting on defects and mechanical properties of fibres*

At the level of the single fibre, its seems evident from literature that over the retting duration the fibre mechanical properties will follow a bell-shape trend, due to the amount and diversity of enzymatic activities [109] executed by the fungal and bacterial microorganisms [137]. Quantified enzymes mostly poly- and oligo-saccharides hydrolases, despite the expected recalcitrance of lignin in the functional properties of fibre; hence, there is the need to also identify and asses oxydases (i.e. laccases). From a mechanical property point of view, there is first an increase in tensile strength in the early phase of the retting process, up to an optimum retting duration, before a sustained reduction in tensile strength of the fibres, this condition is often referred to as over-retting [68, 65, 101]. Trends in both strain at break and Young's modulus stand out in comparison to the development of tensile strength. The strain at break decreases with retting duration. The tensile strength of mechanically extracted single fibres from the same field confirm that both the under-retted fibre and the over-retted fibres over 70 days have lower strength (480 and 340 MPa after 10 and 75 days respectively; Liu et al. [104]) compared to the optimal retting duration (660 MPa after 39 days). Interestingly, the apparent elastic modulus of single fibres does not evolve substantially during retting, remaining between 15 and 17 GPa. In contrast, the strain to failure decreases by 30% with retting duration, starting at 3.5% after 10 days of retting [101].

Liu et al. report comparable trends with higher values for all reported characteristics, and highlight the effect of the hemp growth stage [104]. Indeed, if stems are harvested early, and the stem and cells have not matured, tensile strength only decreases with increasing retting duration. This is in contrast to the bell-shape trend observed for mature stems with mature cells.

Mazian et al. report a substantial difference in tensile strength between non-retted (170 MPa) and retted (340 MPa) fibre bundles [67]. But the authors did not observe a significant reduction in strength for a prolonged retting duration (of 63 days); this is in contrast to the previously described bell-shaped evolution in tensile strength with retting duration. The Young's modulus was 8 GPa for un-retted samples and increased to values of 12 GPa for the retted samples, independent of retting time. They also observed that the strain at break of the fibre bundles increased with retting time [67] until the stem was over-retted; this is again in contrast to the gradual decrease in failure strain with retting duration reported for single fibres [65, 67].

6.4. *Impact of retting on parietal architecture and biochemistry*

Most publications thematically related to this section attempt to link physical properties with the development of biochemistry and thus implicitly with parietal architecture. A sensitivity analysis reports that at the level of single fibres, the Young modulus is a first-order factor [138] for mechanical performance, and is directly related to the amount of crystalline cellulose in the cell wall. Del Masto et al. have shown that the stiffness of a fibre is strongly influenced by the dispersion in the morphological characteristics of the fibres. Tensile test simulations show the strong influence of the degree of ellipticity (vis. fibre cross-section shape) on the form of non-linearity of the tensile stress-strain response. The results suggest that this morphological effect is strongly coupled with structural properties and physical mechanisms, such as the viscoelastic behaviour of cell wall components [126]. It may be assumed that retting directly affects the morphology of the fibre by modifying the fibre ultrastructure (changing of the crystallinity of the cellulose, measured through the crystallinity index (CI)). For example, the CI decreases when over-retting begins. As a consequence of the observed decrease in cellulose crystallinity, a strong reduction in stiffness, strength and elongation at break is suspected [65]. In the mentioned work, a decrease in cellulose crystallinity from 78% to 73% was observed before and after over-retting. This led to a predicted loss of 10% in tensile strength, which was consistent with the experimental values. However, a recent x-ray diffraction (XRD) investigation on fibre bundles during retting show an increase in cellulose crystallinity from 53% to 73% at 63 retting days [67]. A similar trend was recently shown on flax fibres [42]. One may hypothesize that the over-retting stage was not reached in these studies. What is imperative to point out here is the re-occurring difficulties in comparing data between various studies carried out using different techniques. With XRD, for example, a single to double crystallinity value of the cellulose can be determined, depending on the treatment of the measured data (see the discussion in Placet et al. [65]).

The same criticism can be made when determining biochemical components. The reported changes in the chemical composition during the retting process are sometimes contrasting and inconsistent; this can only be explained by the fact that the composition of the fibre and fibre bundle has been mixed up [96]. The retting process first acts on the bundles by depectization that degrades pectin-enriched structures, like the middle lamella. Pectins, with their amorphous nature and short-chain lengths, are good carbon substrates for the colonising microorganisms during retting. These pectin may have some carbohydrate monomers in common with hemicelluloses, for instance arabinose and rhamnose monosaccharides [139]. This can make it challenging to confidently attribute the quantified monomers to one of the two families. In parallel to enzymatic hydrolysis of pectins and hemicelluloses preferentially located in the middle lamella and the thin primary cell wall, the consortia of microorganisms also produce enzymes targeting glycan polymers, and therefore cellulases are also active. There is no direct evidence that the amorphous segments of cellulose are degraded before the crystalline segments. Only indirect observations support this proposition, with a quantitative decrease in glucose in the fibre/fibre bundle, along with an observed increase in cellulose crystallinity. The authors hypothesise a reduction in the amorphous content of cellulose, which is also coherent with the observed increase in measured mechanical properties [42]. The cellulose crystallinity of the fibres/fibre bundles needs to be preserved to promote overall fibre quality. It is known that both tissular and cellular heterogeneity in plant biomass present a significant barrier for enzymatic cell wall disassembly [140], by hampering enzyme penetration [141]. The size of the enzymes may also present a physical limitation to their penetration. Cellulase is one of the largest enzymes, and therefore, its accessibility is limited. However, accessibility can be facilitated by the simultaneous degradation of the surrounding polymers, such as hemicelluloses. The exact knowledge of the cohort of enzymes and its sub-class-specificities contributes to a better understanding of the dynamic bioprocess of retting, and aids the monitoring and management of the retting process for better control on fibre mechanical properties. The influence of parietal arrangement on structure and consequently mechanical properties was recently highlighted at the scale of the bundles by Jankauskiene et al. [142]. The authors compared a large panel of water-retted hemp lots, and they evidenced that the inter-fibre porosity within the bundle has a strong impact on its strength; the higher the separation due to porosity, the lower the strength. This separation seems to be influenced by the biochemical composition, in particular, the changes in pectin distribution.

Polysaccharides are not the only polymers present in hemp fibres/fibre bundles; the role and evolution of lignin, a complex polyphenol macromolecule, is also important. Lignin is biosynthesized in the final stage of fibre-cell wall remodelling, and its content ranges from 2% to 6% of dry matter [37, 33], but can reach values of 11–13% [143]. The reason for these high values is mainly due to the type of analytical method used (Van Soest in this case). There are contradictory reports in literature on the impact of retting on lignin. Some authors report an increase in lignin content, while some a decrease. In the case of an increase being reported, the synthesis of ‘new’ lignin during retting is unrealistic. An analytical bias is possible, if nonspecific methods based on gravimetry, such as Van Soest, are used due to condensate proteins and complexes that are counted towards the lignin fraction [144, 145, 146]. Due to the recalcitrance of lignin, it is possibly not an ‘absolute increase’, but rather a ‘relative increase’ due to the removal of polysaccharides of other cell wall components, such as pectins and hemicelluloses. Although recalcitrant, some enzymes (e.g. peroxidase, LPMO) and biotic processes can depolymerise lignin, and the consortia of retting microorganisms have the ability to do this within weeks.

While the degradation of lignin seems more likely, the question is how does this take place (and how it is described in the literature)? Authors, reporting a decrease in lignin content during retting and at the latest stage of retting, like Mazian et al. [67], most likely analysed samples in which the net balance between initial enrichment of the lignin compartment (quick removal of polysaccharides) and degradation of the polymer is negative. When interpreting the published results, it should be considered that samples are compared with an offset in the production of lignin-degrading enzymes. It must be taken into account that these enzymes are produced in the latter phase of field retting and that secretion takes place under, as yet, unknown control mechanisms of the consortia of microorganisms.

Results from literature sometimes reveal contradictory observations, from a mechanical, biochemical or fibre-optical point of view. In the case of retting, it is difficult to compare batches, as the boundary between under-retting, normal retting and over-retting is unclear, subjectively established and dictated by the experience of farmers. This reflects the lack of coordination and monitoring of the property-governing retting process in the hemp agricultural sector. It further underlines the need to control this stage better to obtain fibres of optimal quality.

6.5. *Hemp stem morphology and impact of retting at the stem scale*

Morphologically speaking, a stem of mature hemp can be considered as a tapering hollow body which exhibits variable length and diameter according to the variety, quality of the soil and environmental conditions [147, 148]. Conventional European hemp stems can reach heights of 2–4 m and diameters around 10–30 mm with a tapered profile from the apex to the bottom of the plant [149]. The internal architecture of the stem is hierarchical and organized from centre to periphery with pith, xylem, vascular cambium, phloem, fibres, cortical parenchyma and epidermis (Fig. 11, B). The fibre network can be completed by a secondary fibre network, preferentially present at the bottom of the stem [31]. These fibres probably have a mechanical support function and develop when the plant needs to increase its flexural stiffness; they are much shorter than the primary fibres (2–3 mm against 20–30 mm) and have significantly smaller cross-sections. On the other hand, the mechanical properties of their walls are similar to that of primary fibres [38].

From a mechanical point of view, it is possible to simplify the representation of this stem cross-section (Fig. 11, A) by considering only the most important parts, i.e. the fibre zone and the xylem of the stem (Fig. 11, C). Although fibres play a significant role in the bending stiffness of the plant, the woody core or xylem has also been shown to make a significant mechanical contribution [150]. The latter consists of conductive tissues with a honeycomb structure [151]. The primary fibre zone is much denser with long gelatinous fibres (20–30 mm on average) and bound together by a very cohesive intermediate lamella composed mainly of pectic compounds. The fibres consist of a sequence of plant cell walls including a primary wall, a secondary wall, and a lumen. The secondary cell wall is the thicker and stiffer layer and is reinforced by cellulosic microfibrils (MFI = 4–11 °; Z-twist) in a non-cellulosic matrix of hemicellulose, pectin and lignin, and provides the majority of the fibres’ mechanical properties [152, 153, 138].

In summary, a hemp (or any bast fibre) stem can be considered as a model for an optimised composite material, with long and stiff fibres around the periphery, distributed evenly and unidirectionally in the direction of the stem and, in the centre, a light foam made up of rigid walls; the central lacuna completes this lightweight, rigid structure. This optimised sandwich structure allows the plant to perform exceptionally well in terms of stiffness, buckling resistance and slenderness.

