Félagsvísindadeild

Cultivation of Industrial Fibre Hemp (Cannabis sativa L.) in Iceland. How can we produce high-quality long fibre for use in textile applications?

Ritgerð til MA gráðu í menningarstjórnun
Nafn nemanda: Bethina Elverdam Nielsen
Leiðbeinandi: Anna Hildur Hildibrandsdóttir
Haustönn – 2022

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Abstract

Though hemp possesses high-quality fibres that are valuable for the production of fine-quality yarns, and signs of hemp cultivation have been traced to about 8,000 years ago, long hemp fibres are not yet commercially manufactured into fine, thin yarns.

But a renewed interest in this newly legal plant has arisen for industrial purposes in numerous fields. Many researchers and businesses are looking into how it could be used as a raw material and as a green solution.

This thesis investigated the potential of cultivating Cannabis sativa in Iceland for long fibre yield and how it should be processed to produce quality fibres for textile applications.

A qualitative investigation was conducted as traditional desk research, where efforts were made to give an overview of the process and involvement in the cultivation of industrial fibre hemp with a focus on long fibre yield.

Relevant data were collected and analysed to gain a broader understanding of the subject and more insight into the research. A systematic literature review was then conducted, emphasising the long fibre yield of hemp cultivation in northern latitudes, which was compared and interpreted in the discussion chapter. Afterwards, other reports were brought in to go more in-depth on processing long hemp fibre for textiles in Scandinavia and Iceland.

This methodology was chosen due to the novelty of the subject and because almost no research has been done on the topic in Iceland.

This thesis concludes that cultivating hemp for long fibre in Iceland is possible, especially with a careful selection of cultivars. However, difficulties still need to be addressed in the production process. Much research is needed in cultivar testing and finding the proper retting process, which has proven to be the biggest obstacle.

List of keywords

Cannabis sativa, industrial hemp, cultivar, long fibre yield, retting, fibre quality, and textile.

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List of Abbreviations and definitions

Abbreviations

cal BCE	The calibrated time scale; Before Common Era
CBD	Cannabidiol
CE	Common Era
CSR	Corporate Social Responsibility
Cv/cvs	Cultivar/cultivars
OECD	Organization for Economic Cooperation and Development
GOTS	Global Organic Textile Standard
ITIS	The Integrated Taxonomic Information System
NGO	Non-Governmental Organization
Nm	The Numero metric count (metres of thread per kilo = (1000 x count) / ply)
THC	Tetrahydrocannabinol
UN GSDs	United Nations Sustainable Development Goals

Definitions

Bracts	A modified leaf or scale, typically small, with a flower or flower cluster in its axil
Cannabidiol	A non-psychoactive constituent of Cannabis sativa (CBD)
Cannabis sativa	A botanical name of one major type of hemp family
Composite material	A combination of two materials with different physical and chemical properties
Cottonization	A process that adapts flax and hemp fibres for spinning with other staple fibres, such as cotton, by removing impurities such as lignin and

	pectin and shortening the fibre length for subsequent spinning processes
Decortication	Mechanical separation of bast fibres and hurd fibres
Dioecious	Individual plants that form either female or male reproductive organs
Herbaceous	Plants with little or no woody tissue
Monoecious	Individual plants that form both male and female reproductive organs
Phenology	The study of relationships between environmental conditions and biological processes such as plant development
Photoperiod	The period of daily illumination received by an organism
Pseudoliths	Archaeobotanical tool
Phytoliths	Opaline silica deposits that form within and between the cells of plants, forming 'casts' of the cells and intercellular spaces
Plasticity	The adaptability of an organism to changes in its environment or differences between its various habitats
Retting	The process by which the pectic material which binds the fibres to the remainder of a stem is broken down and the fibres are liberated
Scutched	To separate the valuable fibres of ex. hemp from the woody parts by beating, combing, or scraping
Taxonomy	The branch of science concerned with hierarchical classification, especially of organisms

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Chapter 1

Introduction

As an artist, my interest has moved towards sustainable solutions in textile and design. I have been exploring everything from waste materials, like plastic, to biomaterials from fungi and bacteria. At some point, I started exploring the hemp plant, but it was not until I was introduced to it for its medical uses that my interest grew. And it did not take long before I was utterly fascinated by the plant and its abundant uses, both as a green solution in many fields and as a healing plant.

