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Industrial application of hemp fibers

History and future prospects of hemp as an alternative resource for pulp

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ABSTRACT

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Following literature review was conducted to find the information on application of industrial hemp's fiber material in pulp and paper manufacturing as an alternative raw material. In addition to main research idea, it was decided to include several related topics that were also reviewed. These additional topics were chosen to provide background on aspects related to pulping and industrial hemp as a fiber resource. Historical development of the material was decided to be included also. Information was gathered through reading various articles, reports, books and compilations. Key findings were analyzed to define advantages and disadvantages of hemp's raw material.

Information was gathered together to form the strength/weaknesses/opportunities/threats analysis in regard to using industrial hemp as a plant for harvesting fiber material. Key findings indicated distinct advantages and deficiencies based on plant's natural characteristics.

It was proven through reviewing that fast growth rates, high yields of fibrous material, stem's fiber qualities and fiber's suitability for pulping were main advantages of the hemp as an alternative resource. Nonetheless, research had shown hemp's significant dependance on climatic conditions and soil qualities. Hemp was found to be highly demanding for huge amount of nutrients, as well as being generally more expensive material for pulping industry. Despite financial risks and economy related deficiencies hemp was still found as a material with a notable potential.

Key words: hemp, alternative, pulp, paper, history

CONTENTS

1 INTRODUCTION

Deforestation and depletion of wood resources throughout most of human history is an irrefutable fact. According to National Geographic (2019) this process has not slowed down, despite many efforts. Observing satellite imagery, there is no doubt that large territories previously occupied by forest ecosystems were either urbanized or converted into agricultural areas. Deforestation took catastrophic turn in tropical and equatorial regions of the Earth, namely in rainforest areas of Oceania and Amazon. The latter has lost more than 17% of its area during last 50 years, and Indonesian forests are continuously replaced by palm oil plantations (National geographic 2019). Regardless the fight against deforestation, not all countries and cultures are interested in subversion of harmful impact their economic development had made. Climatic changes also directly affect forests with wildfires happening all around the world. To minimize the harm, forests are regrown where it is possible, sustainable practices are implemented by forestry industries, and to influence consumers’ choice on manufactured products specific labeling has been established, however till this day the problem has not turned in the opposite direction.

Papermaking is a growing sector of industry. Whether in high-income regions paper consumption is decreasing, it is estimated that in developing countries rise in demand for paper and cellulose-based products will certainly happen (Mayowa 2018, 56). In addition, steady growth of awareness on hygiene and health worldwide results in growing demand for tissue paper products, like wipes, napkins, hand towels (Naithani et al. 2020, 706). Given the fact that activities to eliminate plastic waste and reduce number of plastics reaching environment and ocean are also taken place worldwide, packaging manufacturers might turn to use alternatives to plastics. Cardboards and their engineered composite variations might become a crucial part of solution, or at least a transitional or alternative option for mitigation of the plastic problem. (Devitt 2020.) Thus, an increase in demand for the pulp required for paperboards manufacturing has its right to be expected. In addition, economically developing regions of Asia and Africa might even further increase demand for such packaging, when population there will become less burdened with poverty and will tend to spend more on different products. The main question is not when and where it might happen, but how drastically this will affect the overall consumption of cellulose-based products. What will be the negative consequences for forestry industry and global wood resources?

It is worth mentioning, that wood and its engineered composite derivatives, like *CLT (cross laminated timber)* and *LVL (laminated veneer lumber)* are increasing in popularity as building materials, due to lesser impact on carbon footprint during their production and overall lifecycle (Risen 2014). Developments in wood engineering resulted in broad selection of strong composites comparable with other conventional non-wood building materials. Some of these properties found to exceed qualities of concrete and metal (Risen 2014). It can be assumed that in near future the range of used building materials might be turned in favor of these wood-derivatives. Thus, raw timber demand might also increase drastically for building purposes.

Growing rates of forest depletion technically can be mitigated by implementing complex of diversified measures, affecting each root cause of the problem. Reestablishing raw material base for industries, which have been utilizing timber, has a potential of decreasing rates of tree cutting at least for needs of tissue and paper manufacturing. Transition from wood to paper-waste and fast-growing annual plants is a topic to be reviewed and revised with regard to newer available technologies and deficiencies these alternative materials may pose in the future. This transition to non-wood cultures would directly affect the severity level of the problem, additionally giving prospects for both smaller businesses and farms and would leave more raw wood available for other applications. Non-wood plants include many species, accounted as grasses, but all have cellulose fibers, which are able to be converted into textiles or pulp due to their natural characteristics. Each of them requires specific climatic and environmental conditions to produce fibrous material, what makes it possible for pulpers to choose the crop dependent on facility’s location. Not all of these crops are able to be grown on its full potential in northern America, Europe, Russia and Nordic countries, places where paper manufacturing has been developed to its fullest and massively. Because of that, this paper has chosen for review the plant known to be naturally thriving in Eurasian temperate regions – hemp, often referred as industrial cannabis.

2 CONCEPTUAL BACKGROUND

To bring the reader into understanding hemp potentials and possibilities for the industries of pulping and paper manufacturing, this chapter specifies each related concept: introduces basic processes of papermaking, lists its possible resource base, describes history, biology and ecology of industrial cannabis, mentions related principles of its cultivation and processing, and at last describes its fibers as a source for pulping.

2.1 Overlook to pulping and paper manufacturing process

In this part next questions are answered. First of all, *what is the paper? How is it produced? Where it came from? Which processes paper production includes and what are the resources needed?*

Paper, as well as different cardboards/paperboards and tissues are products made from cellulosic pulp. These are applied in many modern operations, from printing, wrapping, packaging, to usage in hygiene and insulation. (Britt n.d.) Encyclopedia Britannica [1] defines papermaking as a process in which sheets of different resulting qualities are formed on woven screens from water suspension of specifically prepared cellulose fibers (pulp matter). Modern paper manufacturing is a highly technical industrial process, involving complex chemical processes and high degree of mechanization on all of its path. Nevertheless, it is built on ancient principles of operation, which had been set up in 2nd century AC in China. (Britt n.d.) Papermaking process can be divided into two general stages: *pulp production* (fibers-to-pulp) and *paper manufacturing* (pulp-to-paper) (Sappi Tube 2012).

A number of paper- and tissue- mills exclude pulp production stage and require prepared pulp bales transported to them from the pulp distributers and producers. (Valmet 2019; Sappi Tube 2012). Pulp of different fiber lengths and qualities is able to be produced from wastepaper, timber and different types of non-wood materials on specific facilities called pulp mills. Pulping can be done mechanically or include chemical processes. (Britt n.d.) Process of chemical pulping consists of several stages, which are extensively described in film made by Sappi Tube (2012).

Wood logs or recycled wooden off-cuts are transported from sawmills to the pulp mill where they are pre-treated for pulping by chipping and debarking. Wastepaper requires refining, washing, screening and in some cases de-inking before it can be used further (Britt n.d.). Non-wood fibers are pre-treated, according to characteristics of the chosen fibrous material. After this stage fiber material either mechanically processed, forming *groundwood pulp* suitable for paperboard and newsletter paper, or it is fed into the digester for cooking to produce better quality pulp (Britt n.d.). The cooking is carried out in complex engineered machinery, where sophisticated chemical processes are conducted to dissolve *lignin* and separate it from plant cellulose fibers. *Lignin* is a complex polymer, which is one of main components of cellular walls of plants, playing a significant role in rigidity of cells, giving them stiffness and strength. Despite being second most abundant organic material on Earth, only few industrial implementations had been found for it (Riddle et al. 2019, 43; Britannica [1] n.d.). The main purpose of cooking process during pulping is to completely get rid of lignin content. (Riddle et al. 2019, 53) Hereafter yellowish softened fibers are washed to remove any traces of unwanted chemical residues after the cooking and then are bleached. After these processes the making of pulp mass is finished. Pulp then is either dried and bailed for transportation and export, or directly sent to the conveyor for next stages of paper or tissue manufacturing.

Pulp bales, when imported to the processing facilities, at the beginning are sent to dissolver, where they are mixed with water to produce a pulp suspension, also called “stock” (Valmet 2019). On combined pulp-tissue-mills and pulp-paper-mills pulp is mixed with water on its way to next stages and then directly sent into refining blades. There fibers are given variable degree of fibrillated ends to improve their binding properties. After refining, fillers such as calcium carbonate are added to the fiber suspension, by that giving the future tissue or paper more controlled density and opacity. Dyes, ‘sizes’ and optical brighteners may also be blended into the mixture. That mixture then enters the ‘headbox’ of paper or tissue machine, where in both cases the fiber mixture is evenly injected at high pressure and distributed to ‘gap-former’ rolls, which immobilize and rapidly drain the material. As the result continuous web of paper is formed, which is then thoroughly pressed and dried. Drying section of paper mills is the longest section of massive paper machine. On the contrary drying section of tissue machines are much smaller. During this stage qualitative characteristics of products, like thickness, smoothness and consistency, are ensured. Then post-process is happening, where paper passes through a series of sizing and coating presses on its way to reeling and cutting into finalized products. (Valmet 2019; Sappi Tube 2012.)

Since paper production as well as tissue manufacturing requires a significant amount of fresh water within its processes (100 L per kilogram of finished paper), even if up to 90% of it can be recycled by modern paper mills (Sappi Tube 2012), the industry leaves a significant impact on the environment. Energy consumption of paper facilities is yet another concern for environmental engineers. In addition to all of that, paper industry requires extensive base of raw materials, either gathered from forests, plantations, or harvested as non-wood fiber cultures.