Compared to hemp, flax is reported to have a fairly low variation in fibre morphological properties. A possible cause could be the influence of the morphology of the stems on the field retting process. With a diameter of only a few millimetres, the flax stem is much thinner than a hemp stem and almost perfectly cylindrical in shape. Hemp stems are significantly thicker and also strongly tapered along the length of the stem. During the retting of the flax stem, the microorganisms can execute the retting process much more homogeneously. In the case of hemp, as different areas of the stems are also morphologically different, this may lead to a more irregular, inhomogeneous retting, which in turn leads to greater variability in morphological fibre properties. The degradation processes of the microorganisms become increasingly visible on the plant surface during retting, which is also noticeable by a change in the colour of the stem. The colonization by microorganisms makes the stem darker [68, 109, 154]. For flax, this side effect of retting is employed as a management tool of the retting process by monitoring changes in colour and CIELAB measurements (CIELAB or CIE $L^*a^*b^*$ colour space is a colour space defined by the International Commission on Illumination – CIE –) [92]. As Faughey and Sharma report, the Near-InfraRed Spectroscopy (NIRS) method offers the possibility of non-destructive measurement of important flax quality properties [155]. The application of this method has already provided reproducible results in determining the degree of retting of flax stems [156]. For this purpose, a retting sensor has been developed, which primarily measures the blackening of the flax stem due to microbial degradation. The quotient (A1000)

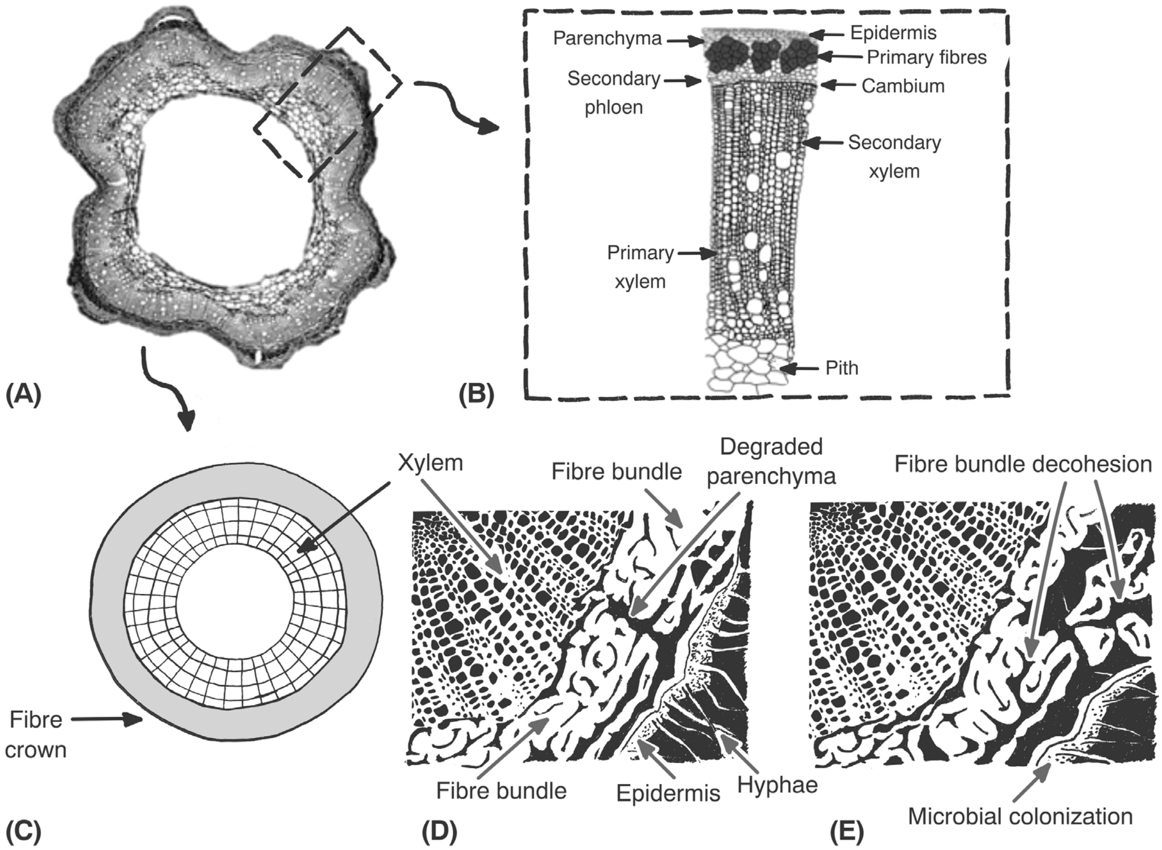


Fig. 11. The organisation of a hemp stem (A) can be schematically simplified (C); retting step induces a significant impact on the cohesion of tissues, inducing a division of the fibres bundles and a progressive separation of the fibre ring from the woody core of the stem (D&E). Inspired from [191, 109, 154].

is used to assess the degree of retting of flax stems {A1000 quotient: A1000 = Abs.(1000 nm)/Abs.(1370 nm)} [156, 86].

Müssig and Martens used this approach as a reproducible method to replace the subjective visual classification of field retting of hemp using a scoring system [68]. To start the baling of the stems after field retting to ensure that the hemp stems are harvested and stored at the highest possible quality, the A1000 value was used as a marker. The following characteristics were chosen as a measure of good quality: easy to decorticate, a low percentage of shives and minimal shortening of fibre bundles with a simultaneous refinement of the fibre bundles [68]. Although the suitability of NIRS as a tool for controlling field retting has been proven, this method seems not yet to be accepted by farmers.

At the beginning of the retting process, only a small amount of porosities can be noticed in the phloem area (Fig. 11, D), though after 42 days (Fig. 11, E), a significant decohesion of bundles, especially close to the epidermis part is highlighted. Thus, retting induces irreversible changes in the hemp stem architecture and especially in the fibre area between bundles and surrounding tissues. These modifications impact the structure and the mechanical performance of the stem [154].

It is possible to quantify the impact of retting on mechanical properties of the stem. To characterise plant stems, simple flexural tests have been developed for many years and reviewed by Shah et al. [157]. Their objective is mainly to link the mechanical behaviour of the stem with plant stiffness, buckling resistance and slenderness [158, 159, 160] and to understand the biomechanics of plants better. The bending behaviour of stems can be described to be similar to that of thin-wall tubes [161], and ovalization during the test needs to be avoided as it leads to substantial shear stress. Experimental parameters such as span length need to be carefully selected, according to the morphology of the stem. For hemp, Réquilé et al. studied the contribution of the fibres to the mechanical properties of the stems, and proposed to use a span length corresponding to a stem aspect ratio (L/D) of 40 to avoid the Brazier buckling effect during testing [107]. In the case of hemp, the xylem contributes less than half of the global stiffness of the stem (45%). Even though there are no published results on the stiffness of retted hemp stems, this test method seems to be promising for rapid mechanical assessment of the impact of retting on stem integrity.

Another way to quantify the impact of retting on stems is to implement a peeling test. Réquilé et al. investigated the peeling behaviour of hemp stems, before and after retting [154]. Based on the analysis of the fracture energy at the fibre/woody core interphase in combination with SEM observations, a significant decrease in fracture energy was measured with increasing retting time. The results show a strong influence of retting on the ease of peeling the outer tissue of the stem [154]. Thus, by bending or peeling tests, mechanical and cohesion behaviour of a plant stem can be assessed and monitored over the retting time. A recent paper reports a new technique that can be used as an indicator for the degree of retting. The method is based on the investigation of the temporal dynamic of volatile organic compounds (VOCs) and odours emitted by plants during retting [162]. The authors report a decrease in VOCs and plant odour with retting duration.

7. Cultivation strategies for fibre hemp

Hemp is considered an environmentally friendly crop, which can be grown in a wide range of environments with limited inputs using sustainable agro-techniques. There are no pesticides or herbicides used in hemp cultivation. Organic or mineral fertilisers are usually applied before sowing and, especially in high stand cultivation for fibre destination, the crop is planted in very narrow rows that render access to the field after sowing practically impossible, but greatly increase the competition of hemp over weeds. The success of hemp cultivation largely depends on decisions and agronomic interventions that are carried out prior to sowing. Fine-tuning of hemp agronomic choices must consider variety characteristics, environmental conditions and of course the end-use of the hemp crop. Considering the scope of this review, the focus end-use is high-quality fibre production. However, it is worth mentioning that hemp is a multi-use industrial crop, also cultivated for its seeds and high-value secondary metabolites [127, 163]. The possibility to grow hemp as a multi-purpose crop is, for sure, relevant from an economic perspective as the income derived from the seeds and/or the inflorescence improves the farmer's income, making hemp farming cost viable (if not attractive). This is particularly relevant if the price of hemp fibre must be reduced (in the coming years) to compete with alternative natural or non-natural fibres. In this regard, combining the production of fibres with that of the inflorescence seems an optimal solution as harvesting time for the fibre and the inflorescence is synchronous, in contrast to delaying harvesting until seed maturity, which reduces fibre quality due to increased lignification and accumulation of secondary fibre [151, 37].

7.1. Varietal selection of hemp

Hemp is a naturally dioecious plant which belongs to the Cannabinaceae or Cannabaceae family. According to Small and Cronquist, this family belongs to the order Urticales and includes two genera, Cannabis for hemp and Humulus for hops [164]. According to Bremer et al., the Cannabinaceae are in the order of Rosales, which also includes nettle (*Urtica dioica* or *urens*) and ramie (*Boehmeria nivea*), other plants valued for their fibre content [165]. In the Cannabinaceae family, the genus Cannabis is associated with a species, *Cannabis Sativa*, but its subdivision, according to the authors, is controversial. Some consider that only two subspecies exist [164], *C. sativa* subsp *sativa* and *C. sativa* subsp *indica*, while for others the subspecies ruderalis, the savage form of the plant should also be considered [166]. Regardless, *C. sativa* is the most widely grown species with varieties selected mainly for fibre and seed production. The species *C. indica* includes psychotropic varieties with a high production of TetraHydroCannabinol (THC) (psychoactive molecule).

During the 20th century, the selection of industrial hemp made it possible to develop non-psychotropic varieties (*C. sativa*) with a TetraHydroCannabinol level below 0.2% (THC, psychoactive molecule) in order to comply with current regulations. The varieties selected and cultivated today in Europe are descendants of the monoecious Fibrimon variety, known for its high fibre content and its hardy character [167]. The varieties mainly cultivated today are nevertheless very polymorphic because they were originally obtained from monoecious plants, naturally present in dioecious populations. The origin of industrial hemp leads to the diversity of development and morphology obtained on monoecious plants. Indeed, the polymorphism that results from this selection method is very strong within a variety. Selection efforts focus on the development of monoecious forms with high female plant expression, with masculinized plants having a shorter lifespan due to their high sensitivity to parasites. This allows better biomass yields to be obtained and also reduces the heterogeneity of the products harvested.

7.2. Selection criteria and trade-off governing variety choice for composite applications

Choosing the right variety is of paramount importance to ensure a successful crop with a high yield of quality fibre [168]. Large production of fibre is obtained by choosing a late variety, that in a given environment maximises stem production [100, 169] with high fibre content. A wide range of fibre content can be found among hemp varieties [167], with the highest fibre level to be found in monoecious varieties that have undergone extensive breeding during the 20th century. Limited information is available on the intrinsic quality of fibre from different varieties, but traditional dioecious genotypes tend to have a superior fibre quality than monoecious ones [170]. Differences in fibre fineness among dioecious and monoecious hemp varieties, due to different single fibre diameter, have been reported [40, 171, 98] but large differences in fibre quality are indirectly caused by variety earliness. In early varieties, having a short growing cycle, the degree of fibre maturity (i.e. filling of the lumen) tends to be lower than in late varieties, but in the latter, the accumulation of secondary fibres tends to be higher, especially in the lower internodes [35].

It is evident that multiple traits should be considered when choosing a genotype for biobased composite applications, but overall it seems advisable to choose a late variety that will produce a high yield of mature fibres. It should be noted that late varieties have a lower seed production, which is a problem in the case of dual-purpose crops [168] and harvesting can fall under unfavourable weather conditions, both for stem drying and particularly for field retting [100, 68]. Even though a number of studies have recently been published on this topic [109, 67], field retting of hemp is a rather unexplored process that depends on a large number of factors that are very difficult to control. In recent years, to reduce the risk of field retting, and improve fibre quality, breeders have developed genotypes that are easier to decorticate and for which the need for retting is significantly reduced or even null. In recent research Musio et al. confirmed that in a “yellow” variety (i.e. with lower lignin content and improved decorticability) [172], compared to a conventional “green” variety, fibre extraction was more efficient [54].