Getting pregnant had been difficult, with many losses and complications. Complications due to Endometriosis[1], which I had been diagnosed with some years earlier. Endometriosis has no cure, only symptoms and pain management through medication and hormonal therapy. I was looking into alternative treatments to reduce the intake of hormones that negatively impacted my daily life. Side effects from hormonal treatment, ranged from joint pain and mood swings to severe anxiety. So, when I started hearing about CBD oil as a pain treatment, I was very interested. One Australian online survey interviewing women from an endometriosis support group found that cannabis and CBD oil were the most effective self-care techniques for endometriosis pain (Armour et al., 2019).

I will not be writing about all the healing ability or all the products this plant can contribute to. As a designer, I am looking for opportunities to make a difference in the field through sustainable solutions, which should always be on the agenda when creating. Thus, the main objective of this study is to explore hemp cultivation for textile fibre production.

As the climate, both on the planet and between people becomes more turbulent, there is a need for more exploration and concretisation of what alternatives there are for achieving sustainability goals, refreshing our soil, and reversing negative trends. Therefore, it is valuable to compile available knowledge of hemp as a textile material and provide an overview of what is required of actors interested in producing quality hemp fibre for textile use.

[1] A disorder in which tissue like the tissue that forms the lining of your uterus grows outside of the uterine cavity (Healthline, n.d.).

This study explores knowledge about cultivating Cannabis sativa in a geographic such as Iceland. Explore the possibility of working the fibre for textile use and the requirements for producing hemp for long fibres.

As well as looking at the specifics of the plant, its origin and how it has been used through time, focusing on the Nordic regions.

I will also explore whether and what Icelandic research has been done and how much knowledge we have of cultivating the plant in Iceland.

The topic of this study is interesting from a social point of view because it is part of a bigger social picture about how this newly legal plant is being studied and how it could be used as a green solution in many fields.

Objectives, Methodology and Research question

The research objective of this thesis is to explore the possibilities of cultivating Cannabis sativa, for textile fibre in Iceland and to find out the requirements for producing high quality fibre hemp, with the goal of laying the groundwork for a critical evaluation of the possibility of long hemp fibre thread, made in Iceland.

For the study, a qualitative investigation was conducted as a traditional desk research. During the literature assessment, it became evident that there is a scarcity of peer-reviewed academic and scientific research in this field. Possibly due to the industry's limited size.

Therefore, the existing data used combined published scientific studies, research reports, field trials, government resources, news reports, and similar documents. The relevant data were collected and analysed to gain a broader understanding of the subject matter, through comparison and interpretation of the data. Other reports were brought in afterwards to go more in-depth on the processing of long hemp fibre for textiles in Scandinavia and Iceland.

This methodology was chosen due to the novelty of the subject and because almost no research has been done on the topic in Icelandic.

When looking at the sector globally, the language barrier was also an issue in the search process. Some documents were found in Danish and Swedish. However, this author expects that more research is available in other European languages, from countries such as France, The Netherlands, and several east European countries, where fibre hemp cultivation is on a bigger scale.

The study examines how industrial hemp should be cultivated to produce quality fibres for textile applications. To acquire more insight into the research issue, the first phase in the research process involved doing a literature study using scientific papers and other literature as a base. Then, a systematic literature review was conducted, with an emphasis on long fibre yield, on hemp cultivation in northern latitudes, which was compared and evaluated.

Efforts were made to give an overview of the process and involvement in the cultivation of fibre hemp with a focus on fibre yield.

At the end of this thesis, the answer to the research question was discussed:

"Cultivation of Industrial fibre hemp (Cannabis sativa L.) in Iceland.

How can we produce high quality long fibre for use in textile applications?"

- What factors in cultivation have an impact on hemp fibre quality?
- What processing methods are necessary for producing high-quality hemp fibres?
- What are the overall effects of hemp cultivation on soil and the environment?

