

**Interreg
Danube Region**



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Hemp Portfolio

**D.2.3.3 Report on the Properties of Hemp:
Green-Tex Portfolio of Hemp Fibres**

**A 2.3 Pilot 2: Testing wider application of natural
fibres in textile production**

Specific objective 2: Testing Green-Tex solutions

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*"When we parted
dewdrops fell down on my sleeves
of pure white hemp–
your coldness harsh as the hue
of the piercing autumn wind"*

13th century, poet Fujiwara no Tekei

<https://sensiseeds.com/en/blog/hemp-songs-poems-history/>

"The Song of Hemp"

*From ancient fields to modern days,
Hemp has walked a thousand ways.
Threads of strength in every strand,
Rooted deep in fertile land.*

*Oh hemp, you grow so wild and free,
A gift of earth, a healing tree.
From rope to cloth, from seed to oil,
You bless the hands that till the soil.*

*Sailors trusted you with rope,
Poets wrote on hemp with hope.
Paper, canvas, food, and balm,
You bring the world a gentle calm.*

1 Hemp



Cannabis sativa L. experimental plant in Poland

Author: S. Bischof

1.1 History of hemp use

Hemp (*Cannabis sativa* L.) is among the earliest cultivated plants in human history and originally grown for its fibers, seeds, and medicinal uses [1]. Hemp has been utilized for over 8,500 years BC (in China) according to [2], i.e., 2,700 years BC (in China), as stated in [1]. Furthermore, geographically, several locations for the species' nativity have been proposed with various theories supporting Central, East, and South Asia [3]. Central and East Asia are considered more likely as the birthplace of *Cannabis* and would have allowed for the wide distribution of the species. Table 1 shows key milestones in the historical evaluation and use of hemp, based on [2].

Table 1: Key Milestones in the Historical Evaluation and Use of Hemp, based on [2].

Year	Starting point	Additional information
8500 BC	Earliest evidence of hemp fiber use in China	Hemp remnants were found in archaeological sites, during investigation gave evidence to investigator, in northern China.
4000 BC	Hemp cultivation begins in India	Later the cultivation spread to USA
2800 BC	The fiber of Hemp were introduced for making of sails of ships in China	Hemp's strong, durable fibers were ideal for sails and ropes.
1000 BC	Hemp used in ancient Egypt for textiles, paper, and medicine	The Ebers Papyrus, an ancient Egyptian historical record, mentions hemp as a medicinal plant.
1st Century	Roman Empire used hemp for rope, sails, and clothing	Pliny the Elder, a Roman naturalist, described hemp as a valuable agricultural crop.
16th Century	Hemp introduced to North America by European colonists	Hemp as a crop started its uses as numerous purposed in colonial states of America.
19th Century	Hemp crossed the millstone in food as well as industrial crop recognition and becomes a major cash crop in the United States of America	Hemp not only proved its existence as industrial crop to be used as rope, sails, paper and clothing but also registered its place in food sector also.
1937	The Marijuana Tax Act in the US restricts the growth and use of hemp	The Act was largely motivated by racist stereotypes about marijuana use.
2014	The Farm Bill legalizes the cultivation of hemp for research purposes	/
2018	The Farm Bill removes hemp from the Controlled Substances Act, allowing for commercial cultivation.	This legalization has led to a surge in hemp production and the development of new hemp-based products.

Cultivation of Cannabis was prohibited for many years in numerous countries because some varieties contain high levels of tetrahydrocannabinol (THC), considered as euphoria-inducing compound. Nonetheless, hemp cultivation has now been legalized in many parts of the world, as numerous countries have distinguished low-THC varieties of *C. sativa* (i.e., <0.3% or 0.2%) from high-THC drug-type varieties (i.e., marijuana).

Historically, hemp has been a cornerstone of ancient and modern civilizations, valued primarily for its strong fibers, edible seeds, and medicinal properties. During the period when textile requirements were primarily fulfilled through domestic handicrafts within family-based communities, hemp and flax represented the predominant and in many lowland regions, nearly exclusive sources of textile raw materials. These fibers were spun into yarns that were subsequently woven into fabrics which constituted the principal material for clothing and household textiles. Hemp-based products share certain characteristics with coarse linen, yet they are distinguished by greater stiffness, roughness, and a lack of luster.

Beyond apparel, hemp yarn has traditionally served as a structural foundation in wool rugs featuring floral motifs and has held a notable role in the production of decorative textiles, such as macramé tapestries. In specific contexts, particularly in Italy and France, finer grades of hemp fibers have been manufactured; these are subjected to bleaching, dyeing, and finishing processes analogous to those applied to linen, enabling their use in garments and bedding. Such refined hemp fibers approach the quality of linen and have become increasingly valued in textile applications, not only due to their rustic aesthetic appeal but also owing to their durability and the tendency of hemp-based products to soften, flexible, and enhance comfort with continued use and maintenance [4].

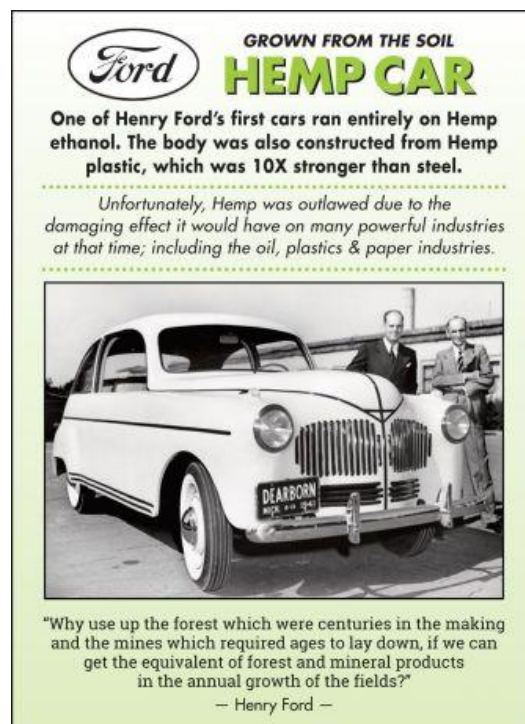


Figure 1: Ford car reinforced with hemp fibers [5]

As one of the earliest domesticated crops, hemp has served diverse purposes ranging from textile production and medicinal applications to industrial and automotive uses. A particularly notable

example occurred in 1940, when Henry Ford developed a prototype vehicle in which hemp was employed as a primary construction material, Figure 1.

1.2 Today's usage of hemp

Due to its multipurpose utility, short production cycle, low capital requirement in cultivation, and easy carbon sequestering material hemp is considered renewable resource [6]. It is important to distinguish between the narcotic form of the Cannabis genus and industrial hemp (food and fiber). Biologically, hemp makes up part of a family (*Cannabaceae*) and genus (*Cannabis*) of plants with a wide assortment of chemicals. Thus, the only parameter that is used to separate industrial hemp from the medicinal one is the level of the psychoactive cannabinoid tetrahydrocannabinol (THC) [7]. Therefore, a variety of the species *Cannabis sativa* L. with a percentage level of less than 0.2% THC is considered industrial hemp in most nations and the EU [8].

There has been a renewed interest in the research and advancement of new alternative natural fibers to minimize carbon emissions, focusing on environmental sustainability and develop strategies for durable, reusable, and recyclable textile, considering growing environmental challenges. The hemp plant is recognized as a future material for industry, and the hemp industry is acknowledged as a developing agricultural sector that is essential for sustainable development, with hemp being highly valued as an emerging source for creating more sustainable products and their derivatives [9].

The enormous ecological potential of hemp, and the diversity of raw materials that can be delivered by the plant, makes industrial hemp interesting for agriculture, medicine, food, textiles, construction and various other sectors [10]. According to Ahmed *et al.*, due to hemp's adaptability across different climates and its multiple purposes, it can be used as a cover crop, for insulation and acoustic purpose in the building sector, paper industry, medicinal purpose, textile industry, biofuel, cosmetics industry, food and beverage industry, and fiber can be used as reinforcement in polymer matrix composites or in bio-composite as a substitute of glass and carbon fiber [5]. Furthermore, according to Manaia *et al.*, interest in these fibers is warranted due to environmental protection challenges as well as their inherent properties such as low density, high specific strength, and stiffness [11].

Moreover, in the context of textile industry there has been renewed interest in the research and development of new alternative natural fibers; among those, industrial hemp is being recognized as important crop for its diverse applications, including ecological, sustainable and industrial benefits in modern industries. The production of hemp reached its peak in the mid-20th century; however, due to the regulation and the development of cheaper materials, the demand has decreased considerably. Currently, hemp has a market share of textile fibers of 0.3% [1]. For the comparison, nowadays fashion and textile market is dominated using polyester (around 54%) and

cotton (with a market share of 22%). The important uses of different parts of the hemp plant in various fields have been shown in Figure 2 [6, 12].

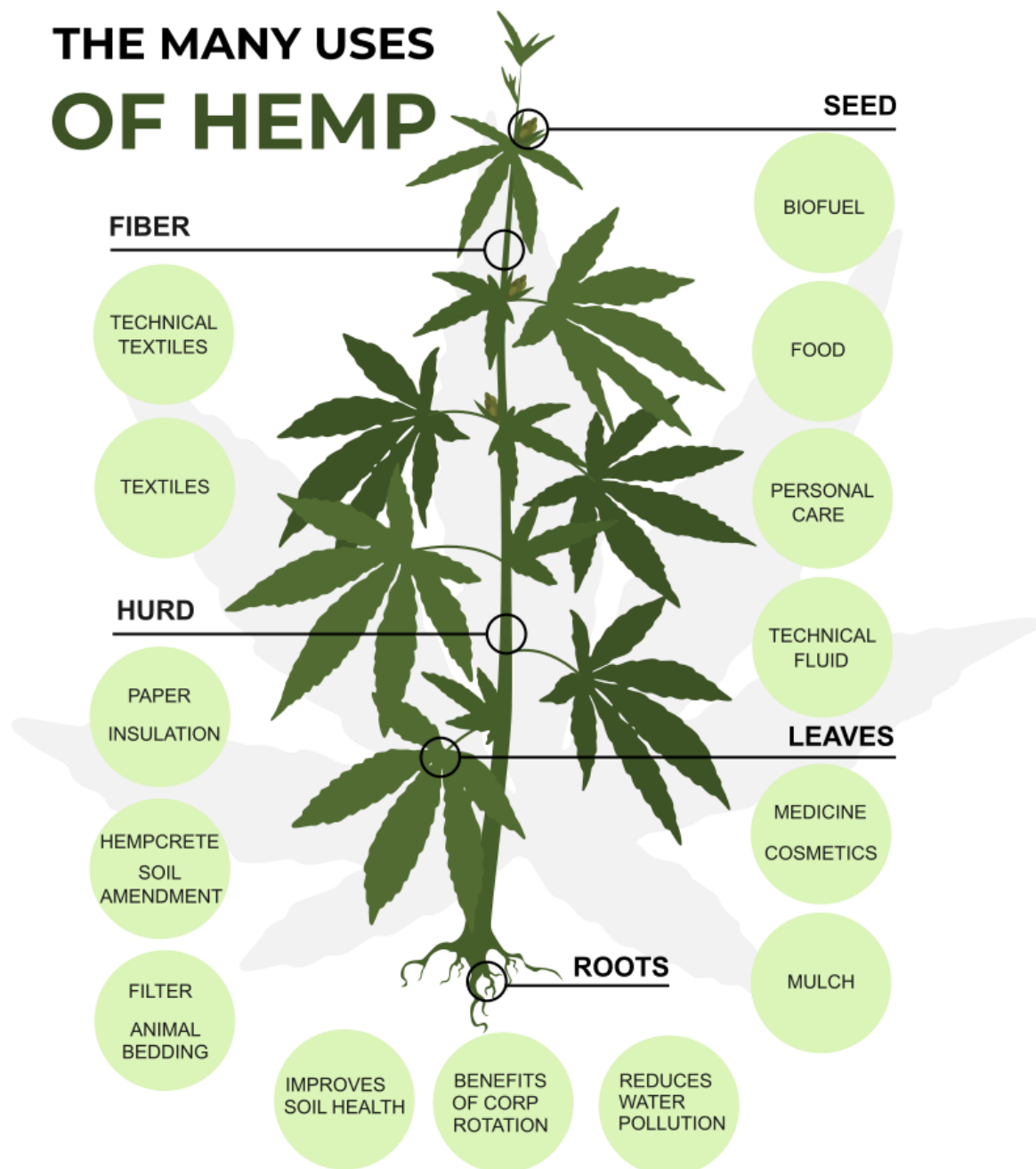


Figure 2: Some of the different applications of *Cannabis sativa* L, divided by the source of the materials, adapted from https://www.freepik.com/free-vector/uses-hemp-infographic_11299156.htm

Textile applications of hemp fibers can be seen in Table 2.