7.3. Effect of environmental conditions on hemp yield and fibre quality and future perspectives under climate change

Hemp is a ubiquitous species, which has been successfully cultivated in a large array of environments for the production of fibre, seeds and secondary metabolites. The production of hemp fibre is affected by environmental condition in a number of ways. Research papers describing hemp production under contrasting environmental conditions [173, 174, 168], irrigation regimes [175] and temperatures [176] have mainly focussed on plant production, and data on the effect of climatic factors on hemp fibre quality are relatively scarce. No specific information on the effect of temperature or water availability on fibre quality is available. Regarding flax, Milthorpe showed that hydric stress during cultivation induces a significant decrease in dry biomass, reduced fibre size, but a similar quantity of fibres [177].

Climatic conditions have a relevant indirect effect on fibre quality affecting the intensity and duration of field retting. In the past, high-quality fibre was mainly obtained by water-retting of the hemp stems, though nowadays this practice is highly regulated due to environmental problems, and was also abandoned due to high labour cost requirements. High-quality fibre production is, therefore, dependent on suitable weather conditions during the phase of field retting.

A major concern for high-quality hemp fibre production is the frequency of storms that can lodge the crop or bend the stems, rendering harvesting of *long hemp* production impossible or challenging. Unfortunately, a feature of the changing climate is the increased frequency of strong winds and storms that can severely damage hemp cultivation. Another feature of climate change is the alternation of extremely dry or wet years that have a strong influence on hemp growth and fibre development. Hemp is extremely sensitive to excess water, especially in the first growing phases, so heavy rains after emergence or cultivation in soils with poor drainage determine stunted growth and reduction in plant density, which in turn result in low yield and poor fibre development. Additional concerns over climate change are related to the frequency and intensity of drought periods. When established, hemp has relatively good tolerance to drought, but in early phases of development, when the taproots are still superficial, plant growth is severely affected by drought, plant density is significantly reduced, but more than that, flowering can be induced and plant height severely shortened [100].

7.4. Soil conditions and plant establishment: keys to a high stand homogeneous crop for high-quality fibre

While it has been proven that plant density has a limited effect on hemp biomass production and fibre yield [100, 178], a high and homogeneous plant density is needed to produce fine fibres suitable for textile applications or high-quality composite applications. Plant density has a large effect on plant biometrics; stems of plants grown at higher density are thinner and have primary fibres with a lower diameter than stems of plants grown at low plant density, similar to observations and measurements on flax [147]. A decrease in stem diameter could be interesting in an objective of fibre extraction with conventional scutching equipment (see Fig. 7; “one m stem sections”). In addition at high plant density, there is a very limited development of secondary fibres [35, 40] which is also a positive point for composite applications, as although these secondary fibres having similar mechanical properties to primary fibres, they have a drastically reduced length, penalizing their aspect ratio and consequently their reinforcement ability. At high plant density, interplant competition for light limits final plant height, but also stimulates stem elongation in the first phases of plant growth, which results in longer internodes at the base of the plant [179]. It was found that longer and finer fibres are located in thin and long internodes [34]. Besides fibre quality (i.e. finesses and presence of secondary fibres), the effect of plant density on stem biometrics affects their suitability for further processing. In particular, density is a strong determinant of stem length and influences the effectiveness of harvesting systems designed to cut the stem into 1 m segments [84]. Density also significantly affects stem diameter, which in turn affects stem decorticability.

Final plant density, and as a consequence the impact this has on fibre characteristics, is determined by the amount of seed used at sowing and by the environmental conditions affecting seed germination and plant establishment. For successful crop establishment, the soil preparation must be optimal and weather conditions favourable [100].

The effect of nitrogen fertilisation on hemp yield is limited, and in a wide range of environments 60 kg ha^{-1} of nitrogen was sufficient to reach maximum stem and fibre yield [176]. Considering that nitrogen fertilisation is one of the most relevant component affecting the environmental impact of field crops, the limited nitrogen requirements of hemp and its high nitrogen use efficiency [178] contribute to the low environmental footprint of hemp fibres. Data on the effect of nitrogen fertilisation on fibre quality is limited, but high nitrogen fertilisation tends to decrease decorticability and fibre quality as a consequence [180]. Barth and Carus compare different bast fibres with regard to their sustainability [181]. In order to avoid different allocation effects and to carry out a comparable ecological balance, they use the same fibre separation process for hemp and flax (total fibre line - disordered line). The study (cradle-to-gate) compares the global warming potential (GWP) per tonne of natural fibre that can be processed into needle felts and finally into compression moulded composites for automotive interior applications. In this comparison, flax and hemp when fertilized with mineral fertilizer show approximately equal GWP values. When using organic fertilizer, hemp performs better [181]. In this context, it should be noted that the processes of spinning and weaving have a substantial impact on the environmental categories, especially with regard to energy use.

In their overview paper on the life-cycle assessment (LCA) of flax and hemp, Müssig and Albrecht point out the challenges in the preparation and interpretation of LCA studies [182]. In order to interpret data on environmental impacts, to compare the results of different LCA studies or to compare the data of own surveys with results from the literature, it is essential to know the exact background, the balancing framework, as well as the allocation methods of an LCA. It is also important to know the functional unit and to precisely define the objective of the LCA. For example, when evaluating different natural fibre reinforced polymers, not only the ecological impact per kg of fibres, but also the ‘function’ of a kg of fibre, in terms of the achievable mechanical properties of the composite material, must be compared [182]. In this context, the functional unit of a composite material can be its stiffness, for example. To calculate the tensile properties of different natural fibre composites on the basis of the fibre properties, the approach of Madsen and Lilholt can be used. They have developed a modified version of the rule of mixtures, supplemented by parameters of the porosity content and the anisotropy of the fibre properties, to improve the prediction of the tensile properties of composites [183]. More information on the life cycle assessment of hemp fibre-reinforced composites can be found in [131, 184, 185, 186].

7.5. Ideotyping hemp for composite applications

The ideal hemp genotype for composite applications should produce large quantities of high-quality fibre (i.e. high finesses, high degree of maturity, high crystallinity of the cellulose and a low amount of structural defects, to mention few) with low environmental impact and high production stability (under both actual and future climate scenarios). In previous breeding programmes, the yield of stems in t/ha was the main focus. Questions of fibre properties (length, fineness or strength) were not considered. In some breeding programmes (e.g., Toonen et al. [187]) the focus was on improving the decoration of hemp stems in order to obtain fibres that contain as little shives as possible. New genotypes should be bred in the future, which in addition to high fibre content and good defoliation properties also provide high-quality fibres. The aim of breeding should be to increase the fibre length while maintaining high stiffness and strength of the fibres.

The height of the crop is a relevant parameter when implementing a harvesting system for longitudinal hemp processing as in the case of “baby hemp” or “one m stem section” (Fig. 7). Plant height can be controlled by combining a variety with a certain photoperiod sensitivity and a specific planting density. To optimise harvesting efficiency for longitudinal hemp, in each environment, the right combination of planting density and variety earliness should be found [100].

Variety earliness is an essential site-specific trait that not only influences stem height and stem yield, but also determines harvesting time and the probability to have favourable weather conditions for field retting. A valuable feature to reduce the risk associated with unfavourable field retting conditions is the introgression of the “yellow” character that drastically reduces retting time.

Additional traits that could increase the economical sustainability of hemp cultivation are high content in secondary metabolites (i.e. cannabinoids and terpenes), or the coupling of high seed yield and high fibre quality at seed maturity. Finally, in perspective of ongoing climate change challenges, the future of breeding envisages the selection of varieties being more drought tolerant.

8. Under what boundary conditions can structural components be built from hemp fibres?

At the product scale, small wind turbine blades have been fabricated from flax composites by various research teams (not commercially/industrially), and so it is conceivable that hemp composites may be used to fashion similar sized blades in the near future. However, much research and testing is needed to understand the behaviour of hemp biobased composites, and attain confidence in their reliability, for hemp composites to be used at a larger industrial scale for structural components.

There is not sufficient literature on high-volume fraction (>50%) aligned hemp biocomposites manufactured through well-controlled manufacturing processes, such as resin transfer moulding and prepregging. Moreover, there is a lack of comprehensive studies on their mechanical performance (fatigue and creep, compression, torsion and multi-axial stress, vibration and impact), environmental and ageing performance (with moisture, fire, low or high temperature), economic feasibility, and life cycle assessment. In addition, there are also no studies at the product scale (or hemp biobased composite scale) on computational modelling (e.g. finite element analysis), manufacturing simulation (e.g. resin flow behaviour) or structural simulation (e.g. strength, fatigue or modal analysis). At the 'system-level' of the product, the compatibility of hemp biobased composites with other materials in the product (e.g. balsa wood core, or a UV and rain-protecting polymer gel coat/paint, or adhesive bonding agents to glue the spar to the skin) may also need specific studies.

This can only be achieved through systematic research and development programmes covering multiple length scales (from mm-scale fibre to m-scale product). Such programmes may also reveal that hemp (and natural fibre) biobased composites may not always be 'drop-in' replacements to glass fibre composites. Instead, some (if not complete) redesigning of the product may be necessary to optimise the use of hemp biobased composites in the application. Indeed, just like the initial use of quasi-isotropic carbon fibre composites in the 'black aluminium' approach was a gross under-utilisation of carbon fibre composite materials, making a hemp biobased composites blade to be exactly identical to a glass fibre composite blade (e.g. same composite lay-up, shape etc.) may be under-valuing the potential of hemp biobased composites, and worse, leading to simplistic conclusions that 'they [hemp biobased composites] do not work'. The question, perhaps, we should be asking is, 'when do they work?' or 'how can we get them to work?'.

Research into hybridisation approaches (e.g. hemp + carbon fibre composites) and biobased resins as alternatives to conventional synthetic resins could provide some answers. At the preform reinforcement scale, currently, mainly 2D random non-woven's (fleeces and needle felts) and bi-axial plain woven fabrics are available in large scale for hemp. For structural products, a larger variety of low (ca. 50 g/m^2) and high (>800 g/m^2) areal density aligned hemp fabrics are needed. These include unidirectional preforms, as have been developed for flax already, but also biaxial and triaxial preforms. Exploring 3D-knitting, braiding, prepregging, yarn/tape winding, automated fibre/tape placement and other manufacturing processes and their requisite preform reinforcements are also vital, as specific products may be more readily manufactured through specific processes. In general, to substantially reduce property loss from misoriented discrete hemp fibres, avoiding crimp at the fabric scale through stitched multiaxials or non-crimped fabrics, and avoiding twist in yarns through low-twist (or twistless), possibly pre-impregnated, hemp rovings and tows would be ideal.

Hemp composite reinforcements need to be developed as flax reinforcements have been developed over the past decade or so. This may prove to be challenging, as hemp, being a very different plant to flax, has a larger shive content and attaining shive-free fine and long fibre bundles will require specific upstream fibre extraction and processing steps. Unlike for flax, the current industrial fibre extraction processes for hemp do not allow production of combed long fibre bundles, and are unsuitable for the manufacture of quality textiles or unidirectional reinforcements. A part of the European industry disappeared with the advent of cotton and synthetic fibres and it is necessary to re-develop fibre extraction systems and spinning mills to support the biobased composite industry in achieving its potential.