Historically wood was not the primary source for paper manufacturing until 1800s and 1900s. When methods of producing groundwood pulp from trees had been invented in 1857 and suitable paper machines had been developed, use of softwoods (wood of coniferous trees) and hardwoods (wood of deciduous trees) for paper production became a reality. Before these developments, rags made of linen and cotton were a scarce but main source for pulping. (Britt n.d.) However, according to VNP (2007) report, nowadays the most commonly used material for pulp production is wood. Either freshly sawn, or in form of leftovers from other industrial applications of wood, timber provided around 90% of all fibrous raw material in early 2000s. In 2015 annual world consumption of paper and cardboard was almost 411 million metric tons, while paper’s main markets were Asia, Europe and Northern America, consequently (Mayowa 2018, 56). In addition, Mayowa (2018) states, that continuous increase of paper, cardboard and tissue usage has led the industry to utilize 35% of all annual worldwide wood harvest.

2.2 Description of non-wood fibers

Since papermaking requires cellulose fibers, it technically can employ different sources of fiber instead of wood. However non-wood plants are contributing only to a fraction of the raw fibrous material for world's pulping needs (Zhong et al. 2018, 3). By year 2007 industrial application of non-wood fibers was expanding only in countries with already established significant quantities of available annual crops for pulping and where forest resources were scarce since the beginning of industrialization. Only there, methods of pulping and papermaking from annual crops have prevailed, with non-woods contributing up to 60% of all demanded cellulosic fibers. During the first decade of 21st century leaders in term of volumes of non-wood utilization, namely India and China, particularly have been fulfilling 70% of their annual demand in raw material from non-woods, including cereal straw and bagasse (leftover fiber from squeezed sugarcane and some other cultures). (Zhong et al. 2018, 3; VNP 2007; Britannica [1] n.d.) When compared to wood, annual growing plants have their own advantages and disadvantages, which will be mentioned further in this chapter. Fibers from these crops possess rich variety of properties able to interest manufacturers in improving their fiber-based products (Zhong et al. 2018, 3). From viewpoint of technology any paper grade of desired qualities can be produced from pulps composed of combination of either only non-wood fibers or their mix with wood fibers (VNP 2007). Pulping methods for non-wood fibers, as well as wood pulping technologies, are ushered into development by changing markets, environmental protection laws and newer available technologies (Zhong et al. 2018, 9, VNP 2007). Nonetheless, environmental protection fines and taxes since the start of 21-st century had resulted in gradual decrease of non-wood pulping rates, especially in China due to deficiencies and environmental hazards of old undeveloped technologies within the country. It became cheaper to replace non-wood pulping facilities with more efficient and sustainable wastepaper pulping and bigger wood-pulping factories, than trying to develop newer technologies for non-woods, as it was stated in VNP report (2007).

Chemical compound of each non-wood material is different. Variability of plant's chemical composition is dependent on soil type and growing conditions. Cellulose content hold from 32% to almost 90% of the material, depending on specie and its harvested part. (Mayowa 2018, 57, 62.) Content ratios of lignin, cellulose and other organic substances in plants are listed within Appendix 1, specifically compiled from report of VNP (2007) and work of Zhong et al. (2018). These non-wood crops contain fibers widely variative in terms of dimensions, on average, dimensionally comparable with short hardwood fibers (Mayowa 2018, 61) used for manufacturing smooth and opaque papers (Britannica [1], n.d.). Small diameters of non-wood put them into production of lower coarseness pulps. However, some exceptional plant species in groups of *bast fiber* and *seed hull fiber* plants have much longer fibers, which have to be shortened to be applied in pulping. Dimensional differences between non-woods divides them into groups of *softwood substitutes* (specialty non-woods with longer fibers) applied in manufacturing specialty papers and textiles and *hardwood substitutes* (common non-woods, including straws) used for producing higher strength, tensile resistant papers. (Mayowa 2018, 58, 61; VNP 2007.)

TABLE 1. Average annual yields of some plant species used in pulping and their fiber dimensions (Sources: Zhong et al. 2018; VNP 2007)

Plant	Fiber yield (tons/ha/year)	Pulp yield (tons/ha/year)	Fiber length/diameter (mm/µm)
HARDWOODS:			
Fast-growing deciduous	15	7.4	0.7–3.0 / 20–40
SOFTWOODS:			
Scandinavian coniferous	1.5	0.7	2.7–5.0 / 32–43
Temperate coniferous	3.4	1.7	
Fast-growing coniferous	8.6	4	
NON-WOODS:			
Bagasse	9.0	4.2	1.0–1.7 / 20
Bamboo	4	1.6	2.7–4.0 / 15
Miscantus	12	5.7	1.2 / 20
Canary grass	8.0	4.0	1.0 / 20
Hemp	15	6.5	20 / 22
Kenaf	15	6.7	2.6 / 20
Wheat straw	4.0	1.9	1.0–1.5 / 13
Rice straw	3.0	1.2	0.5–1.4 / 8–10

The greatest advantage of all non-wood sources, when compared to timber is that they can be planted and harvested within a year period, when trees require many years of growing, or even decades before the harvest can be done (VNP 2007). In addition, some non-wood fibers have high yielding capacity, due to high planting densities, that their ecology allows. In some cases, fiber yield from annual plants can exceed annual fiber turnout from fast-growing woods (overall wood fiber yield, divided by years trees were growing by the moment of cutting). From Table 1 it can be seen that hemp as well as kenaf are able to produce as much fiber as fast-growing deciduous trees and exceed turnout of even fast-growing softwoods. Since plant's speed of growth depends on climate, in hotter and sunnier regions the same plant species will tend to grow faster. For instance, this is the reason why the index of fiber yield for coniferous trees grows significantly from 1.5 to 3.4 and 8.6 tons/ha/year, while plant 'moves' from polar regions to temperate and warm climates, achieving the fastest growth rates. This also applies to non-wood materials. However, some forms of non-woods are growing at low temperatures, what allow their use in colder environments. In addition, when compared to wood, non-wood plants generally contain less lignin, therefore making cooking in the digester a much easier process during pulping, making it cheaper and less burdening for the environment, when modern technologies are in use. (Mayowa 2018, 57).

Another bonus of non-wood raw materials is the fact, that their cultivation is a subject of agriculture. They do not require special equipment and vehicles, other than already implemented in agricultural activities. And most of these plants are already economically "pre-paid", being sown for grain and oilseed (i.e straws and stalks of annual and perennial crops, as byproducts of agriculture, are able to be implemented for pulping). The exact same logic can be applied to industrial plants' residues ('process residues'), like bagasse, flax scraps, cotton linters and discarded hemp stalks, which are left after crops were processed into usable products. However, their raw material cost is usually high, being competitive with cost of wood. (VNP 2007.)

Non-woods are categorized in several ways. Being divided, based on their implementation and origin: *industrial crops*, *naturally growing plants* and *agricultural residues*. The other categorization is based on nature and position of fiber material in the plant. These are: *grass (gramineous) fibers* materials, *bast fibers* plants, *fruit (seed hull) fibers* and *leaf fibers* plants. (Zhong 2018, 4; Mayowa 2018, 58;

VNP 2007). All of them possess features, desired by industries, other than pulping, so the problem for the bulk of non-wood fiber plant species is the competition between end-uses of the materials and their residues. For instance, pulping will often face competition from biofuel production or intends of using materials as animal feedstock and bedding (VNP 2007).

But the main deficiency of non-woods to this day is related to raw material logistics, their seasonal availability and storage. Averaging low bulk of non-wood raw materials restrict the transportation to processing facilities and their size. By that limiting pulping to smaller scale production and resulting in necessity for facilities to be in proximity to raw material suppliers. Additional risks for pulpers exist in seasonal nature of non-wood fiber cultures, what creates the prerequisite for building large storages to supply pulp manufacturers all year round. (Mayowa 2018, 62; VNP 2007.)

Pulping and delignification of non-woods, nowadays are done by methods, which already has been applied in pulping of wood-based materials. These methods are listed below for the knowledge of reader. Zhong et al. (2018) have described in detail most of pulping methods in 'Pulping and Papermaking of Non-wood Fibers'. If briefly described, lignin content of plants can be dissolved and filtered from cellulose fibers by:

- applying diluted solution of *alkaline* chemical agent with addition of variety of cooking agents, which define the technology behind different pulping methods of *alkaline pulping* group.
- the *Kraft* process, which at one point has changed the industry of pulping, but mostly has been implemented for raw wood materials.
- some other chemical methods applied to non-wood raw materials using *sulfite* cooking liquid.
- *organosolv* pulping methods, where organic solvents, such as methanol, ethanol or organic acids are used as a cooking liquor.
- the number of *chemi-mechanical* pulping methods, which combine chemical reactions with physical actions like steam explosion, dipping or grinding.
- *biological* methods, which apply microorganisms or enzymes, presenting advantages from environmental perspective, due to methods' cleanness and energy efficiency. (Zhong et al. 2018, 10–19.)