Table 2: Applications of hemp fibers [13]

Textiles	Technical textiles	Composites and Biocomposites
• Woven fabric • Knitted fabric • Apparel • Underwear • Denim • Socks • Bags	• Ropes • Twine • Nets • Canvas bags • Tarps • Carpets • Geotextiles • Footware	• Transport • Furnishes • Elements of Construction • Garden Architecture • Machine elements • Packages

Hemp's potential applications across various industries is presented in Figure 3.

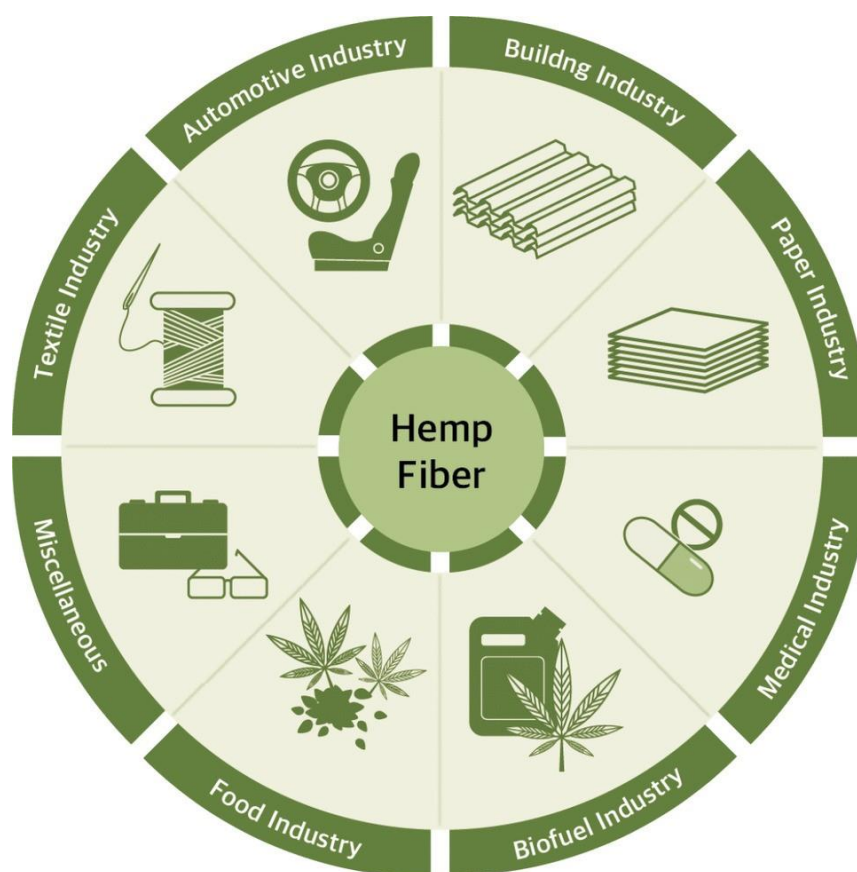


Figure 3: Application of hemp fibers or fiber reinforced composites in various industries [14]

The newest example of hemp application in automotive industry is MATANX vehicle, Figure 4 [15]. A new electric vehicle with a body made of industrial hemp has been developed in Croatia. On the roof there is a sensor for detecting air pollution that recognizes ten harmful particles.



Figure 4: New electric vehicle MATANX with industrial hemp body [15]

Stiffeners and epoxy resin are added to the hemp granules, and the manufacturing process itself is a combination of injection, infusion and vacuum processes. The vehicles named MATANX (Mobile Advanced Trade Advertising Network Exchange) are intended for delivery, advertising and air quality measurement.

Further example where sustainability has emerged as a key factor shaping consumer preferences is the denim or jeans market. Many jeans brands are adopting environmentally responsible practices, including the use of organic cotton and substitution for cotton such as application of other cellulose based fibers and recycled fibres. Additionally, water- and energy-efficient production technologies are introduced. One such example is application of hemp for jeans made by one of the most popular denim brands Levi's Co, Figure 5. Their innovative product is made of cottonized hemp which gives similar performance of softness with less environmental burden.



Figure 5: Cottonized hemp by Levi's Co. Available at: https://www.levi.com/US/en_US/blog/article/this-is-cottonized-hemp

1.3 The anatomy of the hemp plant

As stated in [16], the morphology of the Cannabis plant is influenced by a complex interaction of genetic, developmental, and environmental elements and growing conditions. The structures of leaves and inflorescences evolve during the plant's life cycle, with the development of trichomes and the morphology of achenes indicating both natural variability and the effects of domestication. Environmental factors, notably light quality and photoperiod, can greatly affect plant structure and the production of secondary metabolites. Grasping these morphological characteristics it is crucial for optimizing cultivation, breeding, and the identification of unique cannabis varieties for industrial, medicinal, and research purpose.

Cannabis sativa L. consists of high, sparsely branched plants featuring large leaves and sizable grey-brown grains. It refers to hemp fiber. As stated by [17] hemp is a recognized bast-fiber crop that displays clear phenotypic variation in plant morphology among genotypes [16]. The plant is a herbaceous species that is annual and thrives in warm seasons. It is inherently dioecious, meaning that male and female flowers exist on separate plants; thus, there are distinct male plants and female plants. However, certain commercial varieties are monoecious (one plant contains both male and female flowers). Hemp's morphology (the overall characteristics of biological form and organization of a plant's components) differs based on the cultivation environment. Plants often grow more branching at low plant-density levels but produce long, straight unbranched stems at high plant density. The primary components of a hemp plant include seeds, leaves, hurd, bast fiber and roots. Textiles are produced using fibers derived from the plant's stalks (stem).

Hemp, particularly fiber and grain varieties, features a lengthy stem and minimal branching when grown in dense plantations. As a plant grows, a hard, woody stem forms, varying in height from 1 to 6 m and from 6.35 to 19.05 mm in diameter, with limited leaves except at the upper part of the plant. Male hemp plants typically grow 10%-15% taller, Figure 6 [16].

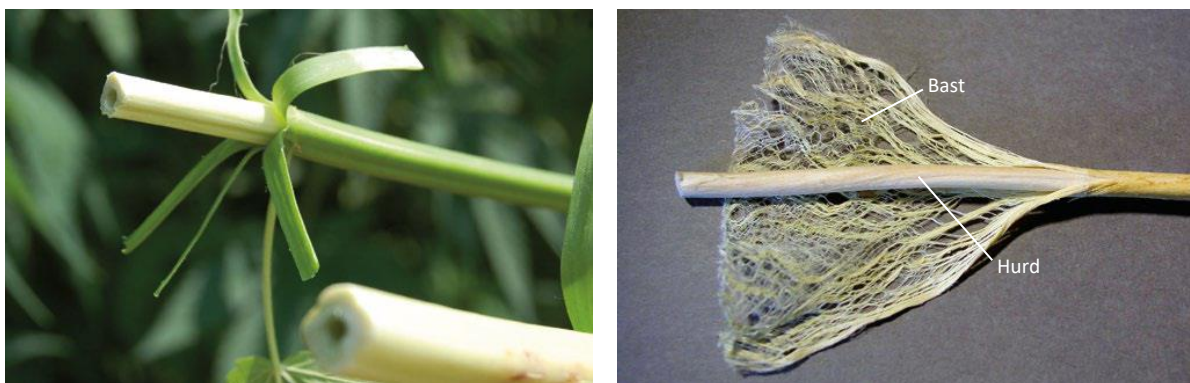


Figure 6: Hemp stem showing long bast fibers from outer bark (phloem) and hurd (or shiv) short fibers from woody inner part [16]

Cannabis plants have straight non-branching stems which have 7 to 10 internodes between the root crown and inflorescences. The longest internodes are found in the central part of the stem and their length ranges from 30 cm to 400 cm.

The stem of *C. sativa* is used to extract natural fibres. The stem consists of two layers; it contains two types of fibres, outer layer known as bast (used in textile, paper, or other industries, e.g. automotive) and inner layer named hurd (used for insulation, acoustic absorbers, etc.), which differ in their biological, chemical, and physical properties [18]. Bast fibres are crystalline cellulosic fibre bundles located in the phloem at the periphery of the *C. sativa* stem. Only the outer layer of the *Cannabis sativa* stalk (bast) is used for textile purposes.

1.4 Properties of hemp fibers

Sustainable, cost-effective, and eco-friendly resources for energy and chemical products are capturing people's interest because of worldwide energy needs and environmental concerns. Hemp as organic, environmentally friendly, renewable and biodegradable cellulosic fiber demonstrates outstanding resilience and toughness characteristics because of its elevated crystalline structure. In addition to its favorable strength characteristics, hemp fiber also demonstrates excellent antistatic, antimicrobial and thermal properties, UV resistance, water permeability characteristics and cause no allergic response for humans [19-20].

Hemp fiber properties are highly influenced by various factors such as variety, growth conditions, retting and pre-processing conditions, and fiber location in the plant stem. Properties of hemp fiber are determined by the structural fiber characteristics, such as length and tertiary structure, among others [1]. The chemical composition of the fibers, maturity, geographical location of the plantation, soil micronutrients, and environmental conditions affect on the mechanical, physical, and chemical properties of the fibers [21, 22]. Its mechanical, thermal, and physico-chemical properties, such as tensile strength, wettability, flammability, and swelling, vary with changes in plant anatomy, fiber processing conditions, growth conditions, and experimental methods. Furthermore, the distribution of the constituents also define the properties of the fibres [23].

According to Yu, the microstructure of hemp fibers features a distinct morphology and crystalline arrangement; hemp fibers exhibit an intricate net-like configuration, with nanofibers creating bundles of cellulose fibers measuring between 30 and 100 nm in width and extending several micrometers in length [24, 25]. This complex structure enhances the fiber's mechanical properties, primarily strength and flexibility.

Hemp fibre resembles other bast fibres because of the similar chemical composition found within this fibre category. Fibers obtained from the stalks of fibrous plants include cellulose,

hemicellulose, lignin, pectin, waxes, fats, and ash [9]. All these different chemical compounds make up the whole structure of the hemp fiber, and they represent distinct percentages of the fiber itself.

Hemp fibers are made up of bundles (technical fibers) of individual cells (elementary fibers), bonded together by the medial lamella, with a predominantly lignin content. Morphologically, an individual cell consists of the primary wall (disorganized arrangements of cellulose fibrils embedded in an organic matrix of hemicelluloses, lignin and proteins), the second wall (three layers of cellulose fibrils with different axial orientations, bonding by hemicelluloses), the tertiary wall (one layer of cellulose) and the lumen.

The main macromolecular compound that occurs in bast fibres is cellulose; the amounts of its dry mass is depending on the fibre type, variety and extraction method [9, 26, 27]. Cellulose provides ensuring the fiber's fundamental features such as: the strength, stability and hydrophilicity of the fibers. Hemicellulose binds cellulose and lignin together and has a major impact on the moisture adsorption and thermal stability of the hemp fibers; while lignin strongly influences the UV degradation of fibers and enhances the cell wall stiffness and hinders its degradation. Ultimately, pectin is found in the middle layer among all types of cells, binding everything together, highlighting the necessity of its removal to free the cellulose fibers [28, 29].

All these different chemical compounds make up the whole structure of the hemp fiber, and they represent distinct percentages of the fiber itself. The chemical composition of hemp fibers provided by various authors varies significantly from one another. The percentage values of the proportions of the primary chemical constituents in Table 3 shows the average proportion of individual elements in hemp fibre presented by various authors. The components found in the fiber rely on various factors, such as the type of hemp plant, climatic factors for cultivation, farming practices of plant farming encompassing weather conditions and technique of fibre processing [30].

Table 3: Chemical composition of hemp fibres based on the different literature references [9]

Cellulose [%]	Hemicelluloses [%]	Pectin [%]	Lignin [%]	Fat/Wax [%]
67-75	16-18	0.8	3.0-5.0	0.7
67	16	0.8	3.3	0.7
66.0-72.5	14-22	0.6-3.5	2.4-5.5	0.2-0.5
67-78	16-18	0.8	3.5-5.5	0.7
68	15	0.8	10	
52-58	15-18	4-10	3-6	
75		9.5		
71.41			6.59	

1.4.1 Chemical properties

The chemical properties of hemp generally correspond to the chemical properties of cellulose, since it is the main ingredient of the fiber, therefore, the behavior of the fiber when exposed to

chemicals generally corresponds to the properties of already processed cellulose fibers [4, 31]. In its solid form, cellulose has a microcrystalline structure with both crystalline and amorphous substructures. Amorphous components like hemicellulose, lignin, and pectin have hydroxyl groups that are more accessible and more reactive, whereas the hydroxyl groups in crystalline cellulose are tightly bound by hydrogen bonds, limiting reagent access and resulting in less effective functionalization and are more resistant to chemicals [14].