Industrial hemp is a broad term used to describe the varieties of Cannabis sativa L. Sativa that produce less than 0.3% tetrahydrocannabinol (THC) (0,2% approved in Iceland). The study will only assess papers on varieties of Cannabis Sativa, not varieties of the narcotic Cannabis Indica. The study deals with the steps of cultivating, harvesting, and processing the hemp fibre for spinning, not manufacturing fabric or the fashion industry. It focuses on hemp grown only for fibre yield, not for seed and flower harvest.

The value of the study lies in gaining a deeper understanding of the key factors to be considered when cultivating hemp for long fibre yield which is necessary in high quality textile production. It is hoped that the outcome of this thesis will offer insightful information for upcoming initiatives and future research in Iceland.

Limitations

The study's limitations are that it can be difficult to apply learnings from field trials from other countries to the Icelandic example. There are limited Icelandic studies available in this field, none that focus on fibres.

Disadvantages in this research is that, even when the secondary data resources are accurate, they may not be updated enough to accommodate recent timelines. The success of the research will depend, to a greater extent, on the credibility of the information available and the quality of the research already conducted.

Chapter 2

Literature Background

The framework of this thesis is long-fibre hemp cultivation in northern latitudes. Hemp is a plant with strong textile fibres, which give the textile long durability, and is considered a sustainable alternative to the textile industry's challenges. The production of textiles is one of the sectors that contribute the most to global pollution, and several recent research has investigated the possibility of using ecologically friendly fabrics to solve this problem (Duque Schumacher, Pequito, & Pazour, 2020).

The cultivation of hemp is also attracting increasing attention in Iceland for various industries (Hampfélagið, n.d.). Changing attitudes have generated an unprecedented demand for the cannabis plant and its products, resulting in the need for new scientific, technological, and agricultural research (Cherney & Small, 2016).

Hemp has many uses and potentials, from medicine and food to building materials and oil absorbents. It is applicable in a wide range of sectors, including the creative industries, with its potential for innovative solutions in design and architecture (Brownell, 2018).

This chapter will explore the history and main concepts of industrial hemp cultivation.

Hemp and sustainability

Climate change and environmental degradation are existential threat to the world. And there has been an increasing awareness of the need for sustainable development, which also benefits the environment and, not least, has a positive effect on the climate. One example is the United Nations Sustainable Development Goals (UN SDGs), which define areas for action that should be pursued by all countries. "Ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and forests" (UN, n.d.). The Sustainable Development Goals are:

Figure 1 Sustainable Development Goals (SDGs) (UN, n.d.).

The trend is an increased demand for products that utilise resources and can be produced with a circular life cycle (Pallesen, 2021).

According to the Department of Agriculture and rural development of the European Commission, hemp has a number of environmental benefits, as seen below.

- **Carbon storage**: one hectare of hemp sequesters 9 to 15 tonnes of CO_2, similar to the amount sequestered by a young forest, but it only takes five months to grow.
- **Breaking the cycle of diseases**: hemp helps to break the cycle of diseases when used in crop rotation. In addition, weeds are not able to grow due to the fast growth and shading capacity of hemp plants.
- **Soil erosion prevention**: dense leaves of hemp become a natural soil cover, reducing water loss and protecting against soil erosion. Hemp covers the ground just three weeks after germination.
- **Biodiversity**: flowering cycle usually occurs between July and September, coinciding with a lack of pollen production from other crops. Hemp produces large amounts of pollen. It also provides shelter for birds and hemp seeds are a food for animals.
- **Low or no use of pesticides**: hemp is susceptible to few pests because of the lack of natural predators, which means that the use of insecticides, herbicides, and fungicides can be avoided in most cases.

(Agriculture and rural development, n.d.).

Cultivating and harvesting hemp adds diversity to the soil and improves its health. The nutrients extracted during the plant's growth cycle return to the soil if the stalks are left on the field to ret. Furthermore, the weed suppression effect is improved when utilising crop rotation in hemp cultivation, where the possibility for weeds is reduced on the next harvest (Prade, 2011).

The whole hemp plant can be utilised in different products. It can be grown organically or with low input of chemicals and has a great yield potential. Hemp is a plant with strong textile fibres, which provides long textile durability and has the potential as a raw material to produce sustainable textiles (Pallesen, 2021).