2.3 Historical background on hemp

It is considered that hemp plant evolved within temperate regions of northern hemisphere, most likely in steppes of central Eurasia, based on plant's ecological constraints. Within this biogeographical region earliest cultivation of the plant has been started and ultimately it has been spread to other parts of the world by human actions. (Warf 2014, 418; Clarke & Merlin 2017, 1.) At a certain point of human history cultivation processes distinguished plant into two subspecies (*Cannabis sativa, L.*) and (*Cannabis sativa,* subsp. *indica*) (Warf 2014, 416), both of which can be referred as industrial hemp and narcotic cannabis, due to many arguments between botanists (Allegret 2013, 5). Despite history and geography of spreading and cultivation for both plants are being closely intertwined, from that point of time plants were not indistinguishable. Hemp was used for fibers, what resulted in a long history of its practical utilization. And the narcotic cannabis was used for its psychoactive qualities in medicine and as a part of religious/shamanistic rituals by different cultures within the region. (Warf 2014, 416–417, 419–420.) Possible routes of both plant types spreading around regions of the world by human activities are indicated in the Figure 1 below, based on the results from books of Warf and Fike.

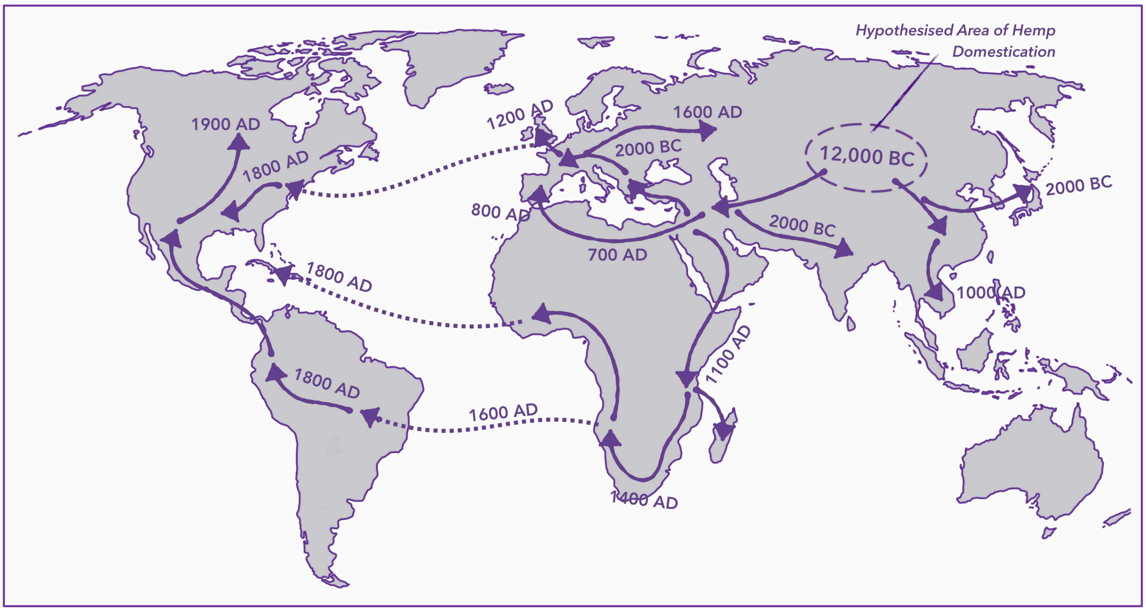

Figure 1. Suggested historical dissemination of *Cannabis sativa, L.* (Gorbachev 2021, *adapted from*: Warf 2014, Fike 2019)

Warf (2014) mentions that hemp (cannabis) is referred by different monikers: ‘*ma*’ in China, ‘*kif*’ in Arabic, ‘*bhang*’ and ‘*ganja*’ in India, and emphasizes that Sanskrit name for hemp: ‘*khanap*’ had given, in one way or another, the base for European denominations of the plant. When referring to linguistic analysis, etymology, there is always a possibility of word misinterpretations, however there is a way to correlate transformation of ‘*khanap*’ into Greek ‘*kannabis*’, Latin ‘*cannabis*’, Assyrian ‘*quanaby’*, Slavic ‘*konopie’, ‘konoplya*’, Gaelic ‘*cainb*’, Germanic ‘*hanf’, ‘hemp’, ‘hampa*’ with plant’s gradual propagation into the Europe through Middle East. (Allegret 2013, 5–7; Warf 2014, 417; Wiktionary)

Core sampling from East European Plain revealed that the earliest evidence of hemp in the palynological (*study of pollen in archeology*) record in Eurasia dates back as early as 150,000 years ago. Definitely, prior to any exposure to humans, cannabis was able to expand out from its regions of origination by natural ways. But, more frequently, the majority of hemp palynological evidence corresponds to the dates from around 10,000 BP *(before present)*. From that point of time traces of pollen more likely reflect ties with human interactions with the plant. (Fike 2019, 4–5.) Due to the fact, that wild cannabis populations were easy to grow and were evolutionally developed to be exploited as a multi-use plant for human needs – it must have been included to the first plants brought into the cultivation (Clarke & Merlin 2017, 3). In addition, recovered cannabis pollen samples from Europe date at the earliest to 3450 BC from the site in northern Italy. Another finds from Germany, Scandinavia, England and France date back to the period from 2900 BC to 1700 BC. No matter, while being cultivated or grown in the wilds, hemp would have had the potential of being a valuable resource for basic aspects of primitive society, especially when growing in a practical radius to human settlements. (Allegret 2013, 6.)

According to Gibson (2006) archeological records indicates oldest use of hemp plant as textile source at several millennia BC. Within regions close to the plant’s origin, namely in China, hemp as a clothing material was depicted on ancient pottery dating back to 6200–4000 BC. It was also found in remains of ropes dating back to 5000–4000 BC. Within Europe textiles implied to be made from either hemp, or flax had been found in Switzerland, Ireland, Greece and Austria dating back to 25th century BC. (Allegret 2013, 6–8.) Allegret also mentions that cannabis was a familiar plant within the Roman society and principles of its cultivation were described by Lucius Junius Moderatus Columella in his agronomy treatise of the 1st century AD. In addition, Allegret then refers to the remains of ropes, which have been made partly of hemp tow, found with the boat of 1st century AD, which has been discovered in Marseille, France.

Not only textiles and ropes were made in ancient times from hemp fibers: the oldest paper made of hemp was discovered in a tomb dating from 26th – 21st centuries BC in China. And in 105 BC the Chinese Minister of Agriculture Tsaï-Lun, has been documented to had started commercialization of paper made from mulberry bark and hemp. (Allegret 2013, 7.) However, the information on origins and earliest uses of hemp are shrouded by complicated rhetoric of both plant's advocates and critics (Warf 2014, 418) and may be veiled by archeological inaccuracies, limited research and misinterpretations.

In Europe, with Roman conquests of early Common Era hemp and hemp-based fiber technologies continued to spread around Mediterranean region. After Roman Empire has fallen, hemp traveled through Western Europe to the northern regions, but rules for the cultivation, established by Roman agronomist Palladius in the 4th century, were still practiced for the duration of Middle Ages. Existing Iconography, such as wood carvings and illustrations, as well as known recommendations of Charlemagne (Charles the Great) prove continuation of hemp use in Europe. But rather than for textiles and clothing it was primarily used as cordage, due to its fiber qualities desired in military and agricultural engineering. At some point of time hemp production became another way to accumulate power and wealth on the continent. (Fike 2019, 13–14; Allegret 2013, 8–9.) According to Serkov, Smirnov & Alexandrova (2018) in Eastern Europe a quantity of smaller nations was cultivating hemp for seeds, oil and fibers mostly to meet their inner demand. These products were traded between closest neighbors, due to deficiencies in farming technologies and underdevelopment of monetary exchange in the region during Medieval times. By this, preventing small feudal Baltic and Russian kingdoms to enter bigger markets.

Demand for hemp fibers has expanded, when European nations started developing navies and sailing technologies. Venetian city-state during its highest point was an example of directly and indirectly supplying its navy and textile industry with imported raw fibers from the regions they were controlling. However few nations were able to produce sufficient supplies, despite plant being grown broadly around the western part of the continent. The demand has opened new markets, bringing Baltic states and Poland into supplier chain. (Fike 2019, 14.) When feudal fragmentation within Russia was abolished and monetary exchange was enforced by economical and territorial integration, in the end of 1500s – beginning of 1600s hemp cultivation has grown in the region to allow exporting (Serkov, Smirnov & Alexandrova 2018, 134). Rise of Portugal, Spain and England as naval powers contributed to their dependance on imported fibers, so Russia, with its political and social changes started supplying England, then Spain and Holland in 17th century. Peter the Great, the first Russian Emperor in the beginning of 18th century introduced economical exporting reforms, which benefitted state's hemp manufacturers, which improved industry in Russia and made the country one of the biggest suppliers of hemp in the world for next century. Despite efforts of colonial empires to develop hemp production in controlled territories to become less reliant on exported hemp, each of them continued being dependent on Russian suppliers. Fiber hemp was brought to the South America by Spain and Portugal in 16th century. France and Britain brought the plant to Northern America and became main contributors to industrial hemp on the continent, but due to economic and agronomic reasons colonial hemp generally was of lower qualities and more expensive, than hemp of Baltic region and Russia. That rendered its production to the domestic uses. (Fike 2019, 14–16; Serkov, Smirnov & Alexandrova 2018, 134.)

Fiber hemp's history of cultivation in the region of Finland has started before introduction of flax to Finno-Ugric populations, with oldest proof of seeds dating back to times of Vikings and earlier. By centuries hemp was adapting to the northern climatic conditions of the region and was known to be cultivated as far north as 66°N latitudes (Kemi–Rovaniemi). During the beginning of 20th century in Finland hemp was grown commercially on about 1500 ha of land, nonetheless when cultivation ceased to exist in 1950's, already established and naturally adapted old hemp landraces had disappeared. (Pahkala et al. 2008, 105.)