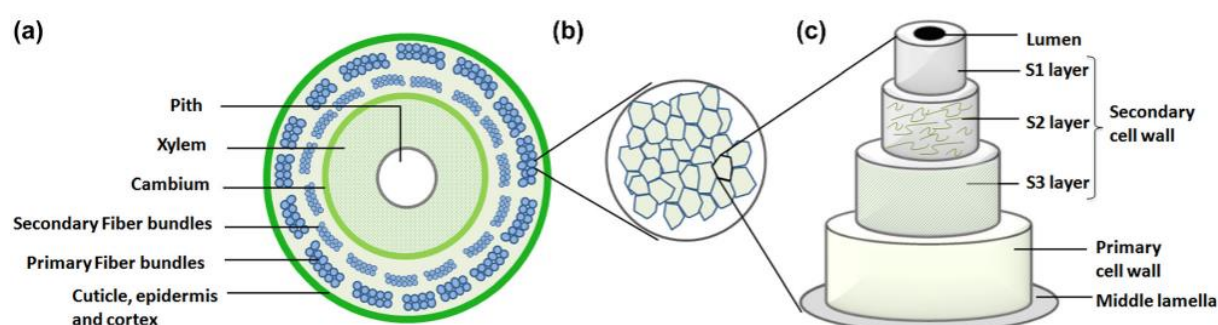
As mentioned in previous chapter, chemical treatments can significantly alter the chemical composition of hemp fibers, i.e. their properties, making them more suitable for textile applications. Researcher Yu found that after chemical treatments with sodium hydroxide and potassium permanganate, the fineness, flexibility, and tensile strength of hemp fibers were significantly improved. The combination of microwave energy and deep eutectic solvent treatments effectively removed non-cellulosic substances, increased cellulose content, and improved thermal stability. Furthermore, enzymatic treatments, can selectively degrade pectins and hemicelluloses, improving fiber fineness and flexibility. Enhancement of the fiber's crystallinity and mechanical properties is making them more suitable for high-performance textile applications [32].

According to Al-Maharma *et al.*, the hydrophobicity of the natural fibers can be enhanced through the application of appropriate chemical treatments, additives, nanocoatings, and bio-based coatings [33]. Treating the natural fibers with chemical and physical methods eliminates the hydrophilic substances from the surface of the fiber, leading to the considerable reduction of the fiber's hygroscopic behavior. With appropriate chemical and physical treatments, hemp fibers can meet the quality standards required for high-performance textile applications [32].

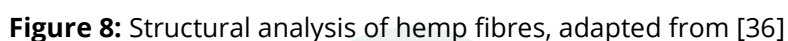
The natural fibers can be treated through using one of the following chemical treatments: Acetylation, Benzoylation, Treatment by Peroxide, Treatment by Isocyanate, Acidic Treatments, Alkalization, Coupling Agents and Grafting, Polymeric Coatings [34].

1.4.2 Hemp fibre structure and morphology

Given that hemp fabric is produced from fibres extracted from the bast (stem) of the *Cannabis sativa* plant—and that bast fibre is one of the primary products for which industrial hemp is cultivated, particularly for textile and apparel applications—this chapter outlines the structure and morphology of hemp fibres (Figure 7).



The hemp fiber's cross-section has an irregular shape, which is not constant through its length. Fibers are created as concentric rings around lumen and xylem in the whole length of stem parallel to the stem axis. The phloem (Figure 7a) contains the primary bast fibers, which consist of a bundle of fibers that runs the full length of the plant stem and is made up cellulose, hemicellulose, lignin, pectin, and wax. The phloem also contains secondary bast fibers that arise from the cambium. The cross-section of the elementary fibers is polygonal. Hemp fiber has a multi-celled structure, which can be seen as a composite material with numerous lumens side by side (Figure 7b). A typical elementary fiber structure of hemp fiber is shown in Figure 7c. The cell wall of the hemp fiber is multi-layered and consists of the primary cell wall (the first layer deposited during cell development) and the secondary wall (S), which is made up of three layers (S1-S3). The elementary fibers are bonded together in the middle lamella by pectin. On the other hand, the maximum concentration of cellulose is located in the S2, which is also the thickest layer and, due to higher cellulose concentration, impact on or determine the fiber properties [36].



Detailed schematic diagram of a transverse section of hemp stem showing the organization and morphology of a bast strip and single fibre (e.g. primary and secondary wall) in the bast layer at different levels of scale is shown in the Figure 8.

At bast fibre level, hemp stems are usually 1.5–2.5 m tall and 5–15 mm in diameter. The stem contains 30–40 wt% bast fibres and is organized in layers comprising from the pith to the surface 1–5 mm xylem, 10–50 μm cambium, 100–300 μm cortex, 20–100 μm epidermis and 2–5 μm cuticle (Figure 8). Hemp bast fibres contain primary and secondary fibres located in the cortex. Secondary fibres are typically shorter (around 2 mm long) and thinner (around 15 μm in diameter) than primary fibres (approx. 20 mm long and 10–40 μm in diameter).

At single fibre level, similar to other plant fibres, hemp fibre cell walls are mainly consist of a thin primary cell wall (70–110 nm) and a thick secondary cell wall (3–13 μm). The secondary cell wall is composed of a S1 layer (100–130 nm in thickness) and a S2 layer (3–13 μm in thickness). The thicker S2 layer is noted to feature a laminate structure made up of 1–4 major concentric layers with a thickness of 1–5 μm (Figure 8).

At the microfibril scale, the fiber cell wall can be viewed as a composite material consisting of cellulose microfibrils serving as reinforcements and non-cellulosic polymers, primarily hemicellulose, pectin, and lignin functioning as matrix [37–38].

1.4.3 Crystallinity and degree of polymerization

In addition to the chemical composition and morphological characteristics, the crystallinity and polymerization degree of cellulose are crucial elements for assessing biomass in material uses and are regarded as potential resistance factors in its biological transformation. The crystallinity significantly affects a fiber's physical and mechanical characteristics, such as strength, stiffness, and resistance to chemicals. There are studies that analyzed characteristics of the crystallinity and degree of polymerization (DP) of cellulose. Most studies analyzed these characteristics to evaluate the material properties of hemp. The previous studies of the crystallinity and degree of polymerization (DP) of cellulose are presented in Table 4.

Stevulova et al assessed the crystallinity of hemp hurds by employing Fourier-transform infrared spectroscopy (FTIR) and X-ray powder diffraction (XRD) [39]. The authors noted that the use of sodium hydroxide, ethylenediaminetetraacetic acid, and calcium hydroxide for chemical modification enhanced the crystallinity. These chemical changes also influenced the reduction of DP of cellulose. This research team also documented the DP of cellulose in hemp hurds following multiple ultrasound treatments [41]. The DP of cellulose was reduced even more by chemical treatments (sodium hydroxide and hot water) along with ultrasound

treatment. Fibers from industrial hemp underwent treatment with sodium hydroxide, acetic anhydride, maleic anhydride, and silane, with their crystallinities noted to elucidate the effects of treatment on fiber structure and tensile characteristics [42].

Table 4: Crystallinity and degree of polymerization of cellulose in industrial hemp biomass, based on [36]

Biomass	Crystallinity [%]	DP of Cellulose	Ref
Untreated and chemically modified hemp hurds	35.7–49.2	585–1302	[39]
	55.6–90.2 (a)		
Tempo-oxidized hemp bast	-	560–1100 (b)	[40]
Natural and treated hemp hurds	-	200–1300	[41]
Chemically treated industrial hemp fibers	84.8–91.6	-	[42]
Untreated and chemically treated hemp fibers	57.4–71.2	1138–1155 (b)	[43]
Hemp Shiv Fiber	38.8–50.1		[44]

(a) Measured by FTIR, (b) Viscosity-average degree of polymerization (DP).

The degree of polymerization and crystallinity of both, bleached and unbleached nanofibers were documented at every stage of the chemical treatment [43]. The mechanical properties of hemp bast and shiv fiber were also examined to clarify the variations in their characteristics [40–44]. While there have been no studies utilizing these properties to clarify the difficulty of industrial hemp in biological conversion thus far, these elements can be linked to the conversion efficiency concerning the availability of reducing ends and structural stiffness.

1.4.4 Main properties of hemp fibers for textile applications

Length

Since the length of hemp plant is 1.5 to 5 m [4], they are too long for spinning, and therefore are cut to a length of about 65 cm. The elementary fibers are short and have a length of approx. 15 to 30 mm.

Fineness

The fineness of technical fibers primarily depends on the intensity of carding, and compared to flax fiber, hemp is coarser. The diameter of the elementary fibers is 15 to 50 micrometers, and their fineness is 2 to 6 dtex [4].

Strength

Hemp fibers are stronger than flax fibers, with a strength ranging from 35 to 70 cN/tex. When wet, the fibers are 5–20% stronger. Their elongation is low, as with all stem fibers - the elongation at break is 1 to 6%, and their flexibility is also low. Therefore, products made from hemp fiber are relatively stiff and prone to wrinkling [31]. The excellent tensile strength of hemp fibers has been utilized in structural applications and in agriculture, aerospace, automotive, construction, sports, household products, and auto components to dampen noise because of their superior sound-absorption qualities.

Density

Fiber density may appear to be a straightforward property, yet it plays a crucial role in numerous facets of fiber production. Initially, it is one of the simplest parameters to assess among various types of fibers, rendering it a preferred test for identification. Moreover, fiber density can be utilized to determine fiber strength and modulus, along with the rough total effective area utilized for the sample.

Due to hemp being an inconsistent fiber with varying density and cross-sectional area both between different samples and within the same sample, it is advisable to adopt an indirect measurement approach for characterization rather than relying on the linear density and diameter method. The exact technique can be selected according to the necessary precision for the application. For instance, the Float/Sink and Density Gradient methods will not provide precise measurements for the specimen (ASTM 2022b). Rather, they offer an estimated value derived from different liquids. Should the hemp fall within a range of densities, these techniques might be appropriate. Nevertheless, if a more precise value is needed, it is advisable to utilize one of the psychometry or buoyancy techniques. These methods leverage physical correlations among various attributes to yield a precise measurement of specimen density. Although none of the previously mentioned techniques are tailored specifically for hemp, minor modifications to the process (for instance, Test liquid) are easily made. Certain studies employ ASTM D3800 for determination of density of high modulus fibers and ASTM D1505 to assess the fiber density of plastics by density-gradient techniques, yielding positive outcomes, leading to the conclusion that this approach is suitable [12]. For this report ASTM D8171-18 was applied and explained in detail in experimental part.

Moisture and water absorption

Hemp fiber is highly hydrophilic, known for its high moisture absorption capacity, due to the presence of hydroxyl groups (OH) of anhydroglucose repeating unit in cellulose structure, as plant-based sources are hydrophilic in nature [43]. Its properties are primarily due to its hollow, porous structure, and high cellulose content, leading to increased moisture uptake. The absorptivity of hemp fiber is influenced by its hydrophilic cellulose, which is resistant to organic solvents and water [24]. The moisture sensitivity of natural fibres is mainly explained by their complex multi-scale structure and biochemical composition. The fibre cell wall rich in amorphous polysaccharides

such as hemicelluloses (~15%) and pectins (~6%) induces an important amount of available hydroxyl groups responsible for water sorption [45]. According to Islam and Hasan, most bast fibers are quite similar in terms of their composition and structure [46].

One of the main challenges with these fibers is their tendency to absorb moisture. Moisture absorption and retention are significant factors affecting the performance of hemp fibers in various applications; moreover, the behaviour of plant-based fibres depends strongly on their humidity according to Placet et al. [47]. However, the moisture absorption is directly correlated with the type of natural fiber [33]. The moisture regain of hemp fibre is typically around 10-12% under standard atmospheric conditions [48]. Hemp fibers generally absorb more moisture when the relative humidity rises [45]. The moisture sorption properties can be modified through different chemical treatments [35]. Moreover, in the context of mechanical properties and moisture interaction, the tensile strength and elasticity of hemp fibers are influenced by environmental conditions, particularly moisture. Studies have shown that water sorption significantly affects the tensile stiffness and strength of hemp fibers, with a remarkable increase in fiber stiffness.