Finally, incorporating hemp fibres into composites makes it possible to reduce the environmental impact of these materials. This is a first step that is already being industrialised, particularly in the field of short fibre thermoplastic composites. In order to complete the thinking and benefit as much as possible from the environmental properties of these fibres, it is necessary, in the years to come, to work on the choice of matrices. The development of biodegradable matrices is essential to further develop end-of-life solutions. Gradual replacement of thermoset polymers with thermoplastic matrices that are recyclable and/or degradable at the end of their life is also an attractive approach. The use of vegetable oil-based resins, which have a low global warming potential and can be thermally recycled at the end of their life cycle together with the natural fibres may also present an ecologically sustainable solution [188]. This shift has already been initiated by the aeronautics sector or certain niche markets with high added value. For economic reasons, it is not yet the case in the ship-building or automotive industries, for example, which are highly sensitive to the cost of materials. Reducing environmental impact (in terms of embodied energy, emitted carbon, end-of-life waste) is probably the big challenges for the next 10–20 years for these industries.

To meet the desired performance at the composite scale, as part of a top-down evaluation, optimisation right down to the fibre scale is necessary. In particular, achieving consistency in fibre quality, optimisation of the first mechanical transformation of the stem, and progress in large-scale retting and varietal selection are priorities.

Consistency in quality of the physical-chemical properties of the fibres would be attainable by sorting the secondary fibre from the primary fibre in the first transformation process, or by reducing the content of secondary fibres though agronomic or genetic approaches. This would lead to reduced scatter in fibre dimensions (geometric properties), as well as mechanical properties. Optimisation of the transformation process would also help produce minimally-damaged fibres that are clean and well-separated from shives.

The retting of hemp is another area needing attention. Retting is well mastered and controlled for flax, but more subjectively and inconsistently implemented for hemp. There is a lack of a general guidance or policy, even at the level of large cooperatives of farmers. This leads to fibres with significant heterogeneity in terms of retting degree; over-retted fibres have diminished properties, while under-retted fibres have more defects, due to the harsher conditions needed during mechanical extraction. The period of harvesting also influences the properties of the fibres; when plants are harvested too late, the lignification of the fibres makes fibre extraction more challenging and affects the integrity of the properties of the fibres. Identifying the end-use of the crop, making a choice between whether enhanced fibre properties or high seed yield is the aim, is important. Current research shows that fibres harvested at seed maturity are less stiff and strong than fibres harvested at full-flowering. However, fibres harvested at a later stage still have an acceptable reinforcement potential and, in addition, it often makes little economic sense to not harvest the seeds [189]. Research is needed to reconcile, through genetics or varietal selection, these two remunerative products (vis. fibres and seeds) for the farmer. Appropriate varietal selection would boost the production of fibre-dedicated cultivar with higher fibre yields (instead of xylem), and favouring shorter heights and diameters of the stem for practical handling. Less lignified fibre bundles could also be a target, as well as less cohesive cambial and parenchymatic layers within the stem.

Finally, in view of global warming, the stress resistance of hemp is often highlighted, sometimes without scientific evidence. The drought tolerance of hemp needs more research; this would also support the selection of cultivation areas. Climate change also underlines the limits and necessary adjustments with regard to field retting. In Europe, droughts are becoming more common over the summer period during which retting would take place, and alternative modes of retting are increasingly being explored. In the coming years, the development of off-field retting through appropriate biotechnologies may become of interest. This may include the use of bacteria to feed on pectic substances and produce biopolymers (like PHA) in exchange.

Hemp is a multi-purpose crop, which can be used to produce a large number of marketable biobased intermediate and end products from all fractions of biomass [163, 190]. Overall, sustainability in the hemp fibre production chain can be achieved by optimising the various processing steps. Under the boundary conditions discussed in this section, and the wider review, the use of hemp fibres for high-performance composites is realistic on an industrial scale in the short-to-medium term. Further optimisation, especially from an economic point of view, is to be expected, through adapted and improved process technologies.

9. Conclusions

Most products, be they structural, semi-structural or non-structural, are required to meet a range of specifications to ensure they function as required for their design life. Structural components, such as the rotor blades of a turbine, have to satisfy essential criteria related to stiffness and strength performance, fatigue performance and environmental durability. They also have to meet desirable criteria such as lightweight, low cost, and increasingly low embodied energy, and improved end-of-life disposal options. From our critical top-down review of the state-of-the-art of hemp composites, hemp fibres, and hemp plants - i.e. entire hemp processing chain - we observe that while the hemp dream lives and hemp may find applications in some high-performance applications in short to medium term, much progress needs to be made in order for truly structural components to be successfully designed and fabricated from hemp composites at an industrial scale. Specifically, there is a need for more product design case-study projects using hemp biocomposites, and multi-scale structural property assessment to support such design. There is also the need for the development and optimisation of a wider range of reinforcement forms, such as unidirectional and multiaxial non-crimped fabrics from zero-twist ribbons, tows and slivers. Moreover, evidence-based selection of fibre extraction, retting, and disintegration process parameters, as well as crop variety is necessary to achieve more consistent fibre quality.

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.

Acknowledgements

Our special thanks go to Kathina Müssig for her creative work with the hand-drawn illustrations.

References

[1] K. Potter, Design of composite products—A personal viewpoint, Compos. Manuf. 3 (3) (1992) 173–182.
[2] M. Carus, The european hemp industry: cultivation, processing and applications for fibres, shivs, seeds and flowers, European Industrial Hemp Association, Hürth, Germany, 2017.
[3] Nova-Institut. Hemp becomes the world's billion-dollar business – worldwide largest conference on industrial hemp in june 2019 in cologne (germany), 2020.
[4] anonymous, Auto body made of plastics resists denting under hard blows, Pop. Mech. Mag. 76 (6) (Dec. 1941) 12.
[5] IEC 61400-23. Wind turbines - part 23: full-scale structural testing of rotor blades, 2014.
[6] IEC 61400-2. Wind turbines - part 2: design requirements for small wind turbines, 2013.
[7] L. Mikkelsen, F. Bottoli, L. Pignatti, T.L. Andersen, B. Madsen, Material selection and design aspects of small wind turbine blades, Indo-Danish Workshop on Future Composites Technologies for Wind Turbine Blades. 2012, 2012.
[8] F. Bottoli, L. Pignatti, Design and processing of structural components in biocomposite materials - rotor blade for wind turbine cars, Technical University of Denmark, Roskilde, Denmark, 2011.
[9] P. Frohnapfel, M. Muggenhamer, C. Schlögl, K. Drechsler, Natural fibre composites for innovative small scale wind turbine blades, *International Workshop on Small Scale Wind Energy for Developing Countries*, 15-17 November 2010, 2010.
[10] D.U. Shah, P.J. Schubel, M.J. Clifford, Can flax replace e-glass in structural composites? a small wind turbine blade case study, Compos. Part B: Eng. 52 (2013) 172–181.
[11] D.U. Shah, P.J. Schubel, M.J. Clifford, P. Licence, Fatigue characterisation of plant fibre composites for rotor blade applications, in: JEC Composites Magazine - Special JEC *Asia*, 73, June 2012, pp. 51–54.
[12] G. Wuzella, A.R. Mahendran, S. Pichler, H. Lammer, K. Resch-Fauster, A. Anusic, R. Schledjewski, Y. Blossl, Green energy from sustainable green composites (green2green), JEC Compos. Mag. 125 (2018) 35–37.
[13] D.U. Shah, P.J. Schubel, M.J. Clifford, Modelling the effect of yarn twist on the tensile strength of unidirectional plant fibre yarn composites, J Compos Mater 47 (4) (2013) 425–436.
[14] J. Baets, D. Plastria, J. Ivens, I. Verpoest, Determination of the optimal flax fibre preparation for use in ud-epoxy composites, 18th International Conference on Composite Materials (ICCM-18), 18th International Conference on Composite Materials (ICCM-18). Jeju, South Korea, 2011.
[15] P. Brøndsted, H. Lilholt, A. Lystrup, Composite materials for wind power turbine blades, Annu. Rev. Mater. Res. 35 (2005) 505–538.
[16] D.U. Shah, Developing plant fibre composites for structural applications by optimising composite parameters: a critical review, J. Mater. Sci. 48 (18) (2013) 6083–6107.
[17] V. Placet, F. Trivaudey, O. Cisse, M.L. Boubakar, What are the possible origins of the nonlinear tensile behaviour of hemp fibres? In ICCM-19, editor, *19th International Conference on Composite Materials (ICCM-19)*, 19th International Conference on Composite Materials (ICCM-19), ICCM-19, 2013.
[18] V. Placet, O. Cissé, M.L. Boubakar, Nonlinear tensile behaviour of elementary hemp fibres. part i: investigation of the possible origins using repeated progressive loading with in situ microscopic observations, Compos. Part A: Appl. Sci. Manuf. 56 (2014) 319–327.
[19] F. Trivaudey, V. Placet, V. Guicheret-Retel, M.L. Boubakar, Nonlinear tensile behaviour of elementary hemp fibres. part ii: modelling using an anisotropic viscoelastic constitutive law in a material rotating frame, Compos. Part A: Appl. Sci. Manuf. 68 (2015) 346–355.
[20] D.U. Shah, P.J. Schubel, M.J. Clifford, P. Licence, The tensile behavior of off-axis loaded plant fiber composites: an insight on the nonlinear stress–strain response, Polym. Compos. 33 (9) (2012) 1494–1504.
[21] D.U. Shah, Damage in biocomposites: stiffness evolution of aligned plant fibre composites during monotonic and cyclic fatigue loading, Compos. Part A: Appl. Sci. Manuf. 83 (2016) 160–168.
[22] H.L. Bos, K. Molenveld, W. Teunissen, A.M. Van Wingerde, D.R.V. Van Delft, Compressive behaviour of unidirectional flax fibre reinforced composites, J. Mater. Sci. 39 (6) (2004) 2159–2168.
[23] D.U. Shah, Characterisation and Optimisation of the Mechanical Performance of Plant Fibre Composites for Structural Applications PhD thesis, University of Nottingham, UK, 2013.
[24] D.U. Shah, P.J. Schubel, M.J. Clifford, P. Licence, Fatigue life evaluation of aligned plant fibre composites through s–n curves and constant-life diagrams, Compos. Sci. Technol. 74 (2013) 139–149.
[25] A. Shahzad, D.H. Isaac, Fatigue properties of hemp fibre composites, 17th International Conference on Composite Materials (ICCM-17), 2009.
[26] D.S. de Vasconcellos, F. Touchard, L. Chocinski-Arnault, Tension–tension fatigue behaviour of woven hemp fibre reinforced epoxy composite: a multi-instrumented damage analysis, Int. J. Fatigue 59 (2014) 159–169.
[27] N. Graupner, F. Sarasini, J. Müssig, Ductile viscose fibres and stiff basalt fibres for composite applications–an overview and the potential of hybridisation, Compos. Part B: Eng. (2020) 108041 page.
[28] W. Garat, S. Corn, N. Le Moigne, J. Beaugrand, A. Bergeret, Analysis of the morphometric variations in natural fibres by automated laser scanning: towards an efficient and reliable assessment of the cross-sectional area, Compos. Part A: Appl. Sci. Manuf. 108 (2018) 114–123.
[29] K. Esau, Plant Anatomy, 75, Wiley, New York, USA, 1953.
[30] M.V. Ageeva, B. Petrovska, H. Kieft, V.V. Salânikov, A.V. Snegireva, J.E.G. Van Dam, W.L.H. Van Veenendaal, A.M.C. Emons, T.A. Gorshkova, A.A.M. Van Lammeren, Intrusive growth of flax phloem fibers is of intercalary type, Planta 222 (4) (2005) 565–574.
[31] A.V. Snegireva, M.V. Ageeva, S.I. Amenitskii, T.E. Chernova, M. Ebskamp, T.A. Gorshkova, Intrusive growth of sclerenchyma fibers, Russ. J. Plant Physiol. 57 (3) (2010) 342–355.
[32] A. Snegireva, T. Chernova, M. Ageeva, S. Lev-Yadun, T. Gorshkova, Intrusive growth of primary and secondary phloem fibres in hemp stem determines fibre-bundle formation and structure, AoB Plants 7 (2015), doi:10.1093/aobpla/plv061.
[33] J. Müssig, H. Fischer, N. Graupner, A. Drieling, Testing methods for measuring physical and mechanical fibre properties (plant and animal fibres), in: Industrial Applications of Natural Fibres - Structure, Properties and Technical Applications, John Wiley & Sons, Ltd, Chichester, UK, 2010, pp. 267–309.
[34] B. Ch. Kundu, The anatomy of two indian fibre plants, cannabis and corchorus with special reference to fibre distribution and development, J. Indian Bot. Soc. 21 (1942) 93–128.
[35] S. Amaducci, F. Pelatti, P.M. Bonatti, Fibre development in hemp (cannabis sativa l.) as affected by agrotechnique: preliminary results of a microscopic study, J. Ind. hemp 10 (1) (2005) 31–48.
[36] H.M. Van Der Werf, in: *Hemp today*, chapter: Fiber hemp in France, Quick American Archives, San Francisco, USA, 1995, pp. 213–220. pages.
[37] D. Crônier, B. Monties, B. Chabbert, Structure and chemical composition of bast fibers isolated from developing hemp stem, J. Agric. Food Chem. 53 (21) (2005) 8279–8289.
[38] A. Bourmaud, J. Malvestio, N. Lenoir, D. Siniscalco, A. Habrant, A. King, D. Legland, C. Baley, J. Beaugrand, Exploring the mechanical performance and in-planta architecture of secondary hemp fibres, Ind. Crops Prod. 108 (2017) 1–5.
[39] V. Placet, J. Méteau, L. Froehly, R. Salut, M.L. Boubakar, Investigation of the internal structure of hemp fibres using optical coherence tomography and focused ion beam transverse cutting, J. Mater. Sci. 49 (24) (2014) 8317–8327.
[40] S. Amaducci, A. Zatta, F. Pelatti, G. Venturi, Influence of agronomic factors on yield and quality of hemp (cannabis sativa l.) fibre and implication for an innovative production system, Field Crops Res. 107 (2) (2008) 161–169.
[41] P. Mikshina, T. Chernova, S. Chemikosova, N. Ibragimova, N. Mokshina, T. Gorshkova, Cellulosic fibers: role of matrix polysaccharides in structure and function, in: Cellulose-Fundamental Aspects, Rijeka: InTech, 2013, pp. 91–112.
[42] A. Bourmaud, D. Siniscalco, L. Foucat, C. Goudenhooft, X. Falourd, B. Pontoire, O. Arnould, J. Beaugrand, C. Baley, Evolution of flax cell wall ultrastructure and mechanical properties during the retting step, Carbohydr Polym 206 (2019) 48–56.
[43] A. Bourmaud, C. Morvan, A. Bouali, V. Placet, P. Perre, C. Baley, Relationships between micro-fibrillar angle, mechanical properties and biochemical composition of flax fibers, Ind. Crops Prod. 44 (2013) 343–351.
[44] W. Garat, N. Le Moigne, S. Corn, J. Beaugrand, A. Bergeret, Swelling of natural fibre bundles under hygro-and hydrothermal conditions: determination of hydric expansion coefficients by automated laser scanning, Compos. Part A: Appl. Sci. Manuf. 131 (2020) 105803.