Gradual decline of hemp production in the world started when at first steam engine ships were invented, replacing hemp-based ropes with metal cables, and when cheaper jute fibers had entered the market (Serkov, Smirnov & Alexandrova 2018, 135). Invention of threshing machine for cotton started popularizing its use and cultivation, and after many years cotton has dominated clothing industry by the end of 19th century. Flax and hemp clothing suffered serious competition and did not survive. After World War I hemp and flax were becoming less and less important in different industrial fields. With development of new chemical processes hemp, flax and cotton were replaced by wood in sector of papermaking. In addition, hemp has become the target for anti-narcotic propaganda campaigns started in the USA in 1930s, which resulted in Marijuana Tax Act, making cultivation of the plant uneconomical for farmers. (Allegret 2013, 19, 22.) In Russia since 1918, sown areas for hemp were depleted after chaos of Revolution and Civil war, leaving the culture to household uses. Yet the industry was resisting, developing new mechanical methods of processing and was constantly improving by Soviet breeders. Despite the ruin, that World War II has brought to the Europe, Soviet Union tried to restore rates of its former production, until policies in agriculture of 1957 made it non-profitable, by favoring corn cultivation. (Serkov, Smirnov & Alexandrova 2018, 135–136). After the WWII USA started imposing their view on hemp to the UN, what resulted in “worldwide” ban campaigns. Hemp production has been associated with narcotic strains and all plants varieties were put under drug laws, with most of hemp-based products being considered controlled substances. (CRS 2019, 1). However, China, India, USSR, Eastern European countries, France and Italy tried to resist this decision (Allegret 2013, 22). The final destructive decision for the hemp cultivation in massive quantities in Russia was made in 1961, when USSR confirmed joining UN convention on narcotic substances, as highlighted by Serkov, Smirnov & Alexandrova, what resulted in steady industry decline.

However, hemp as the source of different products is not going anywhere. Developments and projects can be recognized in many countries. Growing number of possible applications in different industries gives hope that the material may return back. And ultimately global and local economics will decide on hemp’s potential and plant’s further development. (Fike 2019, 20; Allegret 2013, 23.)

2.4 Hemp’s biological characteristics

Hemp had a long history of selective breeding for different uses, which resulted in significant differences on genome level. Strains of hemp are distinguishable by characteristics they possess and biochemical differences they hold. (CRS 2019, 5). Biologically, plant can be divided into several species/subspecies, which are subject to botanists’ continuous argues, as it was mentioned in part 2.3. According to Congressional Research Service report, only hemp with very low delta-9 THC content (dominant psychotropic substance in narcotic cannabis) is allowed to be used for industrial needs. Despite the fact, that hemp can be bred also for flowers and seeds, only fiber-hemp variants are of interest in this paper.

To begin with, hemp as well as flax, kenaf, jute, ramie belong to the group of bast fiber plants, what technically describes annual plants with highly developed phloem (vascular tissue) in which long, elastic and densely spaced fibers are located in form of bundles or strands. These fibers, formed mostly of cellulose, play supporting role in plants, being able to bear high-loads, due to their flexibility and finesse. (Zhong Liu et al. 2018, 4; Mayowa 2018, 59; Britannica [3] n.d.)

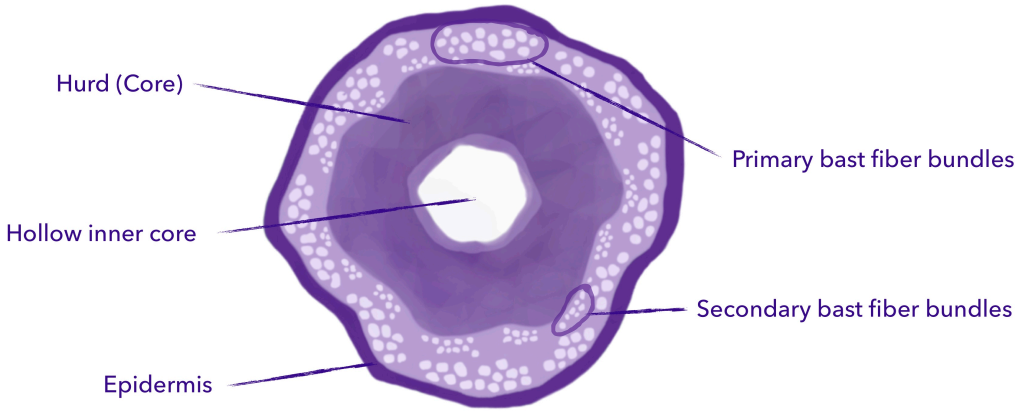

Figure 2. Schematic representation of cross section of hemp stalk (Gorbachev 2021, *based on:* Fibershed 2020)

From Figure 2 the basic idea on hemp stalk’s structure can be obtained. Hemp stem can technically be divided into outer bast fibers zone and the woody core, also named hurd or shive. Both zones have their unique properties and composed of different plant tissues. “Bast zone” is formed by phloem, sclerenchyma and cortex. “Core zone” constitutes 70-80% of the stem and is formed by both living and dead xylem cells (Riddle et al. 2019, 44). These distinct plant’s parts able to be divided from each other by process of decortication. Processes of retting and mechanical peeling also able to free fiber bundles from the remaining stem. In Picture 1 hemp stalk have been split to demonstrate the differences in structure between parts of the stem. The picture shows structure of relatively fresh stalk.

Picture 1. Image of hemp stalk with distinctly divided central woody core and loosened bast fibers (Sources: Natrij 2002 (Wikipedia))

Major chemical components of hemp are cellulose and lignin – exact constituents of most forms of plant matter (Riddle et al. 2019, 43). Hemp is comparable with other bast fiber plants by fibers’ properties and their chemical composition. (Comparative table for different non-wood materials are given in Appendix 1). Fibers, that are valuable for textiles, cordages and pulping, are collected from the primary fibrovascular bundle portions of the stalk between the protective epidermis and inner core. Hemp’s fiber bundles often reach length of 1–5 meters, however they are composed of shorter overlapping cellular fibers of 1–5 cm in length, chained by cohesive polymeric gums named pectins. (Riddle et al. 2019, 44; Britannica [2] n.d.). Long bundled fibers with high cellulose and low lignin content make up bulk of hemp’s bast, contributing to 70–90% of phloem’s matter. The remaining tissue within bast is formed by shorter cellular fibers with higher lignin concentration. Secondary bast fiber bundles, which are located closer to the core, are less valuable for production, due to shorter fibers' length – around 2 mm. However, woody core fibers have even shorter length – around 0.5–0.6 mm, being comparable to the shortest lengths of the hardwood fibers. Nonetheless their length defines them as the least valuable for industrial needs. (Riddle et al. 2019, 43–44; Small 2017, 104). Smaller fibers, which form primary and secondary bundles, are presented by elongated cells of cylindrical form with thick cellular wall and irregular polygonal cross-section. Their membrane-defined inner cellular space, named *lumen*, is wrapped by three *secondary cell walls* and one *primary wall*, which are formed by cellulosic microfibrils (fiber-like strands made of cellulose polymers connected by hydrogen bonds). The microfibrils are 10–30 nanometers in diameter. (Riddle et al. 2019, 44; Britannica [4] n.d.) Each of these layers play different role in cell's life and are defined by specific allocation of microfibrils. On Figure 3 the layers of cellular wall are schematized.

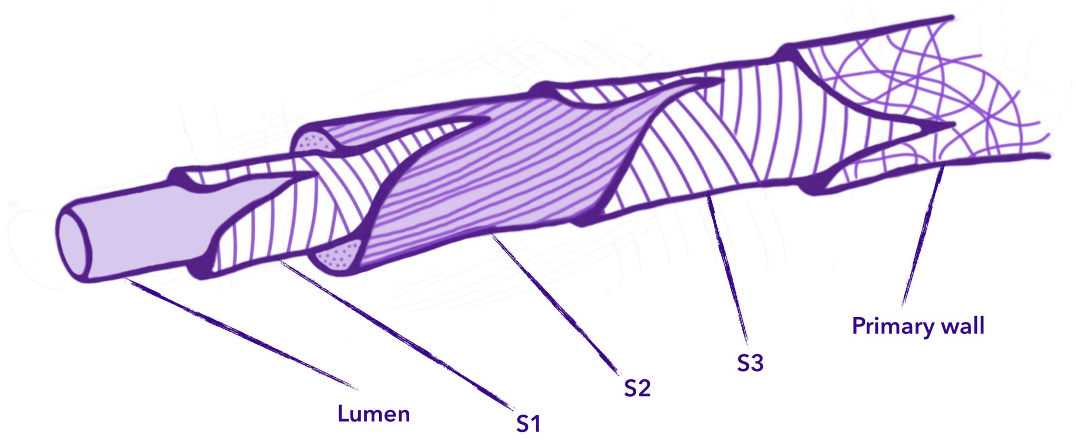

FIGURE 3. Structure of fiber's cellular wall (Gorbachev 2021, *based on* Riddle et al.)