Thermal properties

Thermal conductivity is one of the most interesting characteristics for thermal insulation materials; it depends on several parameters such as a morphology, density and homogeneity of materials [49]. Hemp fibers exhibit advantageous thermal characteristics, crucial for uses that need thermal insulation [24]. The general rule is: the lower is the thermal conductivity of the insulating material, the greater its ability to resist heat transfer and, hence, the greater is the effectiveness of the insulation. Considering hemp fiber's low thermal conductivity, due to its porous structure, which traps air and reduces heat transfer, and low density, makes it a good thermal insulator. Sair et al. studied composite materials based on the polyurethane matrix and treated hemp fibers, with the aim of preparing thermal insulation materials for the building and public works sector. Results of measured properties, such as wateruptake, thermal conductivity, and mechanical properties showed that polyurethane-hemp fibers composite present good insulating properties compared to the traditional insulation materials (glass wool, mineral wool etc.) [49]. Furthermore, hemp-based materials like hempcrete – the mixture of hemp hurd (the woody inner portion of the hemp stalk) with lime mortar and water, with the mixture sprayed or cast in a method that is similar to forming concrete), have been used especially for non-load bearing building structures, because of its excellent thermal (insulation) and acoustic properties [50]. Therefore, due to its thermal resistance properties, hemp fibers are valuable in production of a material for thermal insulation [51].

Fire resistance

Hemp fibers, characterized by their high cellulose content, exhibit intrinsic flammability [52]. Nevertheless, their flame-retardant performance can be substantially enhanced through targeted modification strategies [53]. Conventional chemical treatments employing phosphorus, and

inorganic salt-based compounds, the incorporation of functional nanoparticles such as silicon dioxide (SiO₂) and aluminum hydroxide (Al(OH)₃), as well as bio-derived modification approaches, have all demonstrated efficacy in improving flame retardant properties. Collectively, these interventions increase the limiting oxygen index (LOI), mitigate heat release during combustion (HRC) [54], and thereby broaden the potential application of hemp fibers in advanced material domains, including building insulation, polymer composites, and protective textile systems [55-58].

UV protection

Natural hemp fibers inherently resist ultraviolet radiation owing to their lignin composition and compact structure. When further functionalized—through processes such as natural pigment dyeing, nanoparticle treatments, or blending with complementary fibers—hemp fabrics can attain markedly enhanced Ultraviolet Protection Factor (UPF) values, positioning them as highly suitable materials for sustainable, sun-protective textiles, offering inherent high UPF without additional chemical treatments. For sustainable design in textiles, hemp provides a natural advantage in UV protection, making it preferable for outdoor wear, children's clothing, and eco-conscious sun-protective garments [59].

Antimicrobial properties

Hemp has well-known antibacterial performance due to its wide variety of chemical constituents: cannabinoids, hydrocarbons, simple alcohols, aldehydes, ketones, acids, esters, flavonoid glycosides, vitamins, pigments and many other [60].

Hemp extracts obtained with organic solvents exhibit very good antibacterial activity against *S. aureus*, according to Borchardt [61], while aqueous extracts did not exhibit any antimicrobial activity. Additionally, the phenolic compounds of hemp lignin exhibited strong inhibition of several micro-organisms' growth (e.g. *E. coli*, *A. niger*, *S. cerevisiae*).

Biodegradability

The significance of biodegradability lies in its capacity to prevent the accumulation of waste, which would otherwise contribute to long-term environmental pollution. By employing biodegradable resources such as hemp, it is possible to design products that naturally decompose and reintegrate into the environment without causing lasting harm to ecosystems. Hemp, as a plant-based fiber, shares the inherent property of biodegradability common to all natural fibers. Its composition is predominantly cellulose—a natural polymer present in plant cell walls—which readily undergoes microbial degradation under suitable environmental conditions [62-64].

1.4.5 Hemp Life Cycle Assessment, LCA

Life Cycle Assessment (LCA) studies have provided valuable insights into the environmental performance of natural fiber-based products, among which natural fiber-reinforced polymer composites, particularly those incorporating hemp fibers were addressed. The LCA is used to evaluate the environmental impacts associated with product systems along with their cradle to grave life cycle, as presented in Fig 9 [65].



Figure 9: LCA “cradle to grave” scheme according to the norm DIN EN ISO 14040

These evaluations consistently highlight notable ecological benefits of hemp-based composites, especially in terms of reduced energy demand and lower greenhouse gas emissions, making them advantageous in weight-sensitive sectors such as automotive and aerospace.

Nonetheless, these benefits are not uniformly observed across all environmental impact categories. Agricultural practices linked to natural fiber cultivation can pose challenges, particularly regarding land use and water consumption. Furthermore, the variability of outcomes depending on the chosen functional unit and the significant influence of matrix materials within the composites underscores the inherent complexity of assessing such systems [14, 65].

1.5 Hemp processing

Hemp fiber production consists of a systematic sequence of agricultural and mechanical operations that convert raw stalks into refined textile fibers suitable for industrial application [66]. Hemp processing scheme is presented in Figure 10.



Figure 10: Hemp processing scheme, adapted from [35]

Although there are differences in the European and Asian traditions of processing hemp into fiber, the core traditional processing steps of hemp can be summarized as follows:

Harvesting: Stalks are typically cut by hand using sickles when male plants begin to shed pollen, ensuring fibers are flexible rather than coarse.

Retting (biological decay): stalks are exposed to moisture to allow bacteria and fungi to break down pectin, the natural "glue" binding fibers to the woody core (usually dew or water retting).

Breaking (Scutching or decortication): once dried, retted stalks are "broken" manually using wooden mallets or fluted rollers to crush the woody inner core. Scutching follows, where the broken stems are beaten or scraped to knock away the woody shards. Breaking can be performed on automatic device decorticator as well.

Hackling (Carding): the remaining fiber bundles are drawn through "hackles" (metal-toothed cards somewhere called combs) to separate short, tangled fibers (tow) from long, straight ones (line fiber) and remove any final wood particles.

Softening and bleaching: fibers are often treated to improve texture. Traditional methods include boiling them in water mixed with wood ash (a natural lye) or lime, followed by sun-bleaching to turn the fiber creamy white.

Spinning: fibers are twisted into yarn using a drop spindle or spinning wheel. Fine garments often require "wet spinning," where fibers pass through warm water to soften the pectin for a smoother finish.

Weaving / Knitting, and other textile technologies related with production of specific textile products.

1.5.1 Harvesting

LONG FIBRE TEXTILE HEMP: CROP ITINERARY



Figure 11: Hemp crop fact sheet, Crop itinerary. Available at:

<https://hemp4circularity.nweurope.eu/blog/hemp4circularity-news-12/hemp-crop-fact-sheet-104>

INTERREG NWE project Hemp4Circularity aims to implement an innovative, local and biobased ecological fibre - the long fibre hemp - in the textile value chain of North-West Europe, from

growers to weavers/knitters, from field to fashion. Within the project they have developed Hemp crop fact sheet, with the recommendations for the growing and harvesting phases.

1.5.2. Retting

Retting, or maceration, represents the initial step in the extraction of plant fibers. It involves separating fiber bundles from the cutinized epidermis and the lignified cells of the woody core through biological degradation supported by biochemical and partially physical mechanisms [67]. As a key determinant of fiber quality, maceration has become a major focus of contemporary research and development, particularly regarding its industrial-scale implementation [68]. Maceration is broadly defined as the soaking of plant material to induce softening [6]. It is most performed using water, dew, or enzymatic baths—collectively referred to as biological maceration—or through chemical treatments, which constitute chemical maceration. In some instances, physical fiber-separation techniques may also be classified as maceration when a liquid medium is used to support fiber release in combination with mechanical action [69].

Biological retting is a long-established and widely practiced method for fiber extraction, typically carried out as either water retting or dew retting. Water retting is performed in open or closed tanks; however, the former practice of submerging plant material in natural water bodies such as rivers, lakes, streams, or coastal areas has been abandoned due to its environmental impact. This method produces chemical compounds, including CO_2 , H_2 , and CH_3 , that can harm aquatic ecosystems and contribute to the mortality of resident organisms. Dew retting, in contrast, is more commonly used today because of its lower operational costs [70–72].

The primary purpose of biological soaking is the removal of pectin, the adhesive substance that binds fibers within the plant stem. Although pectins are not water-soluble, soaking promotes their gradual leaching and stimulates the growth of microorganisms that secrete pectin-degrading enzymes. Both water and dew retting rely on pectinolytic enzymes produced by naturally occurring microflora. Successful biological retting requires careful control of environmental factors such as humidity, temperature, and duration to achieve desirable fiber quality. Dew (field) retting, which involves spreading stalks in the field for 3–6 weeks to be moistened by dew and rainfall, is less labor-intensive but yields darker and coarser fibers. Water retting is faster, typically 7–15 days, and produces lighter, higher-quality fibers.

Within biological maceration, enzymatic baths, also known as enzymatic treatment or biological cleaning, are increasingly used. In this approach, specific decomposition enzymes are added directly to the soaking medium containing the plant material. Enzymatic treatment is considered a promising alternative to traditional retting due to its shorter processing time, environmental compatibility, and operational efficiency. Enzymatic soaking usually lasts between 8 and 48 hours [73].

Effective fiber isolation requires the removal of both pectin layers. The outer pectin binds fiber bundles to the bark, while the inner pectin holds individual fibers together within each bundle. Because these layers differ in chemical composition, they also differ in their susceptibility to microbial and chemical degradation. The outer pectin is less resistant and therefore breaks down more readily, facilitating the release of fibers from surrounding tissues.

Pectinases are the primary enzymes used in maceration to promote fiber liberation from plant tissues. These pectinolytic enzymes form a diverse group capable of hydrolysing pectic substances abundant in plant cell walls. In addition to their industrial significance, they contribute to ecological processes by supporting the decomposition and recycling of plant residues. Their effectiveness in maceration depends on tightly controlled conditions, as their activity is highly sensitive to pH, temperature, and enzyme concentration. According to Foulk et al. [74], detailed knowledge of enzyme mixture composition enables the tailoring of enzymatic treatments to produce fibers with specific properties, such as improved strength and fineness, suited to targeted applications. Strength remains a particularly important attribute for many end uses of natural fibers.

Chemical retting is often preferred over biological methods because it produces fibers of consistently high quality, is independent of weather conditions, and generally requires shorter processing times. A range of chemical treatments may be applied depending on the fiber type and intended use. Among these, alkalization is the most common, accelerating the removal of pectin, lignin, and hemicellulose. This process is typically carried out using sodium hydroxide (NaOH), or caustic soda. Caustic treatment affects several fiber characteristics: it increases elongation at break, enhances surface roughness, and improves tensile strength, while also altering electrical and thermal stability. However, higher NaOH concentrations can reduce tensile strength, indicating potential damage to the cellulose structure.

For more complete removal of lignin and most hemicelluloses, treatments with aqueous ammonia or mild organic acids offer an alternative to conventional alkaline soaking. Chemical methods also provide a reliable substitute for dew retting, whose use has declined due to climate-related variability and the associated risk of significant crop losses. Unlike biological processes, chemical soaking is unaffected by weather fluctuations and preserves the intrinsic quality of the fibers. Nonetheless, concerns related to waste management and the potential for moderate fiber damage have reduced the appeal of these treatments compared with earlier practice [75].

Beyond maceration, fiber isolation also includes mechanical and other physical methods for separating fibers from plant stems. Physical techniques typically employ electromagnetic radiation, elevated temperature, and/or pressure to detach fibers from the woody core. Common approaches include steam explosion, osmotic degumming, microwave treatment, and ultrasound. Microwave treatment promotes fiber release by converting electromagnetic energy into heat, weakening the bonds between fibers and woody tissues [76–77]. Ultrasonic treatment offers another efficient and environmentally friendly option, using high-intensity, low-frequency waves to disrupt cellular structures and enable rapid fiber separation [23,24]. Physical processes are characterized by their speed and versatility, making them promising candidates for continued research and technological advancement.

1.5.3 Decortication or Scutching

Mechanical fiber isolation relies on mechanical forces to break the bonds between fibers and the woody core. The most widely used method is decortication, in which plant stems are processed through machines that apply compression, shearing, and/or impact forces. Various types of decortication equipment exist, including crushing rollers, hammer mills, and ball mills, each designed to achieve effective fiber separation.

Manual mechanical separation includes removal of residual plant matter on scutching device. It is performed by striking the fibers with a wooden or metal implement to detach any remaining bark and extraneous material.

Following decortication, a post-decortication cleaning stage is usually undertaken, during which the isolated fibers are further separated from residual fiber fragments, woody stem material, and fine particles. This is achieved through techniques such as carding, combing, scraping, and peeling.

1.5.4 Carding (Hackling)

After decortication or scutching, the fibers undergo hackling (carding or combing) processes that eliminates residual impurities and arranges the fibers in a parallel orientation, thereby improving their uniformity and quality. Carding primarily serves to align and blend fibers into a continuous strand known as a sliver. It is a critical stage in preparing hemp fibers for spinning into yarn or thread done by hand (Figure 12) or machine.