[45] R. Coste, M. Pernes, L. Tetard, M. Molinari, B. Chabbert, Effect of the interplay of composition and environmental humidity on the nanomechanical properties of hemp fibers, ACS Sustain. Chem. Eng. 8 (16) (2020) 6381–6390.
[46] A. Bourmaud, J. Beaugrand, D.U. Shah, V. Placet, C. Baley, Towards the design of high-performance plant fibre composites, Prog. Mater. Sci. 97 (2018) 347–408.
[47] L. Marrot, A. Lefeuvre, B. Pontoire, A. Bourmaud, C. Baley, Analysis of the hemp fiber mechanical properties and their scattering (fedora 17), Ind. Crops Prod. 51 (2013) 317–327.
[48] H.E. Hayward, The Structure of Economic Plants, 48, Macmillan, New York, NY, USA, 1951.
[49] J. Beaugrand, S. Guessasma, J.-.E. Maigret, Damage mechanisms in defected natural fibers, Sci. Rep. 7 (1) (2017) 1–7.
[50] A. Ashori, J. Harun, W.D. Raverty, M.N.M. Yusoff, Chemical and morphological characteristics of malaysian cultivated kenaf (hibiscus cannabinus) fiber, Polym. Plast. Technol. Eng. 45 (1) (2006) 131–134.
[51] R.N. Hobson, D.G. Hepworth, D.M. Bruce, Postharvest technology: quality of fibre separated from unretted hemp stems by decortication, J. Agric. Eng. Res. 78 (2) (2001) 153–158.
[52] M. Grégoire, B. Barthod-Malat, L. Labonne, P. Evon, E. De Luycker, P. Ouagne, Investigation of the potential of hemp fibre straws harvested using a combine machine for the production of technical load-bearing textiles, Ind. Crops Prod. 145 (2020) 111988.
[53] A. Melelli, O. Arnould, J. Beaugrand, A. Bourmaud, The middle lamella of plant fibers used as composite reinforcement: investigation by atomic force microscopy, Molecules 25 (3) (2020) 632.
[54] S. Musio, J. Müssig, S. Amaducci, Optimizing hemp fiber production for high performance composite applications, Front. Plant Sci. 9 (2018) 1702.
[55] M. Tanguy, A. Bourmaud, J. Beaugrand, T. Gaudry, C. Baley, Polypropylene reinforcement with flax or jute fibre; influence of microstructure and constituents properties on the performance of composite, Compos. Part B: Eng. 139 (2018) 64–74.
[56] J.P. Manaia, A.T. Manaia, L. Rodriges, Industrial hemp fibers: an overview, Fibers 7 (12) (2019) 106.
[57] J. Mérotte, A. Le Duigou, A. Kervoelen, A. Bourmaud, K. Behlouli, O. Sire, C. Baley, Flax and hemp nonwoven composites: the contribution of interfacial bonding to improving tensile properties, Polym. Test 66 (2018) 303–311.
[58] J. Mérotte, A. Le Duigou, A. Bourmaud, K. Behlouli, C. Baley, Mechanical and acoustic behaviour of porosity controlled randomly dispersed flax/pp biocomposite, Polym. Test 51 (2016) 174–180.
[59] N. Graupner, J. Rössler, G. Ziegmann, J. Müssig, Fibre/matrix adhesion of cellulose fibres in PLA, PP and MAPP: a critical review of pull-out test, microbond test and single fibre fragmentation test results, Compos. Part A: Appl. Sci. Manuf. 63 (2014) 133–148.
[60] J. Müssig, N. Graupner, Characterisation of fibre/matrix adhesion in biobased fibre-reinforced thermoplastic composites, in: Textile Finishing: Recent Developments and Future Trends, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2017, pp. 485–556. Scrivener Publishing LLC, Beverly, MA, USA.
[61] J. Müssig, N. Graupner, Test methods for fibre/matrix adhesion in cellulose fibre-reinforced thermoplastic composite materials: a critical review, Rev. Adhes. Adhes. 8 (2) (2020), doi:10.7569/RAA.2020.097306.
[62] J. Andersons, E. Spārniņš, B. Nyström, R. Joffe, Scale effect of the tensile strength of flax-fabric-reinforced polymer composites, J. Reinforc. Plast. Compos. 30 (23) (2011) 1969–1974.
[63] J. Müssig, M. Hughes, Flax and Hemp fibres: a natural solution for the composite industry, in: F.F. Reux, I. Verpoest (Eds.), Prepared for JEC by the European Scientific Committee of the CELC, Paris, France, JEC composites, 2012, pp. 39–60.
[64] G. Coroller, A. Lefeuvre, A. Le Duigou, A. Bourmaud, G. Ausias, T. Gaudry, C. Baley, Effect of flax fibres individualisation on tensile failure of flax/epoxy unidirectional composite, Compos. Part A: Appl. Sci. Manuf. 51 (2013) 62–70.
[65] V. Placet, A. Day, J. Beaugrand, The influence of unintended field retting on the physicochemical and mechanical properties of industrial hemp bast fibres, J. Mater. Sci. 52 (10) (2017) 5759–5777.
[66] A. Le Duigou, A. Bourmaud, E. Balnois, P. Davies, C. Baley, Improving the interfacial properties between flax fibres and plla by a water fibre treatment and drying cycle, Ind. Crops Prod. 39 (2012) 31–39.
[67] B. Mazian, A. Bergeret, J.-.C. Benezet, L. Malhautier, Influence of field retting duration on the biochemical, microstructural, thermal and mechanical properties of hemp fibres harvested at the beginning of flowering, Ind. Crops Prod. 116 (2018) 170–181.
[68] J. Müssig, R. Martens, Quality aspects in hemp fibre production—Influence of cultivation, harvesting and retting, J. Ind. Hemp 8 (1) (2003) 11–32.
[69] J. Beaugrand, F. Berzin, Lignocellulosic fiber reinforced composites: influence of compounding conditions on defibrization and mechanical properties, J. Appl. Polym. Sci. 128 (2) (2013) 1227–1238.
[70] H.N. Dhakal, S.O. Ismail, Z. Zhang, A. Barber, E. Welsh, J.-.E. Maigret, J. Beaugrand, Development of sustainable biodegradable lignocellulosic hemp fiber/polycaprolactone biocomposites for light weight applications, Compos. Part A: Appl. Sci. Manuf. 113 (2018) 350–358.
[71] S.O. Ismail, H.N. Dhakal, E. Dimla, J. Beaugrand, I. Popov, Effects of drilling parameters and aspect ratios on delamination and surface roughness of lignocellulosic hfrp composite laminates, J. Appl. Polym. Sci. 133 (7) (2016) 42879.
[72] S.O. Ismail, H.N. Dhakal, I. Popov, J. Beaugrand, Comprehensive study on machinability of sustainable and conventional fibre reinforced polymer composites, Eng. Sci. Technol., Int. J. 19 (4) (2016) 2043–2052.
[73] J.L. Thomason, M.A. Vlug, Influence of fibre length and concentration on the properties of glass fibre-reinforced polypropylene: 1. tensile and flexural modulus, Compos. Part A: Appl. Sci. Manuf. 27 (6) (1996) 477–484.
[74] J.L. Thomason, M.A. Vlug, Influence of fibre length and concentration on the properties of glass fibre-reinforced polypropylene: 4. impact properties, Compos. Part A: Appl. Sci. Manuf. 28 (3) (1997) 277–288.
[75] N.P.J. Dissanayake, J. Summerscales, S.M. Grove, M.M. Singh, Energy use in the production of flax fiber for the reinforcement of composites, J. Nat. Fibers 6 (4) (2009) 331–346.
[76] R.C. Clarke, M.D. Merlin, Cannabis. Evolution and Ethnobotany, University of California Press, Berkeley and Los Angeles, 2013 chapter Chapter 5: History of Cannabis Use for Fiber. ISBN 978-0-520-27048-0.
[77] G. Schnegelsberg, *Systematik der Textilien.* (Das Wissenschaftliche Taschenbuch, Abteilung Technik), Wilhelm Goldmann Verlag, Munich, Germany, 1971 .- in German.
[78] G. Schnegelsberg, Handbuch der Faser - Theorie und Systematik der Faser, Deutscher Fachverlag, Frankfurt am Main, Germany, 1999 (Handbook of fibre - theory and systematics about the fibre) .- in German.
[79] S. Goutianos, T. Peijs, The optimisation of flax fibre yarns for the development of high-performance natural fibre composites, Adv. Compos. Lett. 12 (6) (2003) 237–241.
[80] R.C. Clarke, Traditional fiber hemp (cannabis) production, processing, yarn making, and weaving strategies—Functional constraints and regional responses. part 2, J. Nat. Fibers 7 (3) (2010) 229–250.
[81] J. Sponner, L. Toth, S. Cziger, R.R. Franck, Hemp, in: Bast and Other Plant Fibres, Woodhead Publishing Series in Textiles, 2005, pp. 176–206.
[82] W. Konczewicz, M. Zimniewska, M.A. Valera, The selection of a retting method for the extraction of bast fibers as response to challenges in composite reinforcement, Text. Res. J. 88 (18) (2018) 2104–2119.
[83] M. Muzyczek, The Use of Flax and Hemp For Textile Applications, in: R.M. Kozlowski, M. Mackiewicz-Talarczyk (Eds.), Handbook of Natural Fibres (Second Edition), Woodhead Publishing, 2020, pp. 147–167.
[84] S. Amaducci, J. Müssig, A. Zatta, F. Pelatti, in: *Textiles For Sustainable Development*, Chapter HEMP SYS: Design, Development and Up-Scaling of a Sustainable Production System For HEMP textiles: An integrated Quality Systems approach. How to Affect Hemp Fiber Quality, Nova Science Publishers, New York, 2007, pp. 73–80.
[85] M.G. Hayo, Werf Van der, Turunen Lea, The environmental impacts of the production of hemp and flax textile yarn, Ind. Crops Prod. 27 (1) (2008) 1–10.
[86] R.W. Kessler, U. Becker, R. Kohler, B. Goth, Steam explosion of flax—A superior technique for upgrading fibre value, Biomass Bioenergy 14 (3) (1998) 237–249.
[87] A.B. Thomsen, A. Thygesen, V. Bohn, K.V. Nielsen, B. Pallesen, M.S. Jørgensen, Effects of chemical–physical pre-treatment processes on hemp fibres for reinforcement of composites and for textiles, Ind. Crops Prod. 24 (2) (2006) 113–118.
[88] J. Dreyer, J. Müssig, N. Koschke, W.-.D. Ibenthal, H. Harig, Comparison of enzymatically separated hemp and nettle fibre to chemically separated and steam exploded hemp fibre, J. Ind. hemp 7 (1) (2002) 43–59.
[89] E. Steffes, Die Renaissance der europäischen Bastfaserspinnerei durch Verspinnung von Hanffasern auf Autocoro®-Rotorspinnmaschinen, W. Schlafhorst AG & Co., Mönchengladbach, Germany, 2000 Technical report.- in German.
[90] N. Graupner, L. Berger, N. de Beus, A. Bruns, T. Brückner, M. Carus, J. Eckert, B. Frank, J. Friedrich, H.-.W. Hilgers, S. Kunst, K.-.H. Lehmann, C. Medack, M.-.I. Popzyk, A. Scharf, I. Walenta, D. Weber, M. Wonneberger, J. Müssig, Natural fibre-reinforced composites for structural applications based on novel low twisted bast fibre yarns, Biocomposites Conference Cologne (BCC), 7th Conference on Wood and Natural Fibre Composites, nova Institut GmbH, Hürth, Germany, 2019 (14 – 15 December 2019, Maternushaus, Cologne, Germany). Hürth, Germany: nova-Institut GmbH.
[91] A.-.C. Corbin, D. Soulat, M. Ferreira, A.-.R. Labanieh, X. Gabrion, P. Malécot, V. Placet, Towards hemp fabrics for high-performance composites: influence of weave pattern and features, Compos. Part B: Eng. 181 (2020) 107582.
[92] D. Akin, Flax – Structure, Chemistry, Retting and Processing, in: J. Müssig (Ed.), Industrial Applications of Natural Fibres – Structure, Properties and Technical Applications, John Wiley & Sons, Ltd., Chichester, United Kingdom, 2010, pp. 89–108.
[93] J. Müssig, Untersuchung Der Eignung heimischer Pflanzenfasern für die Herstellung von Naturfaserverstärkten Duroplasten - vom Anbau zum Verbundwerkstoff -, VDI Verlag GmbH, Düsseldorf, Germany, 2001 Number No. 630 (ISBN 3-18-363005-2) in Fortschritt-Bericht VDI, Reihe 5, Grund- und Werkstoffe / Kunststoffe.
[94] S. Amaducci, H.-.J. Gusovius, Hemp – Cultivation, Extraction and Processing, in: J. Müssig (Ed.), Industrial Applications of Natural Fibres – Structure, Properties and Technical Applications, John Wiley & Sons, Ltd., Chichester, United Kingdom, 2010, pp. 109–134.
[95] S. Wang, H.-.J. Gusovius, C. Lühr, S. Musio, B. Uhrlaub, S. Amaducci, J. Müssig, Assessment system to characterise and compare different hemp varieties based on a developed lab-scaled decortication system, Ind. Crops Prod. 117 (2018) 159–168.
[96] M. Liu, A. Thygesen, J. Summerscales, A.S. Meyer, Targeted pre-treatment of hemp bast fibres for optimal performance in biocomposite materials: a review, Ind. Crops Prod. 108 (2017) 660–683.
[97] H. Fischer, J. Müssig, Bast Fibre Processing and Uses, in: B.P Singh (Ed.), Industrial Crops and Uses, Cambridge, USA, CABI, 2010, pp. 326–348.
[98] J. Petit, E.M.J. Salentijn, M.-.J. Paulo, C. Thouminot, B.J. van Dinter, G. Magagnini, H.-.J. Gusovius, K. Tang, S. Amaducci, S. Wang, B. Uhrlaub, J. Müssig, L.M. Trindade, Genetic variability of morphological, flowering, and biomass quality traits in hemp (cannabis sativa l.), Front. Plant. Sci. 11 (2020) 102.
[99] E.M.J. Salentijn, Q. Zhang, S. Amaducci, M. Yang, L.M. Trindade, New developments in fiber hemp (cannabis sativa l.) breeding, Ind. Crops Prod. 68 (2015) 32–41.