- *Primary cell wall* is formed by randomly arranged mesh of microfibrils, hemicelluloses and some other biochemicals. This layer limits initial shape and size of the cell, determines consequent changes in them and seizes cell's growth when becomes rigid;
- *Secondary walls* (S1, S2, S3) appear in cells, whose functions in plants life are to carry fluids and provide mechanical support. These walls are formed usually by the end of growth and elongation of primary cell layer. They are found in dead, or near-dead fiber cells and in wood fibers. Microfibrils within relatively

> thin S1 and S3 layers are positioned spirally. Within them left-hand and right-hand spiral variations periodically cross/overlap each other. *Middle wall* S2 forms the bulk of cellular wall. Microfibrils within this layer are oriented parallel to each other, forming one steeply inclined helix, whose angle defines either fiber's strength or its stretchability.
>
> (Riddle et al. 2019, 44; Atlas of plant and animal histology 2019)

Fiber qualities and overall economic value of hemp products are dependent on several factors related to biology, growing techniques and the processing. Namely, these are: *strain of the plant*; *stem's thickness and length*; *maturity of plant when it is about to be harvested*; *type of harvesting*; the *degree of retting during bailing* and *storage*. (Riddle et al. 2019, 44–45.) These factors will be discussed further in this part and in the part 2.4, which is devoted to ecology, agriculture and harvesting of hemp.

Growth and life of hemp depends on its reproductive morphology. Naturally, cannabis is a dioecious specie, with distinct differences between male and female plants, which define plant's traits and requirements. Their ratio in populations is almost equal. Being a dioecious plant, hemp could not fertilize itself, so it is dependent on and prone to cross-fertilization. However monoecious strains of hemp have been produced by breeders, being entirely dominated by female phenotype plants. Female plants are generally stronger and live relatively longer than male plants. Male plants have shorter vegetative phase, lesser root system, thinner stem and usually start deteriorating by the time of their flowering, what negatively affects yield of both fiber and seeds (Chabbert et al. 2013, 28–29.) Additionally, sexual dimorphism of cannabis makes male plants grow at faster rate and reach up to 15% higher length than female ones, also having coarser fibers for yarn, what have specialized them for rope production (Allegret 2013, 12; Chabbert et al. 2013, 30).

Regardless of strain, root and stem morphology remains similar. Hemp's root system (about 9% of total hemp's biomass) allocates superficially from 10–60 cm below the ground, its main taproot able to reach depth of 2 m. The stem growth up to 4.5–5 meters high, rarely branches and its diameter on average is 1–3 cm, broadening from apex to base of the plant. At low sowing densities the plant has an increased chance of branching, on the other hand, when the density is high, plant will develop tall straight unbranched stem. Approximate representation of these differences can be observed from Figure 4. Finesse of stalk's diameter is directly dependent on the plant density (number of individual plants per unit ground area). The higher is this density the finer are stems. (Chabbert et al. 2013, 28–30.) According to Riddle et al. (2019) the desired supply of total biomass can be fulfilled by either maximizing growth of larger individuals, or by growing smaller plants with maximum non-restricting planting density.

FIGURE 4. Schematic representation of height and branching of same genotype fiber-hemp cultivated at different sowing densities (Gorbachev 2021)

Fiber yield received from hemp is dependent on stem's diameter. On practice, larger diameters of stalks result in smaller proportion of longer bast fibers per mass of the material. On the contrary, finer stems have greater proportion of bast fibers. Due to the fact that bast fibers are more valuable than core's matter, growers and processors favors optimization of plant density with selection of specifically fiber-oriented varieties, adapted to required climatic, soil and local latitude conditions. Stem's fineness also affects the quality of decortication processes, being an important characteristic for compatibility issues of incoming material into processing. Moreover, it should be noted, that stalk's biomass upbuilds exclusively by the end of vegetative phase. After flowers start their development, plant starts to bind bast fibers together to prevent its stem from lodging, thereby accumulating lignin and pectin gums within sclerenchyma, what results in gradual degrade of fiber qualities needed for industrial uses. Thus, harvesting for fibers have to be carried out before plant will enter its reproductive state. (Riddle 2019, 45.)

2.5 Hemp's ecology and agriculture

As it was mentioned in part 2.2 non-wood fiber plant will tend to have different cellulose and lignin contents in dependence with soil qualities and growing conditions. Thus, amount of total biomass and qualities of hemp's fibrous material are reliant on certain conditions the cultivators will seek to adhere for each region and even for each field. Cultivating hemp is not difficult in terms of agriculture, but requires right management on many of its stages, starting from field selection, date of sowing, seeding depth and seed preparation and ending with maintaining right conditions while plant is still growing. (Riddle et al. 2019, 45; Kostuik & Williams 2019, 59.)

Depending on the natural zone hemp will show differences in its growing patterns and morphology. In relation to geography some strains of the plant are more suitable for either fiber or oilseed harvesting than the others, even when in other natural conditions plant may tend to behave differently. This became clearer when result of study made by Grigoriev et al. (2009) are read, where central European, southern and northern strains of the plant have been grown in harsh conditions of Kola peninsula.

Naturally, wild hemp thrives in open environments with plenty of sunlight and warmth, where it grows up to 4.5–5 m high. It requires well-drained nitrogen-rich soils and temperate climates with adequate moisture. (Clarke & Merlin 2017, 1–2, 31). Natural weedy populations of plant can be found on open banks of water-bodies, margins of used agriculture lands, and other areas disturbed by human actions, for example – rubbish piles, ditches and roadsides. These populations will differ from cultivated ones, lacking most of their valuable and useful features. (Small 2017, 8–9.) While describing climatic limitations of hemp, Small (2017) underlines that wild plant variants show more tolerance to extremes of climatic and environmental conditions, when compared to its domesticated counterparts. Nonetheless trials for cultivated strains has been conducted in harsher conditions of northern latitudes, which have shown that within climatic conditions of Kola peninsula in Russia some variants of hemp were able to grow up to 1.4 m and produce strong and flexible fiber material (Grigoriev et al. 2009, 48). Additionally, Finnish experiments, which took place in Kanta-Häme (60°49'N) resulted in plants reaching height of 2 meters on fertilized silty clay soil, what also proved ability to produce significant yields of hemp stem matter within the North (Pahkala et al. 2008, 107–108, 112, 114).

For cultivated strains many soil types are found to be suitable. Nonetheless, soil with characteristics, like compaction, salinity, high acidity or high basicity have to be avoided. Water in soil should never be standing and pH should range from neutral to slightly acidic (6.5 to 7.0). Hemp tends to grow the best on adequately tilled high fertile (rich in humus) soils formed on loam and sandy loam basis. (Kostuik & Williams 2019, 60.)

Results of study conducted in Manitoba, Canada has derived amount of nutrients needed for the plant in local soil conditions (Kostuik & Williams 2019, 60). In that region, in accordance with soil maps, rich in humus black soils like CH – *chernozem (borols)* and KS – *kastanozem (mollisols)* are presented. Slightly poorer in organic matter, yet generally fertile *grey forest soils (alfisols)* are also presented in Manitoba. (Science Borealis 2015.) Thus, results of the research can be applied to a number of high fertile soils. No matter the soil type, industrial hemp requires fertilizers application. Generally, nitrogen is a key nutrient for hemp, as it is for any other plant. The rates of nitrogen uptake by hemp during its vegetative phase make it possible to refer to the plant as ‘nitrogen-hungry’. The oilseed hemp variations, while actively elongating, were able to remove from soil up to 7 kg of N from a hectare per day, requiring from 112 to 224 kg/ha of total nitrogen from applied fertilizers for the growth season, regarding to soil’s irrigation status. Yet, for fiber hemp such rate of heavy nitrogen fertilization is not desirable. During plant’s elongation, that excessive total nitrogen will deteriorate plant’s fiber qualities, namely leading to thinner cellular walls and consequential weakening of bast fibers. In that case, recommended amount of nitrogen is around 50–60 kg per hectare and fertilizers are applied before seeds are planted. So, the addition of nitrogen into the soil, whether it is fiber or oilseed hemp strain, is highly recommended in right dosage, at the right placing and at the right time. In addition to that, hemp is found to be non-tolerant to any seed-placed fertilizers, so fertilizers have to be banded with soil prior to sowing, or precision placed away from seeds. Another important chemical compound affecting hemp growth is phosphorus. Around 50 lb (56 kg) of available P_2O_5 have to be presented in soil for oilseed plants and 60 lb (67 kg) for fiber hemp variants. However certain limitations for phosphorus application exist, dependent on soil moisture, structure and temperature. Availability and environmental circulation of potassium are also important factor for hemp growth. It affects root growth and defines strength and length of hemp stalks and overall plant's decease and environment resistance. Naturally long stems of hemp associate it with extremely high uptake of potassium. More than 330 kg of potassium per hectare are required for both seed and fiber hemp during their growth cycle. Nonetheless, little amount of these nutrients is deposited in seeds and leave the field after harvesting for oilseed. By some on-field retting techniques mobile potassium as well as nitrogen are able to be returned into the soil through leaching, thus became available for next crops. Due to the fact that most of the nutrients are accumulated in green stalks, by decisions of cultivators the fate of leftover nutrients is chosen. In case of choosing total biomass harvesting, green bailing, water-based (wet) retting techniques these nutrients are removed from field for good. (Kostuik & Williams 2019, 60–61; Riddle et al. 2019, 46.)