Hand carding is slower and more labor-intensive but allows for precise control over fiber alignment. During this process, the fibers are first cleaned and loosened to remove impurities and debris.



Figure 12: Traditional hackling of hemp fibers using a metal comb

Fibers can be passed through a carding machine equipped with wire teeth or cylinders, which align the fibers and eliminate tangles or knots. The result is a smooth, uniform sliver that can be spun with greater consistency. Machine carding is faster and more efficient, though less exact.

1.5.5 Spinning

The prepared fibers (hemp sliver) are then spun into yarn or thread, either manually on drop spindle or by spinning wheel.

1.5.6 Weaving or Knitting

The spun yarn or thread is subsequently woven or knitted into fabric, which can be utilized to produce a wide range of apparel and textile products.

1.5.7 Finishing

Finally, the fabric undergoes several finishing processes, which may include washing, dyeing, printing and different final finishing, depending on the requirements of the final product.

Table 5: Preferable finishing processes

Finishing Type	Preferable Processes	Sustainability Notes
Dyeing	Enzymatic pre-treatment, reactive dyes, vat dyes, natural dyes	Enzymes reduce chemicals; reactive dyes give high fastness
Printing	Pigment, reactive, digital pigment printing	Low water use; good definition with enzyme pre-treatments
Softening	Enzymatic softening, other bio-softeners mechanical softening,	Enzymes + mechanical = most sustainable

Transforming raw hemp into soft, high-quality textiles demands precise finishing steps. While traditional methods depended heavily on aggressive chemical treatments, contemporary practice is moving toward environmentally responsible approaches, including enzymatic processing, low-impact dyeing, and mechanical softening.

These treatments impart the fabric's final texture, appearance, and durability, ensuring it meets the desired quality standards depending on required end use.

2 Green-Tex Portfolio

2.1 Green-Tex traditional processing

2.1.1 Cultivation and harvesting of the hemp

Hemp was cultivated at the premises of ZAKON cooperative, according to the contract initiated by Majur County. ZAKON cooperative is registered for the production and sale of industrial hemp in Pisarovina, Zagreb County.

For the experiment, a **Futura 75** hemp species was applied. This variety of industrial hemp is certified by the European Union and ideal for warm and dry climates. It has high fibre content in stem: 30-35%. The seeds were planted 14th of June 2025, reaped 4th of October 2025 and harvested 4th of November 2025, after the process of field retting.



Figure 13: Harvesting of hemp at Pisarovina in November 2025

2.1.2 Traditional retting

Two traditional retting methods have been applied:

1. Field retting (also known as dew retting), and
2. Water retting.

Field retting involved cutting hemp stems and spreading them across the field, where they are naturally colonized by microbial communities. The activity of these microorganisms, particularly pectinolytic species, is strongly influenced by the local microbiota, stem moisture content, and prevailing climatic factors such as humidity and temperature. Consequently, the efficiency of field retting varies geographically and depends on weather conditions conducive to microbial proliferation. This process typically requires several weeks to complete. Therefore, the **duration of field retting was 20 days**.

In contrast, water retting was carried out by immersing hemp stems in tanks, which promoted the rapid development of pectinolytic microbial populations, Figure 14. Water penetration into stem tissues enhances moisture absorption and accelerates microbial activity. As a result, water retting generally requires less time than field retting (approximately 1–2 weeks). For this experiment the process of water retting was performed for **20 days**.



Figure 14: Water retting at Majur County (water was changed twice)

2.1.3 Post-retting processes

All post-retting processes were performed by partner 6: the Majur County, at their premises. After two methods of retting (maceration) were carried out, in which a biochemical process causes the decomposition of pectin, post-retting processes of rinsing and drying the hemp stalks followed. Stalks were dried for 2 weeks on air.

The bark with the fibre adhering to it then removed from the stalk by peeling by hand if possible (Figure 15) or by running the stalks through a breaking machine (scutching operation).



Figure 15: Drying of hemp stalks, followed with manual separation of hemp fibres from hurd

In some growing areas the bark is removed from the fibre by machine scutching in a manner similar to flax mechanical treatments. In other areas, machinery which combines the breaking and scutching operation is used.



Figure 16: Preparatory process – stripping leaves and flowerheads

Prior to scutching, additional preparatory process of stripping of externalities (leaves and flowerheads) must be performed (Figure 16). Separating fibres from dried retted stalks was carried out by traditional mechanical method on scutcher (scutching - beating or scraping), Figure 17.



Figure 17: Scutching of hemp, followed with carding (hackling) process

After scutching the hemp is usually dressed, generally by a hand operation, to ensure thorough cleaning of the fibre. Fibre strands are pulled usually between a wooden needles at hackle (Figure 17).

If required, the fibres can be further softened by “beetling” which consists of pounding, by hand or by running it through a stamping or rolling machine [78].



Figure 18: Hand spinning using drop spindle or spinning wheel

During hand spinning with a drop spindle (Figure 18), the spinner rotates the spindle with one hand while using the other to form thread. As needed, the spinner moistens the fibers, to improve cohesion. Moistening also reduced internal tension generated during twisting, preventing the formation of unwanted loops when the thread was later rewound.

Spinning wheel was also applied. It requires positioning of the thread to be guided through the hollow section of the flyer support containing the bobbin. Rotation was achieved by pressing a foot pedal, whose movement drove a large wheel. This wheel, in turn, produced a slower rotation of the flyer relative to the bobbin, enabling both twist insertion into the yarn and winding onto the front bobbin.

In hand-spinning with a mechanized device, parallel fibers were manually drawn from the prepared *kančela*, while a horizontally positioned spindle, powered by an electric motor, produced the required number of twists over a defined length. When necessary, the spindle was repositioned vertically to wind the oriented fibers into yarn.

2.1.4 Decortication

Only one part of the hemp samples was mechanically treated on decorticator at the premises of Cooperative ZAKON (Figure 19). Already in 2023, TTF initiated scientific collaboration with Cooperative ZAKON (Cooperative for the production and sale of industrial hemp products) on the topic of eco-design and application of hemp biomass as feedstock for different bioproducts, so as the transformation of economy from linear to circular bioeconomy.



Figure 19: Conventional decorticator operated by the ZAKON Cooperative.

The hemp stalks were processed at the decorticator and cleaned afterwards manually. Separated fibres will be used in the next period as reinforcement of biodegradable green composite materials. Such materials have advantage of high strength and light mass and therefore can be applied in automotive or construction industries.

2.2 Analysis of hemp fibres

In addition to the main cellulose content raw hemp technical fibres contain lignin and other substances that affect stiffness and scratch resistance. Technical hemp fibres are coarser and stiffer than other fibres types, such as flax, and have a relatively high lignin content (4 to 8%).

Therefore, for the purpose of clothing production the fibres must undergo chemical treatment called degumming, which additionally removes pectin, lignin and other non-cellulosic components to make the fibres more flexible and comfortable. The traditional use of sodium hydroxide solution is effective and still in usage for removal of non-cellulosic components bound to hemp fibres and release of the fibres, despite the possibility of cellulose damage and environmental burden.

The most used methods of hemp degumming are:

- Boiling in water or steam which naturally loosens the fibers.
- Alkaline treatments which break down plant compounds making the fibres more flexible.
- Enzyme degumming methods as environmentally friendly methods that avoid harsh chemicals, preserving the natural sustainability of hemp.

In this experiment, samples of hemp fibres, previously field retted or water retted, were impregnated with sodium hydroxide solution 4 and 8 wt. % for 15 hours at room temperature before the treatment with boiling water at 110 °C for 40 minutes. Ahiba Turbomat laboratory apparatus with 6 beakers with magnetic stirring was applied for the experiment.

Additional sample of water retted hemp fibres was boiled in sodium hydroxide solution 4 wt. % for 30 minutes, with the aim of achieving the destruction of technical hemp fibres on elementary fibres. The legend of the tested hemp fibre specimens is shown in Table 6.

Table 6: Hemp fibre specimens - legend

Specimens	Description of the treatments
FR or F	Field retting for 20 days
WR or W	Water retting for 20 days
FR 4%NaOH	Field retting and additional post-treatment - impregnation (soaking) with 4% NaOH (15h at room temperature), followed with boiling in water (T=110°C, t=40 min)
WR 4%NaOH	Water retting and additional post-treatment - impregnation (soaking) with 4% NaOH (15h at room temperature), followed with boiling in water (T=110°C, t=40 min)
FR 8%NaOH	Field retting and additional post-treatment - impregnation (soaking) with 8% NaOH (15h at room temperature), followed with boiling in water (T=110°C, t=40 min)

WR 8%NaOH	Water retting and additional post-treatment - impregnation with 8% NaOH (15h at room temperature), followed with boiling in water (T=110°C, t=40 min)
WR-4%NaOH boiling	Water retting and additional post-treatment - boiling in 4% NaOH (T=100°C, t=30 min)
WR-H ₂ O boiling	Water retting and additional post-treatment - boiling in H ₂ O (T=100°C, t=30 min)
FR-H ₂ O boiling	Field retting and additional post-treatment - boiling in H ₂ O (T=100°C, t=30 min)

The following analysis were performed:

- Fibre moisture content (%)
- Fibre moisture regain (%)
- Fibre density (g/cm³)
- Fibre spectral properties
- Fibre morphology (optical microscope and SEM)
- Fibre chemical analysis (FTIR), elemental chemical analysis (EDS)

2.2.1 Fibre moisture content and moisture regain

Moisture absorption represents one of the key properties of textile fibres. Beyond influencing the thermophysiological comfort of products manufactured from these fibres, it also reflects their capacity to absorb moisture from the surrounding environment. Under identical atmospheric conditions, fibres exhibit varying abilities to retain moisture.

Moisture content in fibres can be quantified through parameters such as humidity, regain, and commercial addition. The equilibrium state of moisture absorption and desorption can be illustrated graphically using sorption isotherms (for both absorption and desorption) and humidity hysteresis. Because moisture content significantly affects nearly all physical and mechanical properties of textile fibres, its accurate determination is essential.

The standard atmosphere for testing is specified as an environment with a temperature of 20 °C ± 2 °C and a relative humidity of 65% ± 4% [4]. Measurement of fibre moisture is conducted in accordance with **ASTM D 2654-89a**.

The process of determining both the moisture content (MC) and moisture regain (MR) began by calculating the mass of the sample after it had been air-dried. Afterwards, the sample was placed in a climatic chamber and subjected to standard atmospheric conditions for a period of 24 hours. Post conditioning, the sample's mass was calculated, followed by a drying period of another 24 hours. The moisture regain and content are calculated according to Equations (3) and (4). Testing was carried out in triplicate to ensure precision and consistency.

$$MC\% = \left(\frac{m1 - m2}{m1} \right) \times 100 \quad (1)$$

$$MR\% = \left(\frac{m3 - m2}{m2} \right) \times 100 \quad (2)$$

Where: *MC%* represents moisture content, *MR%* represents the moisture regain, *m1* represents the mass of an air-dried sample, *m2* represents completely dried sample's mass, while *m3* represents the conditioned sample's mass.

Table 7: Moisture regain (MR%) of the hemp fibre specimens calculated according to equation (4)

Specimens	WR	FR	WR + 8% NaOH	FR + 8% NaOH	Boiling in 4% NaOH
Moisture regains (MR %)	11.23	12.43	8.93	9.64	8.22

The results presented in Table 7 indicate noticeable differences in moisture regain (MR%) caused by the applied chemical treatments. Field-retted hemp fibers exhibit somewhat higher values compared with water-retted fibers (FR 12.43% vs. WR 11.23%).

A similar trend is observed in samples that underwent water and field retting followed by degumming with 8% NaOH and boiling in water, although the overall moisture regain values are lower (8.93% and 9.64%). Samples treated by boiling in 4% NaOH for 30 minutes show an even lower moisture regain of 8.22%. These results may be attributed to the higher cellulose content [79] and the partially achieved cottonizing effect, which is also evident from the visual appearance of the fibers, presented at Figure 21.

2.2.2 Fibre density

Density is defined as the mass per unit volume of fibre [4, 80]. Most textile fibre exhibit densities ranging from 0.9 to 2.5 g/cm³. This property significantly influences the overall weight of fibre-based products. Beyond mass, density also affects the aesthetic and tactile characteristics of the final material; fibres with higher density typically exhibit superior drape, whereas those with lower density tend to produce lighter and more voluminous fabrics [4].

Stem fibres, such as hemp and flax, generally have a relatively low density, usually around 1.35 g/cm³, although it can vary considerably (such as Hempline Inc. hemp fibres with a density of 0.86 g/cm³).