[100] S. Amaducci, D. Scordia, F.H. Liu, Q. Zhang, H. Guo, G. Testa, S.L. Cosentino, Key cultivation techniques for hemp in europe and china, Ind. Crops Prod. 68 (2015) 2–16.

[101] V. Placet, C. François, A. Day, J. Beaugrand, P. Ouagne, in: Industrial Hemp Transformation for Composite applications: Influence of Processing Parameters on the Fibre Properties, Springer, 2018, pp. 13–25.

[102] H.L. Bos, M.J.A. Van Den Oever, O.C.J.J. Peters, Tensile and compressive properties of flax fibres for natural fibre reinforced composites, J. Mater. Sci. 37 (8) (2002) 1683–1692.

[103] M. Liu, D. Fernando, A.S. Meyer, B. Madsen, G. Daniel, A. Thygesen, Characterization and biological depectinization of hemp fibers originating from different stem sections, Ind. Crops Prod. 76 (2015) 880–891.

[104] M. Liu, D. Fernando, G. Daniel, B. Madsen, A.S. Meyer, M.T. Ale, A. Thygesen, Effect of harvest time and field retting duration on the chemical composition, morphology and mechanical properties of hemp fibers, Ind. Crops Prod. 69 (2015) 29–39.

[105] M.L. Baker, Y. Chen, C. Lague, H. Landry, Q. Peng, W. Zhong, J. Wang, Hemp fibre decortications using a planetary ball mill, Can. Biosyst. Eng. 52 (2) (2010) 2–7.

[106] D.G. Hepworth, R.N. Hobson, D.M. Bruce, J.W. Farrent, The use of unretted hemp fibre in composite manufacture, Compos. Part A: Appl. Sci. Manuf. 31 (11) (2000) 1279–1283.

[107] S. Réquilé, C. Goudenhooft, A. Bourmaud, A. Le Duigou, C. Baley, Exploring the link between flexural behaviour of hemp and flax stems and fibre stiffness, Ind. Crops Prod. 113 (2018) 179–186.

[108] B. Chabbert, J. Padovani, C. Djemiel, J. Ossemond, A. Lematre, A. Yoshinaga, S. Hawkins, S. Grec, J. Beaugrand, B. Kurek, Multimodal assessment of flax dew retting and its functional impact on fibers and natural fiber composites, Înd. Crops Prod. 148 (2020) 112255.

[109] L. Bleuze, G. Lashermes, G. Alavoine, S. Recous, B. Chabbert, Tracking the dynamics of hemp dew retting under controlled environmental conditions, Ind. Crops Prod. 123 (2018) 55–63.

[110] T. Sauvageon, Characterization and Valorization of Hemp Fibers from Abandoned Soils and Materials: Steam Explosion Treatment thesis, Université de Lorraine, France, , 2017.

[111] A. Keller, Compounding and mechanical properties of biodegradable hemp fibre composites, Compos. Sci. Technol. 63 (9) (2003) 1307–1316.

[112] T. Sauvageon, J.-.M. Lavoie, C. Segovia, N. Brosse, Toward the cottonization of hemp fibers by steam explosion - part 1: defibration and morphological characterization, Text. Res. J. 88 (9) (2018) 1047–1055.

[113] A. Keller, M. Leupin, V. Mediavilla, E. Wintermantel, Influence of the growth stage of industrial hemp on chemical and physical properties of the fibres, Ind. Crops Prod. 13 (1) (2001) 35–48.

[114] A. Thygesen, A.B. Thomsen, G. Daniel, H. Lilholt, Comparison of composites made from fungal defibrated hemp with composites of traditional hemp yarn, Ind. Crops Prod. 25 (2) (2007) 147–159.

[115] M. Gomina, VIII – Flax and hemp composite applications, in: F.F. Reux, I. Verpoest (Eds.), Flax and Hemp Fibres: a Natural Solution For the Composite industry, 2012, pp. 141–162. Paris, JEC Composites, prepared for JEC by the European Scientific Committee of the CELC.

[116] J. Müssig, K. Haag, The use of flax fibres as reinforcements, in: O.O. Faruk, M. Sain (Eds.), Biofiber Reinforcements in Composites, Cambrige, USA, Woodhead Publishing Ltd., 2010, pp. 35–85.

[117] L. Pil, F. Bensadoun, J. Pariset, I. Verpoest, Why are designers fascinated by flax and hemp fibre composites, Compos. Part A: Appl. Sci. Manuf. 83 (2016) 193–205.

[118] A. Thygesen, B. Madsen, A.B. Bjerre, H. Lilholt, Cellulosic fibers: effect of processing on fiber bundle strength, J. Nat. Fibers 8 (3) (2011) 161–175.

[119] S. Guessasma, J. Beaugrand, Damage kinetics at the sub-micrometric scale in bast fibers using finite element simulation and high-resolution x-ray micro-tomography, Front. Plant Sci. 10 (2019).

[120] L.G. Thygesen, M. Eder, I. Burgert, Dislocations in single hemp fibres—Investigations into the relationship of structural distortions and tensile properties at the cell wall level, J. Mater. Sci. 42 (2) (2007) 558–564.