Other important factors for hemp cultivation are climatic conditions, humidity, temperature and amount of sunlight and heat. Certain amount of heat received from sun is required for each plant to grow and develop. Heat that is required for the cultivated culture to develop is calculated through several methods, one being the *sum of active temperatures*, which is applied in Russia and some other countries, another one being *growing degree days* (GDD), which is more commonly used worldwide. For vegetation stage of oilseed hemp, the sum of active temperatures (total sum of *average daily temperatures* for days when temperature was exceeding the threshold of 10°C) should be in the range of 2200–2900°C. For comparison, corn variants require 1100–2900°C, oat 1000–1800°C, oilseed flax 1600–1800°C and fiber flax needs 1100–1500°C. (Gataulina 2018.) Fiber hemp requires slightly less heat than oilseed type. From the point of total required GDDs no solid and logical answer has been found, however from the work of Legros et al. (2013) it was noted that total value of required heat depends on soil nutrients availability and the variant of hemp. During active growth phase, development of both woody core dry matter and fiber mass require heat in a linear fashion. More nitrogen in soil leads to lesser heat requirement. Yet, regardless of total received temperature and the date of sowing hemp en masse enters flowering on a specific date, depending on latitude and plant's variation, due to the fact that flowering stage is determined by photoperiod. (Legros et al. 2013, 73, 81). Mayowa (2018) states that hemp reaches maturity in 80–150 days. According to Kostuik & Williams (2019) most of plant's variations require around 110 frost-free days to reach flowering phase. Russian compilation papers and abstracts state that vegetative stage duration for central-Russian landraces is around 100–115 days, when for northern variants this duration is the shortest, taking 60–70 days due to seasonal limitations. Southern types of European hemp, growing in Ukraine, south of Russia and Kazakhstan require 130–160 days to mature in general, but grow to their fullest reaching double height (4 m) and fiber content of central-Russian hemp variants.

Optimal temperatures for plant's photosynthesis are in range from 25°C to 30°C. The best growth is observed between 14°C and 27°C. Despite still able to grow and give quality fiber material in northern locations hemp does not tolerate cold temperatures (Small 2017, 36, 125), with frosts of –5°C being baneful for male plants and –9°C killing the rest of hemp's population at any point of its development (Pahkala et al. 2008, 114). However, hemp shows more tolerance to hot temperatures and arid environments, than to the cold, when adequate amount of water is available for it through rainfalls or irrigation. Yet the plant is still sensitive to droughts, what should be taken into account to prevent hemp's dwarfing. In temperate regions with sufficient rainfalls the irrigation is unnecessary for cultivation, due to general hemp's requirement of 50–70 cm of precipitation per growing season. On the contrary, when oversaturated or waterlogged the plant shows no tolerance for that, especially the young plants. (Small 2017, 36, 125).

Hemp as an agricultural plant can be implemented into the traditional crop rotation with either cereals or legumes, by this opening new opportunities for farmers. Hemp cultivated after hemp should be avoided to prevent depletion of soil nutrients, to decrease chances of plant's deceases and to prevent reduction of fertility rate and quality of oilseed products. For oilseed strains there are also limitations to prior cultures, which have to be taken into account. However, rotation of fiber hemp variants can be done after any previous crop, because not so many fungal infestations of plants, which affect yields of fiber material have been found. (Riddle et al. 2019, 38, 44; Kostuik & Williams 2019, 60–61.) To support fiber processing facilities of a major output, depending on the obtained fiber yield significant territories of farmland are required (approximately 3200 ha of cultivated land supply annual demand of the industrial unit processing 3 tons per hour of fibers) (Riddle et al. 2019, 41).

Harvesting technologies are selected in regard to processing technologies, in general. Majority of currently implemented processing facilities require industrial hemp to be delivered in form of bales, due to good packing density this way pose for transportation and storage and general ease of integration. (Riddle et al. 2019, 47). For instance, it is the bales of hemp stalks, which are fed into high-tech advanced processing plant, called HempTrain™, a special design for decorticator invented by Canadian Greenfield Technologies Corp. Packaging raw hemp materials in bales are done by two ways, first one implementing whole stalks and other implementing cut hemp stalk material. However, most of decortication techniques require straw not being cut too shortly. Dependent on the region and available agricultural machinery one of baling methods will be chosen. In Europe, hemp stalks are usually cut to be baled. In addition, baling has to be performed, when hemp straw material is mostly dry. (Riddle et al. 2019, 47).

Retting is an important process implemented after the harvesting. It is a microbial process, during which bacteria digest most of cellular tissue surrounding fibrous material, which hold fibers together. Proper retting practices define the final fibrous product qualities regardless the best practices of its cultivation or natural conditions. Degree of retting influences further processability of the stalk material during its decortication and separation, so the process is thoroughly monitored. Over-retting deteriorates fibers, under-retting leads to inefficient and challenging decortication. Fiber hemp producers choose between ‘dew’ retting method and other retting methods (water retting and modified wet retting) to benefit ether from returning nutrients back into the soil or from producing uniform better-quality fiber material. (Riddle et al. 2019, 46–47; Kostuik & Williams 2019, 60–61, Britannica [5] n.d.).

2.6 Information on hemp’s end uses

Industrial hemp historically was used for its strong fiber properties. In part 2.3 significance of its many applications in development of societies was emphasized and explained. In addition to already mentioned applications, other uses are listed within this chapter.

Hemp’s straw during separation processes divides into bast fiber material and hurd, each being used separately in general. Despite bast fibers of hemp are at least twice the value of woody core’s fibers, hurd is more economically valuable in term of using its mass, which often 2–3 times larger. The hurd able to provide equivalent or more revenue than the fibrous part for each kg of input material. (Riddle et al. 2019, 51.)

Traditional consumer products made of hemp fibers, like ropes and clothing had become obsolescent or been replaced, however in some cases they made a return as special niche-products. Hemp bast fibers are turned into the pulp needed for manufacturing specialty papers for bibles, envelopes, banknotes, technical filters and etc. (Small 2017, 111, 115). Yet, there are opportunities for producing papers of more common implementation. More basic implementation for hemp pulp was not only shown by the results of PureVision company in converting whole hemp stalks into usable pulp matter (Pulp & Paper Canada 2019) but also has been described and emphasized by many renowned industrial hemp advocates.

Products derived from woody core of hemp can require the least amount of processing, being implemented as animal bedding and cat-litter pellets or be sold as a raw material for hempcrete (construction material produced from hurd fibers mixed with lime) production (Riddle et al. 2019, 51). However, other uses are available and newer ones are being developed. Another application includes the woody core utilization either in conjunction with bast fibers or without them in the pulping regardless of fiber lengths difference. According to Naithani et al. (2020) through right cooking/defibrillation techniques pulp can be obtained from exclusively hurd fibers, which in combination with hardwood pulp material can be used for creation of quality tissues. In addition, from woody core, the lignin can be extracted and be used in chemical industries, where whole range of value-added products can be manufactured (PureHemp Technology n.d.). Also, PureHemp Tech mentions that sugars technically can be extracted after processes of biorefining and then be sold to other industries.

Based on many different sources Figure 5 was made to represent end-products, which can be made from materials and derivatives of hemp plant.

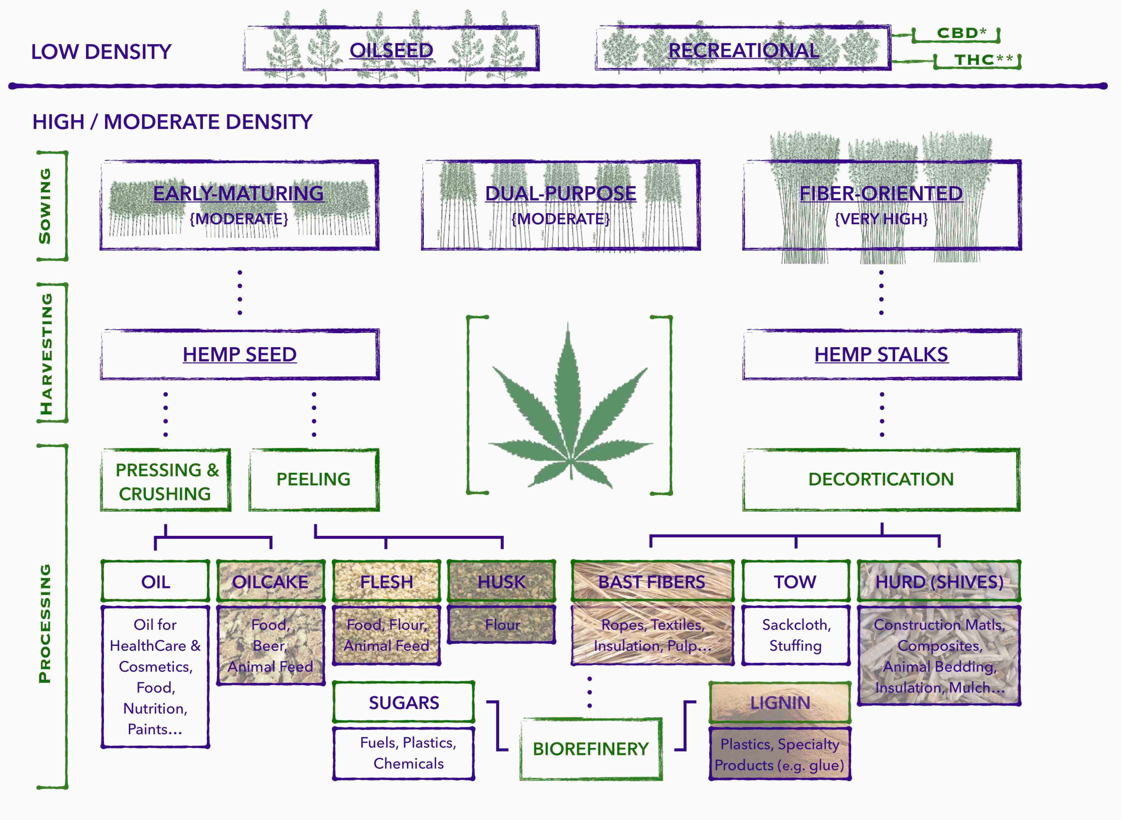

Figure 5. Varieties of hemp plant and products derived from hemp's processing. (Gorbachev 2021)

From the figure, the obvious division of product lines can be observed, in regard to hemp's type: oilseed variants are used to produce hemp seed yields, while fiber-oriented strains are grown for stalk biomass. The low planting density recreational types are grown for flowers, containing high concentrations of *CBD (cannabidiol) and **THC (tetrahydrocannabinol) chemicals. CBD oils may be implemented in care products and medicine, if CBD has the proper legal status. THC is forbidden in industrial applications due to its nature of being a psychoactive compound.