Fibre density was measured using a solid-liquid density analyzer, presented in Figure 20. The actual density values were determined in accordance with ASTM D8171-18. Nitrogen gas (N₂) of high purity was utilized due to its capability to seep into the minuscule pores, thus augmenting the precision of the measurement volume, respectively density samples, previously determined mass. The measures for one sample lasted 15 times to guarantee accuracy on the Ultrapyc 1200e gas pycnometer, provided by Anton Paar, and the results are presented in Table 8.



Figure 20: Automatic gas pycnometer for fibre density testing (Anton Paar)

Table 8: Fibre density of the hemp fibre specimens

Specimens	Mass (g)	Volume (cm ³)	Vol. Stan. Dev.	Density (g/cm ³)
WR	1.3059	1.0590	0.0275	1.2331
FR	1.3179	1.0691	0.0082	1.2328
WR 8% NaOH	0.6056	0.5407	0.0118	1.1201
FR 8% NaOH	0.4843	0.5374	0.0214	0.9012
Boiling in 4% NaOH	1.0977	0.8981	0.0052	1.2222

Table 7 demonstrates fibre density properties of differently treated hemp fibers. The values of untreated hemp fibres density are usually within the range 1.3-1.6 g/cm³ and corresponds to flax fibers (1.4-1.5 g/cm³), according to [81].

Density values of the water-retted and field-retted hemp fibers fall within a very narrow range (1.2331–1.2328), indicating that retting method alone does not significantly alter the intrinsic density of the cellulose-rich fiber structure. This is expected because both water and field retting primarily remove pectin and other non-cellulosic components through microbial or moisture-driven degradation, without substantially modifying the crystalline cellulose framework that determines fiber density [82].

In contrast, alkaline treatment led to a measurable decrease in fiber density. This reduction is attributed to several chemical and structural effects of NaOH treatment. The first one is removal of hemicellulose, pectin, and surface impurities which is reducing the overall mass of the fiber while increasing internal porosity. Additionally, NaOH penetrates the fiber wall, causing swelling of cellulose microfibrils and partial disruption of hydrogen bonding. This increases the fiber volume without a proportional increase in mass and further lowers fibers density [83].

2.2.3 Fibre morphology - optical microscopy

A digital optical microscope has revealed the visual appearance of hemp fibres its, texture and color. Additionally, the degree of fibrillation of differently treated samples of technical hemp fibres was investigated by images obtained with digital microscope Dino-Lite, as longitudinal view of the hemp fibres, presented at Figure 21.

Field retting (FR)



Water retting (WR)



FR-4%NaOH+ H₂O boiling



WR-4%NaOH+ H₂O boiling



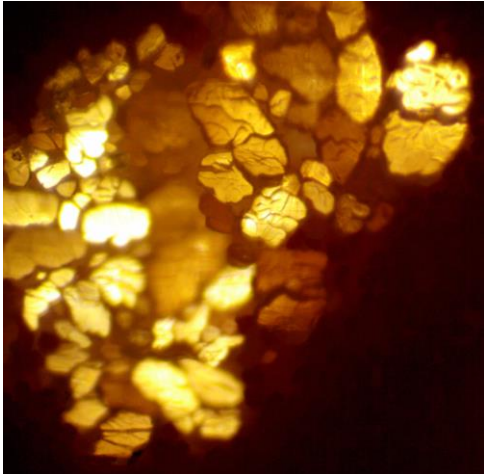


Figure 21: Dino-Lite microscopic images (magnification 50x) of longitudinal view of hemp fibre

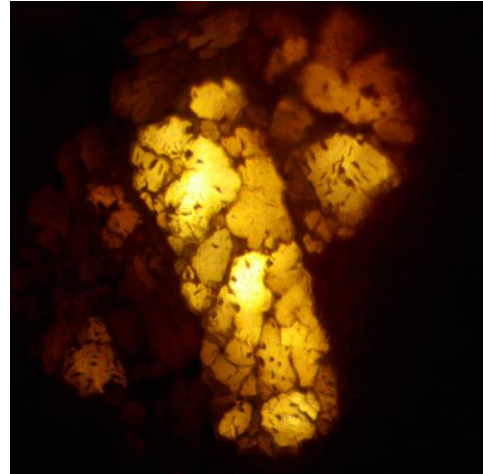
A distinguishing feature of hemp fibers, in contrast to flax, is that their cell ends are blunt and often exhibit lateral branching. The fibers are generally cylindrical, displaying characteristic surface irregularities such as frequent nodes, longitudinal fissures, and areas of swollen tissue.

Cross sections of differently treated hemp fibers are presented on Fig. 22.

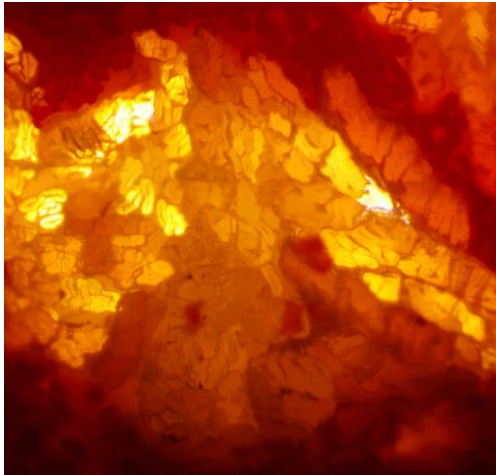
WR



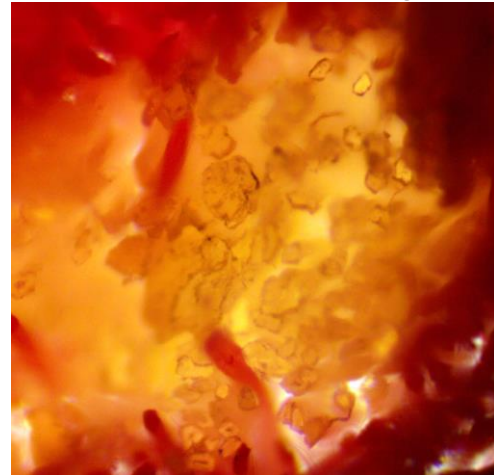
FR



WR-8% NaOH+ H₂O boiling



FR-8% NaOH+ H₂O boiling



WR-boiling in 4% NaOH

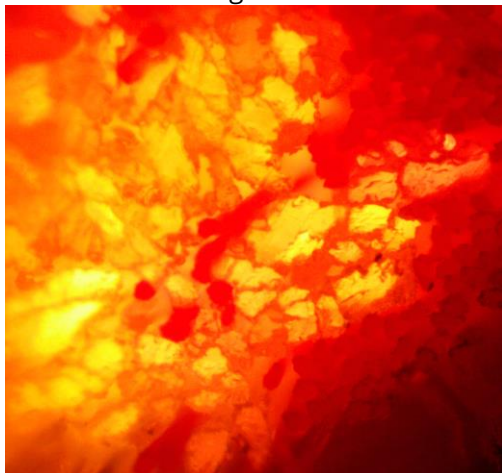


Figure 22: Microscopic cross-section (morphology) of the hemp fibre samples (magnification 100x)

Images of cross-section of the hemp fibre samples were obtained on KERN binocular illumination (transmitted) microscope with digital solution (magnification 100x), Figure 22. By analyzing the cross-section images, it is possible to determine a significant influence of the degumming process on the appearance of the cross-section.

A less pronounced lumen, especially in water retted hemp samples, is noticeable. Also, by comparing the cross-sections of water retted and field retted hemp fibres, a slightly larger lumen and a more occasional appearance of fragments of parenchymal tissue are observed on field retted sample (FR). In addition, a larger number of separated elementary fibres (although not completely separated) is observed in a case of field retted samples impregnated with 8% NaOH and boiled in water (FR 8% NaOH). Separation of elementary fibres are not completely visible even in a case where of hemp fibre sample boiled in a 4% NaOH solution for 30 min.

2.2.4 Fibre morphology by SEM

The surface observation of the fibres was examined using the Mira 3 LMU Scanning Electron Microscope (SEM), manufactured by Tescan (Figure 23). Depending on the type of further microscopy (scanning or optical/light microscope), the preparation is additionally performed. For imaging on a scanning electron microscope, the samples are coated with a thin layer of metal (chromium) for better conductivity to prevent the so-called charging effect in SEM images.



Figure 23: SEM Tescan Mira 3 LMU, Tescan and Sputter coater, Quorum

To gain deeper insight into the morphological characteristics of fibres and the properties closely linked to their structure, analyses are often conducted using scanning electron microscopy (SEM).

Figure 24 shows SEM micrographs of hemp fibers captured at 200× and 1000× magnifications. Micrographs reveal technical fibers (fiber bundles) that consist of elementary fibers (ultimate fibers).

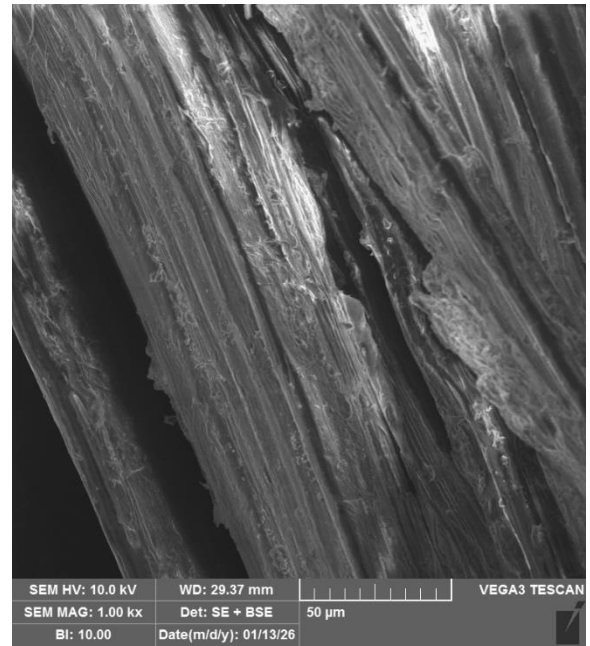
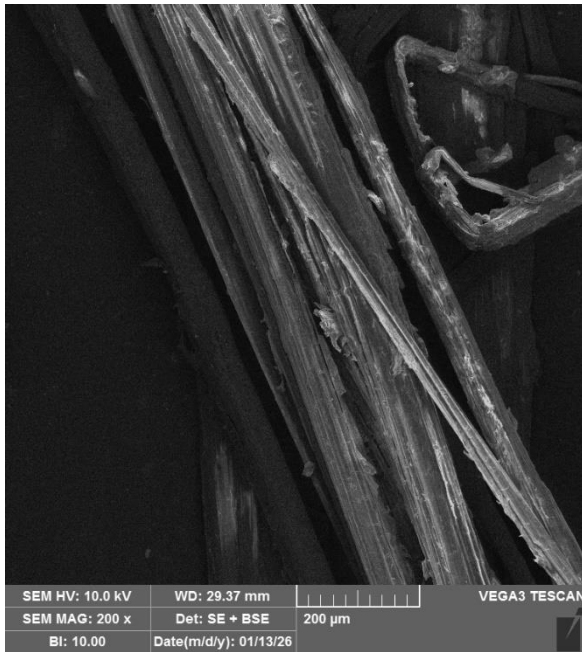


Figure 24. SEM micrographs of field retted hemp fibres (specimen 1) under magnification of 200× and 1000×

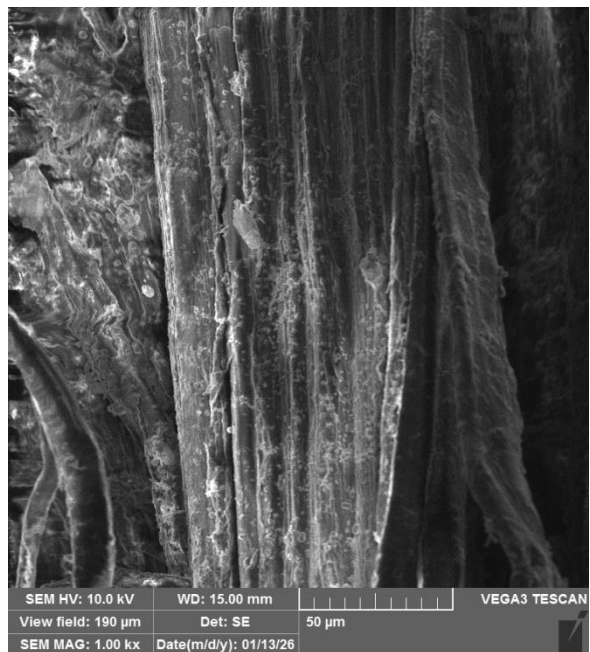


Figure 25. SEM micrographs of water retted hemp fibres boiled in 4% NaOH (specimen 5) under magnification of 200× and 1000×

Although stem fibres share a broadly similar morphology, they differ in aspects such as surface characteristics, secondary wall thickness, and cross-sectional geometry. Importantly, a reduction in lumen surface area combined with an increase in secondary wall thickness enhances fibre strength and elastic modulus [82].