[121] C. Gourier, A. Bourmaud, A. Le Duigou, C. Baley, Influence of pa11 and pp thermoplastic polymers on recycling stability of unidirectional flax fibre reinforced biocomposites, Polym. Degrad. Stab. 136 (2017) 1–9.

[122] L.G. Thygesen, M.R. Asgharipour, The effects of growth and storage conditions on dislocations in hemp fibres, J. Mater. Sci. 43 (10) (2008) 3670–3673.

[123] T. Hänninen, A. Thygesen, S. Mehmood, B. Madsen, M. Hughes, Mechanical processing of bast fibres: the occurrence of damage and its effect on fibre structure, Ind. Crops Prod. 39 (2012) 7–11.

[124] M. Hughes, Defects in natural fibres: their origin, characteristics and implications for natural fibre-reinforced composites, J. Mater. Sci. 47 (2) (2012) 599–609.

[125] A. Hernandez-Estrada, H.-.J. Gusovius, J. Müssig, M. Hughes, Assessing the susceptibility of hemp fibre to the formation of dislocations during processing, Ind. Crops Prod. 85 (2016) 382–388.

[126] A. Del Masto, F. Trivaudey, V. Guicheret-Retel, V. Placet, L. Boubakar, Investigation of the possible origins of the differences in mechanical properties of hemp and flax fibres: a numerical study based on sensitivity analysis, Compos. Part A: Appl. Sci. Manuf. 124 (2019) 105488.

[127] D. Calzolari, G. Magagnini, L. Lucini, G. Grassi, G.B. Appendino, S. Amaducci, High added-value compounds from cannabis threshing residues, Ind. Crops Prod. 108 (2017) 558–563.

[128] P.A. Berbert, D.M. Queiroz, E.F. Sousa, M.B. Molina, E.C. Melo, L.R.D. Faroni, Ph—Postharvest technology, J. Agric. Eng. Res. 1 (80) (2001) 65–80.

[129] T. Prade, S.-.E. Svensson, J.E. Mattsson, Energy balances for biogas and solid biofuel production from industrial hemp, Biomass bioenergy 40 (2012) 36–52.

[130] M. Carus, S. Karst, A. Kauffmann, in: The European Hemp industry: Cultivation, Processing and Applications for fibres, Shivs and Seeds, EIHA conference, nova-Institut GmbH, Hürth, Germany, 2013, pp. 1–9.

[131] K. Wötzel, R. Wirth, M. Flake, Life cycle studies on hemp fibre reinforced components and abs for automotive parts, Die Angew. Makromol. Chem. 272 (1) (1999) 121–127.

[132] J. Müssig, H. Harig, Fahrzeugbauteile vom Acker, Landwirtschaftsblatt Weser-Ems 147 (13) (March 2000) 11–14 (ISSN 0047-4029) .- in German.

[133] H. Gusovius, A. Prochnow, J. Hahn, and J. Müssig. Faserqualität von Hanf., 1999 Landtechnik 54, 4/99 August, 230–231.

[134] S. Alix, L. Lebrun, S. Marais, E. Philippe, A. Bourmaud, C. Baley, C. Morvan, Pectinase treatments on technical fibres of flax: effects on water sorption and mechanical properties, Carbohydr. Polym. 87 (1) (2012) 177–185.

[135] J.D. Evans, D.E. Akin, J.A. Foulk, Flax-retting by polygalacturonase-containing enzyme mixtures and effects on fiber properties, J. Biotechnol. 97 (3) (2002) 223–231.

[136] A. Ribeiro, P. Pochart, A. Day, S. Mennuni, P. Bono, J.-.L. Baret, J.-.L. Spadoni, I. Mangin, Microbial diversity observed during hemp retting, Appl. Microbiol. Biotechnol. 99 (10) (2015) 4471–4484.

[137] D. Fernando, A. Thygesen, A.S. Meyer, G. Daniel, Elucidating field retting mechanisms of hemp fibres for biocomposites: effects of microbial actions and interactions on the cellular micro-morphology and ultrastructure of hemp stems and bast fibres, Bioresources 14 (2) (2019) 4047–4084.

[138] V. Placet, F. Trivaudey, O. Cisse, V. Gucheret-Retel, M.L. Boubakar, Diameter dependence of the apparent tensile modulus of hemp fibres: a morphological, structural or ultrastructural effect, Compos. Part A: Appl. Sci. Manuf. 43 (2) (2012) 275–287.

[139] A. Teleman, Hemicelluloses and pectins, in: Pulp and Paper Chemistry and Technology. Vol. 1: Wood Chemistry and Wood Biotechnology, Walter de Gruyter, Berlin, Germay, 2009, pp. 101–121.

[140] A. Zoghlami, G. Paës, Lignocellulosic biomass: understanding recalcitrance and predicting hydrolysis, Front. Chem. 7 (2019) 874.

[141] J. Beaugrand, G. Paës, D. Reis, M. Takahashi, P. Debeire, M. O'Donohue, B. Chabbert, Probing the cell wall heterogeneity of micro-dissected wheat caryopsis using both active and inactive forms of a gh11 xylanase, Planta 222 (2) (2005) 246–257.

[142] C.A. Fuentes, P. Willekens, J. Petit, C. Thouminot, J. Müssig, L.M. Trindade, A.W. Van Vuure, Effect of the middle lamella biochemical composition on the non-linear behaviour of technical fibres of hemp under tensile loading using strain mapping, Compos. Part A: Appl. Sci. Manuf. 101 (2017) 529–542.

[143] Z.A. Jankauskiene, B. Butkute, E. Gruzdeviene, J. Ceseviciene, A.L. Fernando, Chemical composition and physical properties of dew-and water-retted hemp fibers, Ind. Crops Prod. 75 (2015) 206–211.

[144] J.B. Sluiter, R.O. Ruiz, C.J. Scarlata, A.D. Sluiter, D.W. Templeton, Compositional analysis of lignocellulosic feedstocks. 1. review and description of methods, J. Agric. Food Chem. 58 (16) (2010) 9043–9053.

[145] R. Hatfield, R.S. Fukushima, Can lignin be accurately measured, Lignin and Forage Digestibility Symposium, 2003 CSSA Annual Meeting, 2005 *Crop Science*, number 45, pages 832–839.

[146] B. Sharma, D.U. Shah, J. Beaugrand, E.-.R. Janecek, O.A. Scherman, M.H. Ramage, Chemical composition of processed bamboo for structural applications, Cellulose 25 (6) (2018) 3255–3266.

[147] A. Bourmaud, M. Gibaud, C. Baley, Impact of the seeding rate on flax stem stability and the mechanical properties of elementary fibres, Ind. Crops Prod. 80 (2016) 17–25.

[148] C. Goudenhooft, A. Bourmaud, C. Baley, Varietal selection of flax over time: evolution of plant architecture related to influence on the mechanical properties of fibers, Ind. Crops Prod. 97 (2017) 56–64.

[149] P. Bouloc, Le Chanvre Industriel: Production et Utilisations, Agricole Editions,, France, 2006.

[150] G. Deger, M. Pakdemirli, F. Candan, S. Akgün, H. Boyac, Strength of wheat and barley stems and design of new beam/columns, Math. Comput. Appl. 15 (1) (2010) 1–13.

[151] A. Day, K. Ruel, G. Neutelings, D. Crônier, H. David, S. Hawkins, B. Chabbert, Lignification in the flax stem: evidence for an unusual lignin in bast fibers, Planta 222 (2) (2005) 234–245.

[152] R.F. Evert, Esau's Plant anatomy: meristems, cells, and Tissues of the Plant body: their structure, function, and Development, John Wiley & Sons, 2006.

[153] T. Gorshkova, N. Brutch, B. Chabbert, M. Deyholos, T. Hayashi, S. Lev-Yadun, E.J. Mellerowicz, C. Morvan, G. Neutelings, G. Pilate, Plant fiber formation: state of the art, recent and expected progress, and open questions, CRC Crit. Rev. Plant Sci. 31 (3) (2012) 201–228.

[154] S. Réquilé, A. Le Duigou, A. Bourmaud, C. Baley, Peeling experiments for hemp retting characterization targeting biocomposites, Ind. Crops Prod. 123 (2018) 573–580.

[155] G.J. Faughey, H.S.S. Sharma, A preliminary evaluation of near infrared spectroscopy for assessing physical and chemical characteristics of flax fibre, J. Near Infrared Spectrosc. 8 (1) (2000) 61–69.

[156] B. Quint. Information zur Qualifizierung von Röste: Vorschlag zur Felddatenerfassung / Röstgrad, Begleitsubstanzen (Applikation: taugeröstete Bastfasern). Application Report, Institute for Applied Research (Institut für angewandte Forschung, IAF), AG Prozessanalytik, Reutlingen, Germany, 1996. .- in German.

[157] D.U. Shah, T.P.S. Reynolds, M.H. Ramage, The strength of plants: theory and experimental methods to measure the mechanical properties of stems, J. Exp. Bot. 68 (16) (2017) 4497–4516.

[158] P.M. Berry, R. Sylvester-Bradley, S. Berry, Ideotype design for lodging-resistant wheat, Euphytica 154 (1–2) (2007) 165–179.

[159] M. Gibaud, A. Bourmaud, C. Baley, Understanding the lodging stability of green flax stems; the importance of morphology and fibre stiffness, Biosyst. Eng. 137 (2015) 9–21.

[160] K.J. Niklas, Responses of hollow, septate stems to vibrations: biomechanical evidence that nodes can act mechanically as spring-like joints, Ann. Bot. 80 (4) (1997) 437–448.

[161] T. Leblicq, S. Vanmaercke, H. Ramon, W. Saeys, Discrete element modelling of bendable tubes, Int. J. Mech. Sci. 94 (2015) 75–83.

[162] B. Mazian, S. Cariou, M. Chaignaud, J.-.L. Fanlo, M.-.L. Fauconnier, A. Bergeret, L. Malhautier, Evolution of temporal dynamic of volatile organic compounds (vocs) and odors of hemp stem during field retting, Planta 250 (6) (2019) 1983–1996.

[163] C.M. Andre, J.-.F. Hausman, G. Guerriero, Cannabis sativa: the plant of the thousand and one molecules, Front. Plant Sci. 7 (2016) 19.

[164] E. Small, A. Cronquist, A practical and natural taxonomy for cannabis, Taxon (1976) 405–435 pages.

[165] B. Bremer, K. Bremer, M. Chase, J. Reveal, D. Soltis, S. Soltis, P. Zmarzty, An update of the angiosperm phylogeny group classification for the orders and families of flowering plants: apg ii, Botan. J. Linnean Soc. 141 (4) (2003) 399–436.

[166] R.E. Schultes, W.M. Klein, T. Plowman, T.E. Lockwood, Cannabis: an example of taxonomic neglect, in: Botanical Museum Leaflets, 23, Harvard University, 1974, pp. 337–367.

[167] E.P.M. De Meijer, Variation of cannabis with reference to stem quality for paper pulp production, Ind. Crops Prod. 3 (3) (1994) 201–211.

[168] K. Tang, P.C. Struik, X. Yin, C. Thouminot, M. Bjelková, V. Stramkale, S. Amaducci, Comparing hemp (cannabis sativa l.) cultivars for dual-purpose production under contrasting environments, Ind. Crops Prod. 87 (2016) 33–44.

[169] S. Amaducci, M. Colauzzi, G. Bellocchi, G. Venturi, Modelling post-emergent hemp phenology (cannabis sativa l.): theory and evaluation, Eur. J. Agron. 28 (2) (2008) 90–102.