Picture 2. Bottle of hemp’s oil produced in Russia (Gorbachev 2021)

Hemp oilseed types and dual-purpose variants are mostly cultivated for grain. Seeds can be peeled and marketed as gluten free hemp’s seeds or be pressed into the seed oil, which can be used in food industries or for manufacturing value-added products, like oil paints. In terms of taste and health hemp seeds and oil are considered as high-quality consumer products. Hemp grain production already has established itself on the markets of Canada, the USA and Russia as a health product and food supplement. In addition, oilcake that is left after pressing the hemp seeds for oil is implemented as animal feed and ingredient for beer manufacturers. Husk, which is a waste product of peeling, can be grinded into the flour.

3 METHODOLOGY

The main idea of this literature review was to find and present information on hemp’s possible industrial application as a fiber source for pulping as an alternative for timber, in regard to modern technology and qualities the paper industry seeks for. The explanation for choosing this research question was justified in the introduction for this review. It was also decided to include information on fiber hemp biology, agriculture, natural requirements and historical application to emphasize on the potential this plant has held in agriculture, before its application had declined worldwide. To logically construct this review, each concept related to both hemp and paper production was described in the way to provide decent context for the reader. Results of the review were planned to be structured in a form of SWOT (Strength Weaknesses Opportunities Threats) analysis, as a tool of utility in defining advantages and disadvantages of hemp as an alternative raw material. In the discussion section results of the review were combined with conceptual evaluation.

Due to the fact that in this review paper manufacturing was not the initial goal of description, its basic processes and related terms were chosen to be mentioned. For that matter encyclopedic sources and video materials were selected. From official films available for general public, which were produced by Sappi Ltd. (South African Pulp and Paper Industries) and Valmet Oyj (Finnish developer of pulp, paper and energy technology), idea on processes behind pulp, paper and tissue manufacturing became clear and concise for a brief reference.

Considering that hemp is an uncommon crop and unfamiliar material for papermaking, its place within alternative non-wood pulp materials had to be described in a short manner. A special part was dedicated for non-woods, their characteristics and use in the pulping industry. For that matter search of literature has been conducted using ‘non-wood’ as a primary key word in different search engines. University library search engine was used at first place, then google scholar was implemented. Several works have been chosen as the result, which had included information on hemp’s place within this plants group, despite being generally dedicated to non-wood pulping. One of these works was a technical report initiated by VNP company's interest in finding appropriate non-wood material for the climatic conditions of Netherlands, which also included review on Chinese experience in the field of non-wood pulping. From all these papers tables presenting fiber and non-woods characteristics has been modified and combined into the one, which was added into appendices.

Next chapters in this literature review were dedicated to hemp, its biology, ecological constrains and agriculture. To find more specified literature on these topics, a bunch of articles were studied, which had been published in agricultural and hemp related journals. Through university some of these journals have been assessed. In addition, while searching for materials to exclude possibilities of including biased opinions into the review, published works on Research Gate have been browsed and expertise of several authors has been checked. To find more solid proof of certain points from the articles, some books and compilations have been read and referred. Some of these books were accessed by other means than university library. As addition to scientifically reviewed materials, websites also were quickly browsed to help with contextual understanding.

To start with hemp related information, its history of dissemination and application has been included. Materials like specific book chapters and independent researches has been used to describe history in a chronological order. In addition, Russian research paper was used to provide perspective on plant's history of industrial use in Eastern Europe. For that exact material in Russian language and for some others which were used in other parts of the review, translation into English has been done in particularly accurate way to prevent loss and distortion of theses and conclusions.

Parts on hemp's biology and ecology were the hardest in term of combining available materials and presenting them in a way general reader could understand. For describing features of biology and morphology several books were used. One of the books has been written by French authors, some others have been works of American researchers. To supplement information on structure of fiber cell, an open web database 'Atlas of Plant and Animal Histology' from University of Vigo has been referred. Available materials have been supplementing each other for most of the review, however while listing environmental requirements, a problem for interpretation has appeared. Namely, information on required heat in GDD units for plant’s development differed so significantly from one source to another, so it was decided to turn to web searching. Fact checking on that matter has not provided the answer, so it was decided to include comparable information from Russian textbook provided through agricultural universities and to omit GDD indicators, despite their significance.

During searches for the review part on hemp’s end-uses, generalized web browsing and books’ implications have been used. In addition, news articles have been implemented into the search to find evidence of already established innovative technology behind hemp pulping and usage of the material. Through these articles several companies have been found, which had piloted certain existing processes into newer and sustainable form, able to give prospects for businesses and for development of hemp as the material. Official webpages for these technologies have been referred in the review. However, this kind of materials had an increased chance of unreliability.

4 RESULTS

STRENGTHS

- Wide area of dissemination: from polar circles to tropics. Adaptivity.
- Wide range of strain variations for different climates and implementations.
- Optimal growth temperatures are between 14°C and 27°C.
- Rapid growth. Adapts to high planting densities.
- For cultivation and harvesting requires agricultural machinery.
- Can be established into crop rotation.
- Does not require much water during cultivation.
- The height of stems reaches several meters on average.
- Produces high yields of fibrous matter, exceeding annual yields of softwoods.
- High quality of bast fiber material.
- Established sales markets for each outgoing material.
- All of stem's structural parts can be implemented in pulping: both bast and hurd.
- Produced paper from bast fibers is of a high quality and tensile strength, defining it for specialty use.
- Hurd fibers are able to be implemented for production of papers similar to hardwood paper grades.

WEAKNESSES

- Requires significant expenditures on fertilization when cultivating. Requires a lot of heat for growing.
- Competition for field-space with other crops.
- Serious dependence on climatic and soil conditions.
- Requires proximity of processing industries to the points of cultivation.
- Takes out large amounts of nutrients from the soil.
- Processing is not simple. It requires many skills and practical knowledge.
- Extraction of quality fibers requires retting methods, that are burdening for the environment and do not return nutrients into the soil.
- Currently produced fibers are more expensive compared to cotton for textiles and wood for pulping.
- Lack of significant production of hemp-based pulp and paper. Lack of established supplier chains.
- Often farmers emphasize on cultivation of oilseed variations.
- There is no mass production, that can affect trends in the industry, making it cheaper and more commonly used.
- Lack of massive researches for implementing hemp in paper manufacturing.

OPPORTUNITIES

- General consideration of hemp as a niche product by masses gives opportunities for corresponding marketing and its benefits.
- Ability to develop production technologies from scratch gives a 'start-up' opportunity to profit from technology provision and selling.
- Established pulping technologies can be applied to hemp, requiring mostly minor changes into the process.
- Development of newer and efficient techniques gives prospects for spreading of 'tree-free' paper products.

THREATS

- Climate related risks such as sudden cold snaps or prolonged periods of rainfall can lead to crop failure, if occur during the growing stage.
- The overall quality of fibrous material may turn out to be worse than is required for pulping, by making mistakes in execution of harvesting and retting techniques. What results in financial losses.
- Employed personnel requires education due to partly lost culture of production and processing of hemp.
- Existing laws, if not written to differentiate industrial hemp variants from marijuana, prevents any cultivation and processing of the plant.

Advantages of hemp as an alternative source of fibers for pulping:

To begin with, hemp is a fast-growing annual culture, which grows to 1.5–5 meters on average. In some cases, plant can reach height of 6 meters. Ability of fiber hemp variations to be densely planted poses huge benefit for the industry, due to higher yields of produced biomass. In addition, annual fiber yield from industrial hemp per hectare is exceeding annual fiber yield of coniferous and some deciduous tree species employed in papermaking. The plant is able to be implemented within crop rotation and be grown in many temperate regions, if farmlands are adequately prepared and maintained. Harvesting for biomass can be done usually by the end of plant’s vegetation phase with employment of commonly used agricultural machinery. Hemp is related to bast fiber materials, which have a thin layer of bast, formed by strong and long bundles of fibers, and have a thick woody core, also known as hurd. Since fibers for pulping can technically be extruded from all parts of plant’s stem, pulping facilities can employ separated fibers or use whole stalks. In case of only employing bast fibers into pulping, high quality specialty papers are manufactured. In case of using woody core fibers, more common types of paper products can be manufactured. These paper products will have characteristics closer to papers and tissues made from hardwood fibers. In regard to technologies of cooking and separating fibers during pulping, most of them can be applied to hemp, but require minor changes to them. Some companies are not only changing the existing methods but developing new technology to improve hemp’s processing efficiency and sustainability, also implementing extraction of useful by-products of processing, like lignin and sugars.