Surface with non-uniform geometrical characteristics is specific for most natural fibers isolated from plant stems. Fibre surface of field retted samples appears more compact and still covered with waxes, pectin and residual shives or impurities, while fibre bundles are tightly bound together (Figure 24).

On the samples of water retted fibres boiled in NaOH (Figure 25), rough, etched and more porous surface is noticeable. Pronounced wrinkles and grooves are also observed in the longitudinal view, which are attributed to the use of alkali during the fiber isolation process. Additionally, splitting technical fiber into elementary fibres is visible and characterized by frayed or hair-like edges.

2.2.6 EDS analysis

Characterization of hemp fibres through chemical composition on the micro scale was done by Dispersive X-ray spectroscopy (EDS), Bruker.

Hemp often contains:

- soil minerals
- silica bodies
- calcium oxalate crystals
- dust and field contaminants.

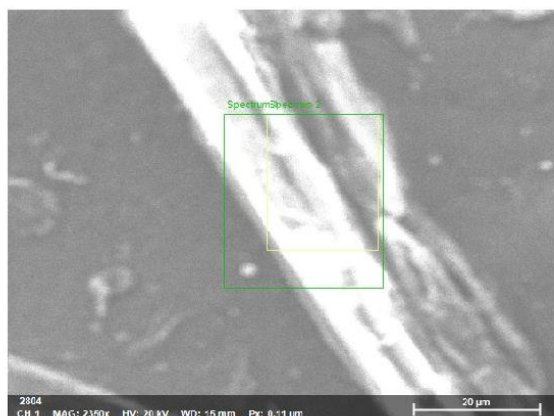
EDS is efficient to confirm whether a treatment has successfully removed or introduced certain components. For example:

- Decrease in Ca, Si, Mg → removal of mineral impurities and shives
- Decrease in Na after washing → effective removal of NaOH residues
- Increase in O/C ratio → removal of waxes and lignin, exposing cellulose
- Appearance of new elements (e.g., P, S, Cl) → evidence of bleaching, flame retardants, or functionalization.

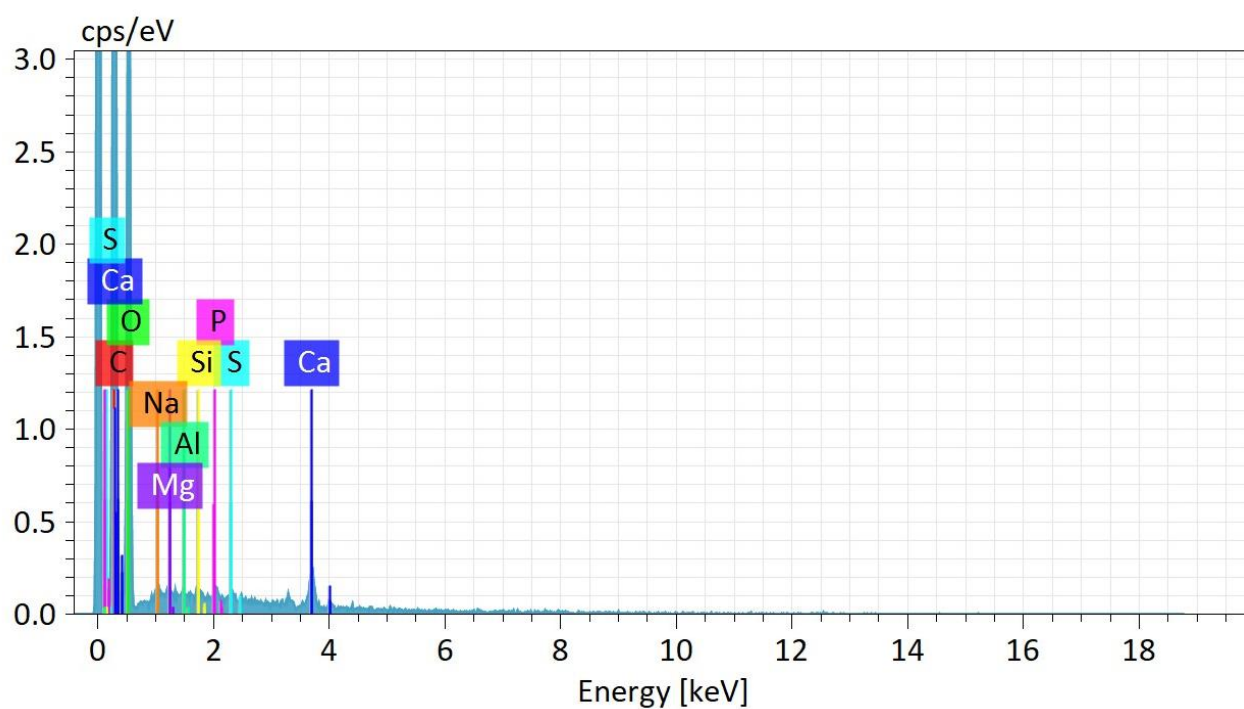
This is essential when demonstrating the efficiency of:

- retting
- alkaline treatment
- bleaching
- enzymatic processing
- surface functionalization.

EDS results are shown in Figures 26 and 27. The dominant weight in both samples belong to carbon (ranging from 59.93 in specimen 1 to 58.77 in specimen 5) and oxygen (ranging from 39.96 in specimen 1 to 40.85 in specimen 5), with the small amount of Ca, and traces of Na, Mg and Al, found in both specimens.



Name	Date	Time	HV [kV]	Magnification
2804	1/13/2026	1:56:33 PM	20.0 keV	23x

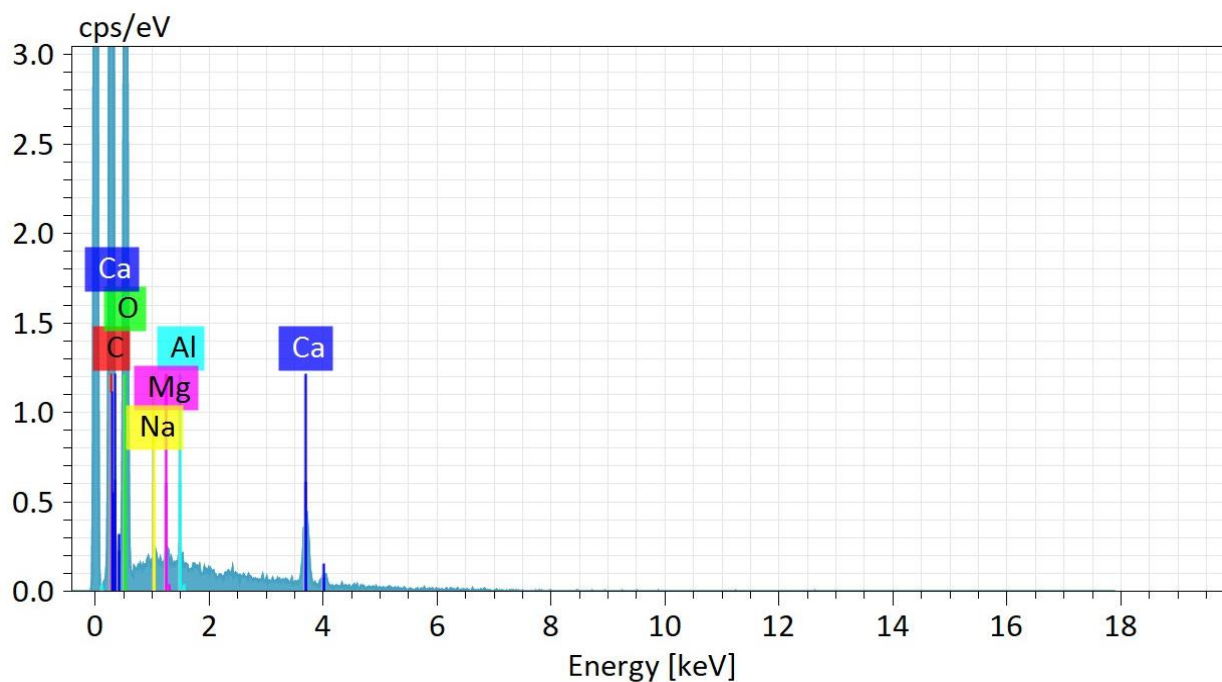


Spectrum	C	O	Na	Mg	Al	Si	P	S	Ca
Spectrum 2	59.93	39.66	0.04	0.02	0.00	0.02	0.03	0.02	0.28

Figure 26: EDS analysis of elements in field retted hemp sample (specimen 1)



Name	Date	Time	HV [kV]	Magn
2802	1/13/2026	1:44:43 PM	20.0 keV	23x



Spectrum	C	O	Na	Mg	Al	Ca
Spectrum 1	58.77	40.85	0.02	0.02	0.02	0.32

Figure 27: EDS analysis of elements in water retted hemp sample treated in boiling NaOH (specimen 5)

2.2.7 FTIR spectroscopy

Fourier-transform infrared (FTIR) spectroscopy was employed to evaluate the chemical modifications induced in hemp fibres by alkaline treatment in sodium hydroxide (Figure 28 and Table 9).

PerkinElmer Spectrum 100 FT-IR spectrometer (Shelton, CT, USA) deploying the attenuated total reflection (ATR) method was applied in absorbance. All spectra were recorded within the range of 4000 cm^{-1} to 380 cm^{-1} , maintaining a resolution of 4 cm^{-1} over four scans. The spectra were analyzed via a PerkinElmer Spectrum 100 v 6.3.5. software (Shelton, CT, USA). The applied baseline correction of all spectra was automatic, and all spectra were then normalized according to the following peak/abscissa parameters: ordinate limit 1.5 A, start 4000 cm^{-1} , end 450 cm^{-1} , auto zero-point 2318 cm^{-1} .

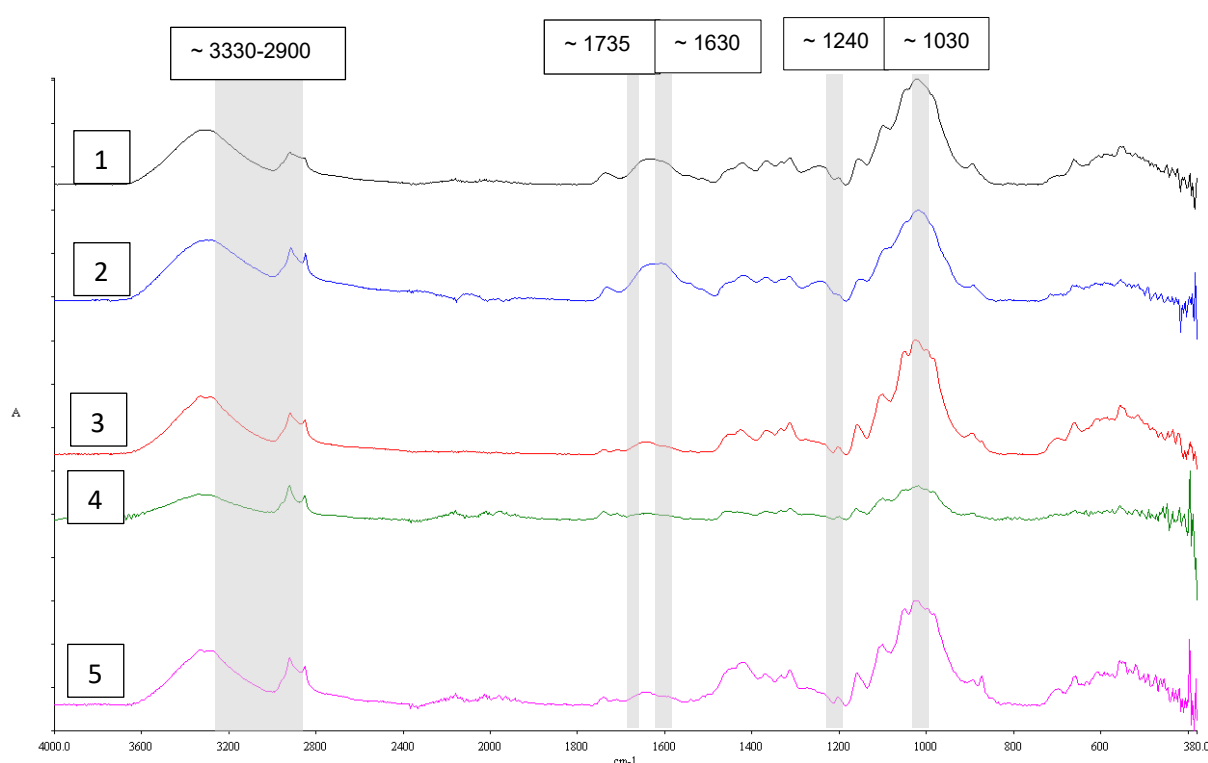


Figure 28: FT-IR spectra of differently treated hemp, with characteristic hemicellulose/lignin peaks and wavelength range. Legend of specimens: 1) water retted (WR); 2) field retted (FR); 3) WR+8% NaOH impregnation and boiling in H_2O ; 4) FR+8% NaOH impregnation and boiling in H_2O ; 5) WR + post-treatment: boiling in 4%NaOH.