[170] J. Berenji, V. Sikora, G. Fournier, O. Beherec, *Genetics and Selection of hemp*, Hemp Industrial Production and Uses, CABI, Wollingford, UK, 2013, pp. 48–71.

[171] J. Müssig, S. Amaducci, Scanner based image analysis to characterise the influence of agronomic factors on hemp (cannabis sativa l.) fibre width, Ind. Crops Prod. 113 (2018) 28–37.

[172] H.C. van den Broeck, C. Maliepaard, M.J.M. Ebskamp, M.A.J. Toonen, A.J. Koops, Differential expression of genes involved in c1 metabolism and lignin biosynthesis in wooden core and bast tissues of fibre hemp (cannabis sativa l.), Plant Sci. 174 (2) (2008) 205–220.

[173] P.C. Struik, S. Amaducci, M.J. Bullard, N.C. Stutterheim, G. Venturi, H.T.H. Cromack, Agronomy of fibre hemp (cannabis sativa l.) in Europe, Ind. Crops Prod. 11 (2–3) (2000) 107–118.

[174] S. Amaducci, M. Colauzzi, G. Bellocchi, S.L. Cosentino, K. Pahkala, T.J. Stomph, W. Westerhuis, A. Zatta, G. Venturi, Evaluation of a phenological model for strategic decisions for hemp (cannabis sativa l.) biomass production across European sites, Ind. Crops Prod. 37 (1) (2012) 100–110.

[175] S.L. Cosentino, E. Riggi, G. Testa, D. Scordia, V. Copani, Evaluation of european developed fibre hemp genotypes (cannabis sativa l.) in semi-arid mediterranean environment, Ind. Crops Prod. 50 (2013) 312–324.

[176] K. Tang, A. Fracasso, P.C. Struik, X. Yin, S. Amaducci, Water-and nitrogen-use efficiencies of hemp (cannabis sativa l.) based on whole-canopy measurements and modeling, Front. Plant Sci. 9 (2018) 951.

[177] F.L. Milthorpe, Fibre development of flax in relation to water supply and light intensity, Ann. Bot. 9 (33) (1945) 31–53.

[178] K. Tang, P.C. Struik, X. Yin, D. Calzolari, S. Musio, C. Thouminot, M. Bjelková, V. Stramkale, G. Magagnini, S. Amaducci, A comprehensive study of planting density and nitrogen fertilization effect on dual-purpose hemp (cannabis sativa l.) cultivation, Ind. Crops Prod. 107 (2017) 427–438.

[179] S. Amaducci, M. Errani, G. Venturi, Plant population effects on fibre hemp morphology and production, J. Ind. Hemp 7 (2) (2002) 33–60.

[180] S. Legros, S. Picault, N. Cerruti, in: *Factors Affecting the Yield of Industrial Hemp - experimental results from France*, in: Hemp Industrial Production and Uses, CABI, Wollingford, UK, 2013, pp. 72–97.

[181] M. Barth, M. Carus, Carbon Footprint and Sustainability of Different Natural Fibres for Biocomposites and Insulation Material - Study providing Data For the Automotive and Insulation Industry, Hürth: nova Institut GmbH, Germany, 2015 (Download this study at: www.bio-based.eu/ecology) .

[182] J. Müssig, K. Albrecht, Are Flax and Hemp Fiber Composites Sustainable?, Flax & Hemp Fiber Composites, a market reality – The biobased solutions for the industry, 2018, pp. 86–94. JEC composites, Co-published CELC/JEC GROUP. Contributors: the experts of the European Scientific Committee of CELC, Paris, France.

[183] B. Madsen, H. Lilholt, Physical and mechanical properties of unidirectional plant fibre composites—An evaluation of the influence of porosity, Compos. Sci. Technol. 63 (9) (2003) 1265–1272.

[184] M. Schmehl, J. Müssig, U. Schönfeld, H.-.B. Von Buttlar, Life cycle assessment on a bus body component based on hemp fiber and PTP, J. Polym. Environ. 16 (1) (2008) 51–60.

[185] M. Ramesh, C. Deepa, L.R. Kumar, M.R. Sanjay, S. Siengchin, Life-cycle and environmental impact assessments on processing of plant fibres and its bio-composites: a critical review, J. Ind. Text. (2020) page 1528083720924730.

[186] A.D. La Rosa, G. Cozzo, A. Latteri, A. Recca, A. Björklund, E. Parrinello, G. Cicala, Life cycle assessment of a novel hybrid glass-hemp/thermoset composite, J. Clean Prod. 44 (2013) 69–76.

[187] M.A.J. Toonen, C. Maliepaard, T.H. Reijmers, H. van der Voet, H.D. Mastebroek, H.C. van den Broeck, M.J.M. Ebskamp, W. Kessler, R.W. Kessler, Predicting the chemical composition of fibre and core fraction of hemp (cannabis sativa l.), Euphytica 140 (1–2) (2004) 39–45.

[188] J. Müssig, M. Schmehl, H.-.B. Von Buttlar, U. Schönfeld, K. Arndt, Exterior components based on renewable resources produced with smc technology—Considering a bus component as example, Ind. Crops Prod. 24 (2) (2006) 132–145.

[189] J. Müssig, K. Haag, S. Musio, M. Bjelková, K. Albrecht, B. Uhrlaub, S. Wang, H. Wieland, S. Amaducci, Biobased 'mid-performance'composites using losses from the hackling process of long hemp–a feasibility study as part of the development of a biorefinery concept–, Ind. Crops Prod. 145 (2020) 111938.

[190] A. Shahzad, Hemp fiber and its composites – a review, J. Compos. Mater. 46 (8) (2012) 973–986.

[191] C. Baley, C. Goudenhooft, M. Gibaud, A. Bourmaud, Flax stems: from a specific architecture to an instructive model for bioinspired composite structures, Bioinspir. Biomim. 13 (2) (2018) 026007.

[192] D. Reis, D. Vian, and B. Bajon. Le monde des fibres. Edition Belin, 2006.

[193] N. Reddy, Y. Yang, Properties of natural cellulose fibers from hop stems, Carbohydr. Polym. 77 (4) (2009) 898–902.

[194] M. Kostic, B. Pejic, P. Skundric, Quality of chemically modified hemp fibers, Bioresour. Technol. 99 (1) (2008) 94–99.

[195] E. Gümüskaya, M. Usta, M. Balaban, Çarbohydrate components and crystalline structure of organosolv hemp (cannabis sativa l.) bast fibers pulp, Bioresour. Technol. 98 (3) (2007) 491–497.

[196] V. Placet, Characterization of the thermo-mechanical behaviour of hemp fibres intended for the manufacturing of high performance composites, Compos. Part A: Appl. Sci. Manuf. 40 (8) (2009) 1111–1118.

[197] A. Duval, A. Bourmaud, L. Augier, C. Baley, Influence of the sampling area of the stem on the mechanical properties of hemp fibers, Mater. Lett. 65 (4) (2011) 797–800.

[198] S.J. Eichhorn, R.J. Young, Composite micromechanics of hemp fibres and epoxy resin microdroplets, Compos. Sci. Technol. 64 (5) (2004) 767–772.

[199] A. Bourmaud, C. Baley, Rigidity analysis of polypropylene/vegetal fibre composites after recycling, Polym. Degrad. Stab. 94 (3) (2009) 297–305.

[200] M. Fan, Characterization and performance of elementary hemp fibres: factors influencing tensile strength, BioRes 5 (4) (2010) 2307–2322.

[201] A. Bourmaud, J. Merotte, D. Siniscalco, M. Le Gall, V. Gager, A. Le Duigou, F. Pierre, K. Behlouli, O. Arnould, J. Beaugrand, C. Baley, Main criteria of sustainable natural fibre for efficient unidirectional biocomposites, Compos. Part A: Appl. Sci. Manuf. 124 (2019) 105504.

[202] V. Placet, A. Bouali, C. Garcin, J.-.M. Cote, P. Perre, Suivi par drx des réarrangements microstructuraux induits par sollicitations mécaniques dans les fibres végétales tirées du chanvre, 20ème Congrès Français de Mécanique, 2011.

[203] M. Le Troëdec, A. Rachini, C. Peyratout, S. Rossignol, E. Max, O. Kaftan, A. Fery, A. Smith, Influence of chemical treatments on adhesion properties of hemp fibres, J. Colloid Interface Sci. 356 (1) (2011) 303–310.

[204] D.N. Saheb, J.P. Jog, Natural fiber polymer composites: a review, Adv. Polym. Technol.: J. Polym. Process. Inst. 18 (4) (1999) 351–363.

[205] R.M. Rowell, H.P. Stout, *Jute and Kenaf*, in: Handbook of Fiber Chemistry, 3rd Edition, CRC Press Taylor, Francis, 2007, pp. 405–452. Boca Raton. FL, USA.

[206] J. Biagiotti, D. Puglia, J.M. Kenny, A review on natural fibre-based composites-part i: structure, processing and properties of vegetable fibres, J. Nat. Fibers 1 (2) (2004) 37–68.

[207] M. Eder, I. Burgert, Natural Fibres – Function in Nature, in: J. Müssig (Ed.), Industrial Applications of Natural Fibres – Structure, Properties and Technical Applications, John Wiley & Sons, Ltd., Chichester, UK, 2010, pp. 22–39.

[208] L.Y. Mwaikambo, M.P. Ansell, Mechanical properties of alkali treated plant fibres and their potential as reinforcement materials. i. hemp fibres, J. Mater. Sci. 41 (8) (2006) 2483–2496.

[209] R. Schledjewski, L. Medina, A.K. Schlarb, Mechanical and morphological characterization of selected natural fibres, Adv. Compos. Lett. 15 (2) (2006), doi:10.1177/096369350601500202.

[210] R.R. Franck, in: Overview, in: Bast and other plant fibres, Woodhead Publishing, Cambridge, UK, 2005, pp. 1–23.

[211] A. Bismarck, S. Mishra, T. Lampke, Plant Fibers as Reinforcement for Green Composites, Natural Fibers, in: Biopolymers and Biocomposites, CRC Press Taylor and Francis Group, Boca Raton, FL, USA, 2005, pp. 37–108.

[212] G. Wilbrandt, S. Tunger, F. Geringswald, D. Hansick, H.and Krügel, Faserstofflehre, 2nd edition, VEB Fachbuchverlag Leipzig, Germany, 1972.

[213] S.K. Batra, Other long vegetable fibers: abaca, banana, sisal, henequen, flax, ramie, hemp, sunn and coir, in: Handbook of Fiber Chemistry, 3rd Edition, CRC Press Taylor and Francis Group, Boca Raton, FL, USA, 2007, pp. 405–452.

[214] W. Bobeth, W. Berger, H. Faulstich, P. Fischer, A. Heger, H.-.J. Jacobash, A. Mally, I. Mikut, Textile Faserstoffe: Beschaffenheit und Eigenschaften, Springer Verlag, Berlin, 1993 Heidelberg-NewYork.

[215] A. Schenek, Naturfaserlexikon, Deutscher Fachverlag, Frankfurt am Main, Germany, 2000.

[216] A.N. Netravali, S. Chabba, Composites get greener, Mater. today 4 (6) (2003) 22–29.

[217] H. Hanselka, Fiber composites of raw renewable materials for the ecological lightweight design, Materwiss Werksttech 29 (6) (1998) 300–311.

[218] L.Y. Mweikambo, Review of the history and application of plant fibre, Afr. J. Sci. Technol. 7 (2006) 120–133.