Overall disadvantages:

Hemp if used as an alternative source for papermaking, currently cost more than wood raw materials. Paper and pulp produced from hemp is several times more expensive than conventional paper. These costs include expenditures on fertilization, management and processing. Even when cultivated on rich soils, hemp requires significant nutrient addition and exposure to a lot of heat. It leaves fields in depleted state after harvesting, so cost of replenishing fields for next crops might be included. If the plant is cultivated on poor soils it is prone to failing or giving lesser quality biomass. Hemp cannot be cultivated on the same field for several years in a row, so the raw material has to be either transported or stored, to supply processing facilities all year round. Any harmful climate conditions posed by sudden and extreme changes, like cold snaps or long raining periods, kill the plant. Processing and retting techniques to separate bast fibers from woody core are time consuming, energy non-efficient, require certain expertise of employed people and require a lot of fresh water, which becomes contaminated by leaking nutrients. Older techniques, used in some countries are even more harmful for the environment, due to serious deficiencies in implemented heating and chemical processes and long period of it not being updated to existing environmental laws. In addition, laws controlling narcotic substances pose risks for cultivation, if not written adequately.

5 DISCUSSION

As it was stated within the introduction growing rates of forest depletion can be mitigated by implementing range of diversified measures. Finding solution for the deforestation is in economic interests of both huge industries and the environment. The base for reestablishment of raw materials was reviewed on the example of industrial fiber hemp. To define its advantages as a replacement of wood, useful information has been gathered. Before each advantage and drawback of hemp is discussed, it is important to mention some other possible actions to reduce rates of forests depletion both deliberate and radical:

- at first, forests might be reintroduced onto barren territories where agriculture has ceased to exist or into disused urbanized areas, at least in the form of plantations to make these areas profitable. Established plantations have to be favored for wood harvesting and be fully restored after each logging. Intact natural forests have to be protected at all costs by corresponding laws and protection initiatives.
- secondly, agricultural methods have to be continuously developing to increase its productivity and efficiency. Grazing and ranching of livestock may be limited to a certain degree and attached to already existing area. Livestock population can be also gradually reduced to a such number, that is technically demanded for human needs. In addition, clearing of forests for agricultural uses have to be strictly controlled. Cultivation of technical crops, like soybean, oil palm, sugarcane and coffee, also has to be limited in regard with its worldwide demand.
- From socio-economic point, education of rural populations, exposed to forests can be carried out. Severe degree of prosecution of Illegal logging activities and unsustainable practices in longer term will be able to form public consciousness on harm of deforestation.

However, the least controversial variants are to grow new forests, use plantations and to gradually transit pulping and papermaking industries to other raw materials. The latter variant after completion of this review can be accounted as realistic and promising.

To begin with, high yields of hemp fibers partly compensate the drawbacks related to lack of all year availability of materials. Nonetheless actions on increasing the base of available raw material should be taken, in order to make the processing cheaper and more desirable for big industries and investors, turning their attention on trying, at least, partial transitioning to hemp fiber material. Increasing rates and volumes of hemp pulp production will help the material become competitive with the wood-pulping market. However, increasing raw material base will require conversion of significant areas of available farmland to hemp cultivation, leaving some crops behind, what has its own disadvantages. Ironically, in the worst-case scenario forest areas can be cleared for industrial hemp’s cultivation, so it has to be kept in mind.

Sustainable methods used in pulping companies have their disadvantages, for example use of recycled paperboard and paper waste is not a long-playing solution, due to the fact that recovered cellulose fibers cannot be recycled indefinitely. However, fibers from some non-wood plants are stated to be recyclable several times more, when compared to wood-based fibers, due to different structure of fiber cells. Hemp bast fibers are more suitable for production of specialty papers than for common paper grades. The qualities bast fibers possess are favored by textile industries for cloth manufacturing. Currently hemp clothes are expensive niche products, which has their own potential as a sustainable clothing. Due to the fact that any hemp variation meets its water demand from precipitation in temperate regions and often does not require excessive irrigation, from the point of sustainable water use, hemp is a textile source less burdening for the environment than cotton. However, in term of other requirements for cultivation, hemp is inferior to flax, which requires less heat and nutrients.

Hemp’s woody core (a.k.a. hurd) fiber material is more suitable for making common types of paper, due to core’s fiber dimensions and qualities being similar to hardwoods. Transitioning to hemp pulp can be started from that point, or at least from employing fraction of such pulp into wood pulp to enhance paper qualities and reduce use of wood. Also, some pulping technologies already are able to implement whole stalks into processing. At this point, it is possible to say, that processing stages like retting and decortication can be in some way neglected with all related to them money expenditures and environmental issues. It is also possible to say that paperboards from hemp pulp are able to be manufactured, similarly by the processes implemented in pulping facilities, which are producing unbleached kraft paper from straws left after crop harvesting. Due to the fact, that paperboard papers do not require bleaching, some spending related to this can be diminished.

Main issues with hemp occur when it comes to its cultivation and natural requirements. Soil is one of main defining aspects for plants growth and fiber qualities. Rich in humus soils, like chernozem or kastanozem are valuable natural resources and already employed for cultivation of other agricultural crops. They can be found only in specific regions of the world, formed by suitable climatic conditions and geology. However, there are other nutrient rich soil types around the world which are fit for hemp cultivation but will require significantly more fertilization for supplying hemp's demand. Through research hemp was found to be a 'nitrogen-hungry' plant species, what is reflected in its fast growth rates and significant biomass yields. In case of cultivating for fiber material, despite the generally lesser consumption of nutrients, fertilization of fields will have to be applied more often than for oilseed variations of plant, because harvesting of total biomass with implementing out-of-field retting techniques won't be able to return any fraction of nutrients into the soil through natural leaking. Water retting techniques are contaminating water bodies with leaking nutrients during the processing, so nutrient removal and retrieval can be established in terms of preventing water contamination and finding the way of returning nutrients into the soil in one way or another. It is important to keep in mind, that soil nutrients are able to be replenished by growing legume cultures on fields, as follow-up crops and also leaving them to ret on site. Nonetheless, for any possible way to replenish soil nutrients, financial expenditures have to be made by cultivators, which further may be included in the cost of raw hemp fiber material.

It is worth mentioning, that green stalks or other leftovers of oilseed hemp can be implemented into production of biofuel, as well as many other remaining straw materials from other cultures. Generally speaking, for non-wood fiber plants this option is not possible and even pose risks for the demand of final products, due to the fact if implemented for biofuel production, there will be no material left for fiber extraction. Despite being a reasonable and sustainable idea, obsession of huge companies and overall society in producing biofuels is called ‘biomania’ by some specialists of non-wood fiber materials. Biofuel production from agricultural residues cannot coexist with non-wood pulping and papermaking. However, there may be a solution in transitioning raw base for biofuels into implementing unwanted plant species or invasive ones. For instance, throughout all Europe and Western Russia toxic and poisonous *Heracleum* (giant hogweed) plants are distributed around disused agricultural fields, roads, rail-roads and other urbanized areas, posing risks to populations and ecosystem. Maybe technologies for their biorefining can be invented or studied to find these species economically benefitting applications.

In conclusion, a lot can be said about industrial hemp and its application in pulping. It has its own burdening disadvantages and limitations, as well as significant environmental and economic benefits. As the result, it is more than possible to call hemp a resource of huge potential, which must be studied, developed and implemented.

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APPENDICES

Appendix 1. Fibre properties and chemical composition of raw non-wood and wood materials (Adapted from tables of Zhong et al. 2018 & VNP 2007)

PLANT	FIBER LENGTH	FIBER DIAMETER	FIBER YIELD	PULP YIELD	CELLULOSE	LIGNIN	HEMICELLULOSE
	mm	microns	(tons/ha/year)	(tons/ha/year)	%	%	%
Hardwoods:	**0.7–3.0**	**20–40**				**23–30**	**19–26**
Eucaliptus	0.7–1.3	20–30					
Fast-growing deciduous			15	7.4			
Softwoods:	**2.7–5.0**	**32–43**			**57**	**26–34**	**7–29**
Scandinavian coniferous			1.5	0.7			
Temperate coniferous			3.4	1.7			
Fast-growing coniferous			8.6	4.0			
Straw and stalk fibers:							
Wheat straw	1.0	13	4	1.9	29–35	16–21	26–32
Rice straw	0.5–1.4	8–10	3	1.2	28–36	12–16	23–28
Oat straw	1.5	13					
Barley straw	1.5	13					
Rye straw	1.5	13					
Corn straw	1.0–1.5	18					
Corn stalk	1.0–1.5	16–20			36–38	18–19	23–25
Sorghum stalk	1.0–1.7	20–47					
Cotton stalk	0.6–0.9	20–30					
Reed and grass fibers:							
Common reed	1.5–2.5	20			42–50	22–25	20–23
Giant reed	1.2	15			50		24–25
Papyrus	1.5	12					
Reed canary grass	1.0	20	8	4			
Miscantus	1.2	20	12	5.7			
Esparto	1.1–1.5	9–12					
Sabai	2.1	9					
Cane fibers:							
Bagasse	1.0–1.7	20	9	4.2	55	18–24	27–32
Bamboo	2.7–4.0	15	4	1.6	52–68	21–31	15–26
Bast fibers:							
Flax	25–30	20-22			70	10–25	6–17
Hemp	20	22	15	6.5	57–77	5–9	9–14
Sunn hemp	2.5–3.7	25					
Kenaf	2.6	20	15	6.7	53	15–18	21–23
Jute	2.0–2.5	20			57	16–26	15–26
Leaf fibers:							
Abaca	6.0	20-24			61	9	11
Sisal	3.0–3.5	17-20			43–56	8–9	21–24
Seed hull fibers:							
Cotton staple	20–30	20			95–97		
Cotton linters	0.6–3.0	20			90–91	3.0–3.5	