Table 9: Typical functional groups of hemp identified in FT-IR spectra

Covalent bonds vibrations	Wavelength range (cm-1)	Peaks (cm-1)	Component
O-H stretching	~ 3330 – 3350		cellulose/hemicellulose
C-H stretching	~ 2900		polysaccharides
C=O (acetyl/uronic esters) stretching	~ 1735 – 1740	~ 1735	hemicellulose
aromatic skeletal vibrations	~ 1630 – 1510	~ 1630	lignin
CH ₂ bending	~ 1425		cellulose I
C-H bending	~ 1370		cellulose
C-O (guaiacyl ring breathing) stretching	~ 1240 – 1260	~ 1240	lignin/hemicellulose
C-O-C stretching	~ 1030 – 1050		cellulose/hemicellulose

The spectra of untreated fibres exhibited the characteristic signatures of lignocellulosic biomass, including contributions from cellulose, hemicellulose, lignin, and surface extractives. After NaOH treatment (specimens 3-5), pronounced spectral changes were observed, confirming the selective removal of external components and partial modification of lignin, consistent with trends reported for alkaline-treated hemp biomass [85].

The most prominent change occurred after NaOH treatment was the disappearance or strong reduction of the carbonyl band at 1730–1740 cm⁻¹, assigned to the C=O stretching of acetyl and uronic ester groups in hemicellulose. This band is widely recognized as a marker for hemicellulose content, and its loss indicates extensive deacetylation and dissolution of hemicellulosic polysaccharides. Similar reductions in the 1730 cm⁻¹ band have been reported for alkaline-treated hemp hurds and hemp waste biomass.

A concurrent decrease in the 1240–1260 cm⁻¹ region, associated with C–O stretching in hemicellulose and lignin, further supports the removal of hemicellulose. The reduction of these bands reflects the expected susceptibility of hemicellulose to alkaline hydrolysis.

Lignin-related aromatic skeletal vibrations at 1600–1510 cm⁻¹ and the guaiacyl-associated band near 1260 cm⁻¹ decreased in intensity after NaOH treatment. Although lignin is more resistant to alkaline degradation than hemicellulose, partial delignification and structural rearrangement are typical under these conditions. The observed attenuation of aromatic bands aligns with findings from chemically modified hemp shives and hemp hurds, where NaOH treatment reduced lignin-associated absorptions due to cleavage of ether linkages and removal of low-molecular-weight lignin fragments [86].

The reduction of lignin peaks also indicates improved fibre purity and contributes to enhanced cellulose exposure, which is desirable for composite reinforcement and enzymatic processing applications.

2.2.8 Fibre spectral parameters

The characteristics of hemp fibres can vary greatly. If the fibre is carefully prepared, it can be very light in color and quite shiny. In general, hemp fibres are pale gray, yellowish, greenish or dark brown in color, depending on the variety and preparation method. It is known that, in addition to all of the above, the retting process significantly affects the color of the separated fibres. Furthermore, the color is also affected by the treatments carried out on hemp fibres with the purpose of reducing stiffness and achieving greater softness and comfort. Therefore, in the experimental part, the color of hemp fibres degummed by various methods on field and water retted samples was determined.

Hemp samples were analysed by the remission spectrophotometry on Check 3 portable device, DataColor, Switzerland (Figure 29).



Figure 29: Check 3 Portable Spectrophotometer, Datacolor

Color measurements of the differently treated samples are presented using the CIEL*a*b* color space. The characterization of color includes the lightness value L^* , which ranges from 0 (black) to 100 (white), the a^* coordinate indicating the position on the green ($-a^*$) to red ($+a^*$) axis, and the b^* coordinate representing the blue ($-b^*$) to yellow ($+b^*$) axis. In addition to these primary parameters, the samples are further evaluated through chroma (C^*), describing color saturation, and hue angle (h°), which defines the perceived color tone. These values together provide a comprehensive description of the visual appearance of the samples, as illustrated in Figure 30.

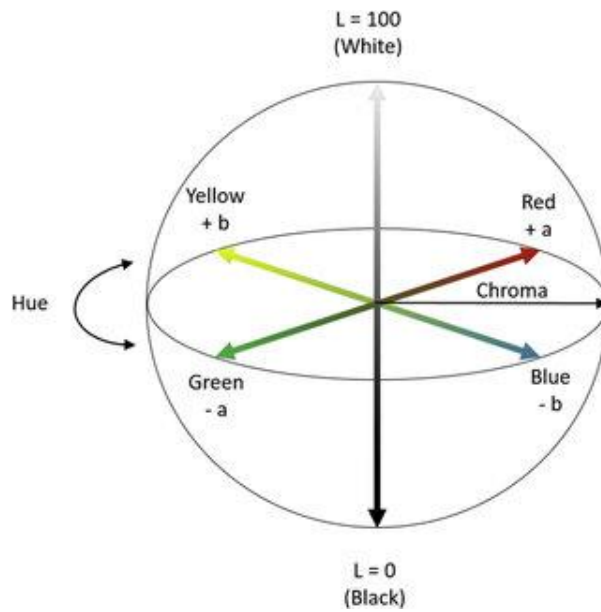


Figure 30: The CIELAB colour space diagram

The results of the color characteristics hemp fibre samples are presented in the Figure 31.

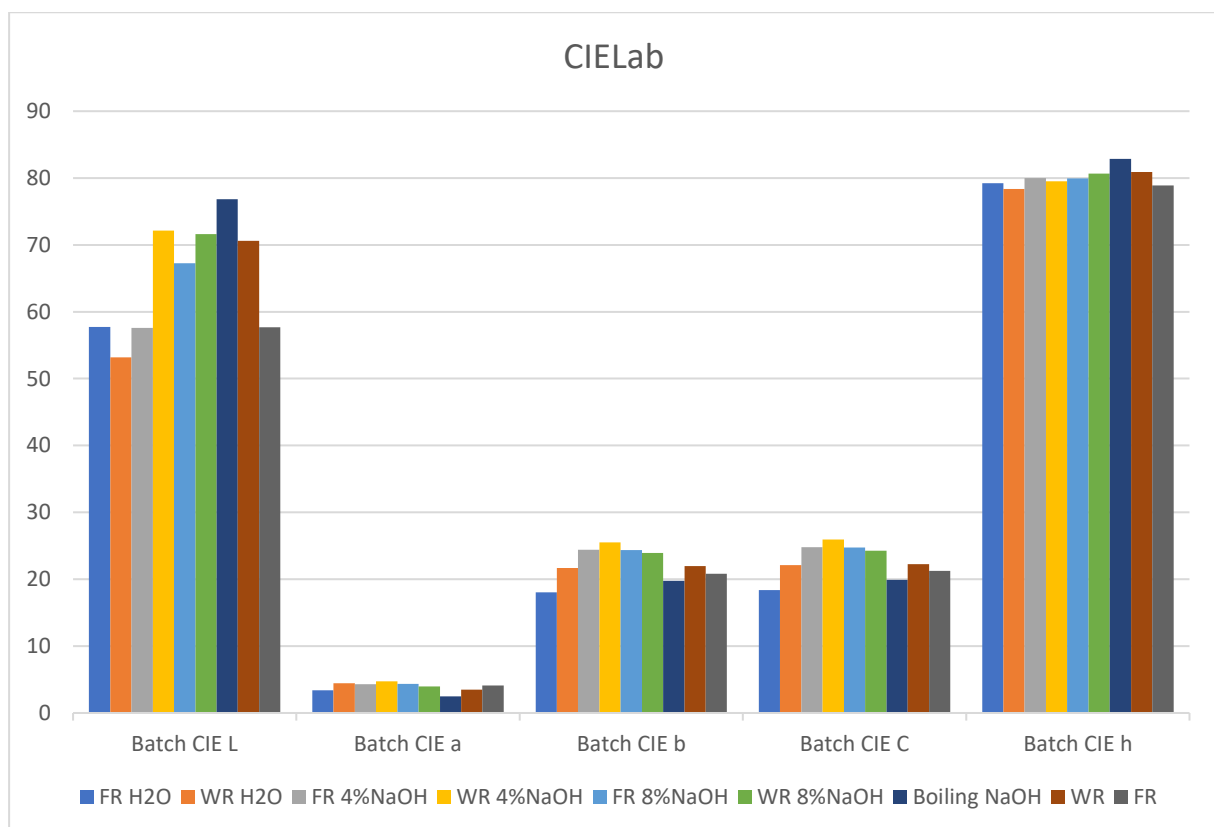


Figure 31: Colour coordinates of differently treated hemp fibres

The highest lightness (L^*) and color saturation (C) values were recorded in the NaOH-boiled samples, as shown in Figure 31. The measurements also revealed notable differences in fiber lightness: all water-retted and alkaline treated samples exhibited higher L^* values than the corresponding field-retted samples subjected to the same treatments.

This aligns with findings from recent studies showing that water retting produces cleaner fiber surfaces with reduced residual epidermal and parenchymatous tissues, leading to lighter coloration and more homogeneous optical properties [87]. In contrast, field retting often results in darker fibers due to prolonged exposure to soil microorganisms, oxidation processes, and uneven degradation of non-cellulosic components.

All samples displayed positive a^* values, indicating a slight reddish hue, and positive b^* values, reflecting a more pronounced yellowish tone, together perceived visually as the characteristic brownish, earthy coloration of hemp fibers. These color characteristics are also evident in the digital optical microscope images presented in Figure 21.

Conclusions

This report outlines the significance of natural hemp fibres, tracing its development from historical use to its contemporary relevance. Global interest in hemp continues to rise, driven by strong market demand. The hemp fibre market was valued at USD 4.46 billion in 2019 and is projected to reach USD 43.75 billion by 2027, corresponding to a compound annual growth rate (CAGR) of 33% for the period 2020–2027. The most recent forecasts extend this growth even further, estimating a market value of USD 95.46 billion by 2032, with a projected CAGR of 32.62% between 2026 and 2032.

Stakeholders across the value chain are increasingly seeking hemp fibre technologies that can be implemented under current industrial conditions. A persistent challenge, however, is the limited availability of specialized machinery required for bast fibre processing, a constraint observed not only in Europe but also in many other regions worldwide.

Within the **INTERREG DRP0200404 Green-Tex project**, the small Croatian municipality of Majur strengthened its local capacities and initiated the revitalization of traditional hemp cultivation and processing. Missing equipment was procured through this and other ongoing initiatives, while a dedicated group of residents received training through a series of educational workshops focused on traditional hemp processing, spinning, and weaving with the aim to preserve and upgrade the heritage and use it as the new green and circular business model.

The University of Zagreb Faculty of Textile Technology was responsible for evaluating fibre quality and providing recommendations for selecting the most environmentally sustainable processing methods. The experimental work compared water retting, field (dew) retting, and chemical treatments with alkali using wide spectrum of analysis performed in Laboratories of Textile Science Research Centre (TSRC).

Comparative analyses of field- and water-retted hemp fibres showed that water retting produced stronger fibres with cleaner surfaces, resulting in lighter coloration and more uniform optical properties. However, conventional water retting requires large quantities of freshwater and contributes to eutrophication, raising substantial environmental concerns. Its application must therefore be limited to controlled conditions, including monitoring of pH, oxygen levels, and temperature, along with appropriate wastewater treatment and shortening of retting cycles (up to seven days).

Field retting offers the advantage of the lowest ecological footprint, as it generates no effluent and leaves no chemical residues. Its main limitations are its strong dependence on weather conditions and the resulting variability in fibre quality. For this reason, field retting is recommended primarily for less demanding applications, such as insulation materials.

Each retting method thus presents specific benefits and limitations that must be carefully weighed when selecting the most responsible and sustainable option depending on applications.

Final remarks

Green- Tex solution with hemp fibers

Hemp is natural and sustainable raw material, valuable for clothing, interior textiles and technical applications - an opportunity for creators, designers, artists, artisans and sustainability promoters!

Hemp yarn was produced manually by drop spindle or by spinning wheel.



*Hemp yarn
produced in
Majur County*

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