The fashion and furniture industry is looking for alternatives to environmentally harmful raw materials and resource-consuming waste of clothes, i.e., greater sustainability throughout the value chain. However, despite the great interest in re-creating the old hemp industries, almost all textile hemp is produced in China using not very sustainable methods. A project in Denmark for sustainable textiles is working to control the biological reddening process using enzymes. The results of the project will be further worked on in a project named "Hemp4tex", which is to solve the identified challenges of producing Danish hemp for strong yarns and high-quality fabrics using new methods and technologies (Pallesen, 2021). This project will be interesting to follow up on for cultivators in Iceland interested in fibre crops.

The overall environmental impact of hemp cultivation is very low because hemp removes greenhouse gases from the atmosphere when cultivated, as most plants do in different degrees, using carbon dioxide for growing. Thus, hemp, as a crop balances the emissions from cultivation, harvest, and transport (Prade, 2011).

An example of this is the company "Hempflax". It is based in the Netherlands, with cultivation sites there and in Germany and Romania. The company separates, processes, and refines the cultivated hemp, providing environmentally friendly products to an array of industries. On their web page, they pride themselves in striving to be a carbon-neutral company. And because of the size of their hemp cultivation, they can keep a negative carbon dioxide balance. The company also focuses on developing techniques to fix this CO2 into construction materials and other finished products to prevent it from being released back into the air (Hempflax, n.d.).

History of hemp

Signs of hemp cultivation have been traced to about 8,000 years ago, from its origin in Central Asia. Archaeological evidence of Cannabis comprises items such as textiles, cordage, fibre, and seeds, and imprints of these materials made in pottery, as well as pseudoliths and phytoliths (McPartland & Hegman, 2018).

Cannabis seeds were recovered from a site associated with the Jōmon culture in Japan, dating to 8,000 cal BCE. In northern China, recovered seeds at a site associated with the

Yǎngsháo culture (5,000–3,000 BCE) pottery impressions of cord or textiles in Yǎngsháo pottery have been identified as hemp (McPartland & Hegman, 2018).

In Europe, evidence connects hemp with Bronze and Iron Age cultures. During the Bronze Age in the Yamnaya and Catacomb cultures in south-eastern Europe. Furthermore, in the Iron Age steppe culture, the Scythians likely introduced hemp cultivation to Celtic, Slavic and Finno-Ugric cultures. Cannabis was used for three commodities then - bast fibre (for cordage and textiles), seed (food, seed oil), and flowering tops (medicinal and psychoactive drugs) (McPartland & Hegman, 2018).

In Scandinavia, there is archaeological evidence, based mainly on the finds of pollen and seeds, that hemp (Cannabis sativa) was grown in Norway and Sweden. In Norway, there are finds from the inner Oslo Fjord area, about 350 BCE–450 CE. From Sweden, in Jämtland, Rödön parish, near Lake Storsjön, there are finds of hemp pollen from about 100–200 CE. From the Viking Age, 800–1,050 CE, there are more finds of hemp pollen and hemp seeds, for example, from the area Lake Mälaren, near Stockholm, and in the area Lake Storsjön, near Rödön (Skoglund, Nockert & Holst, 2013).

In Viking and early Middle Ages, plant textiles were mainly made from locally available raw materials. Several fabrics, including pieces of the famous Överhogdal Viking wall-hanging, which can be seen at Jamtli Museum in Östersund, are made with hemp (in some cases, hemp and flax are mixed), which indicates that hemp was important not only for coarse but also for fine textile production (Skoglund, Nockert & Holst, 2013).

The finds of hemp pollen, flax pollen and seeds do not prove that textile production took place. Only discoveries of retted fibres can do that. There are some early remains of plant fibre textiles from Sweden from around 400–500 CE, from Fullerö in the province Uppland, and from Augerum in Blekinge in the south (Skoglund, Nockert & Holst, 2013).

Plant remains, such as pollen, stems, seeds, and capsules of hemp, were also detected in several waterlogged pits at eight prehistoric sites in Denmark spanning from around 160-900 CE, which show evidence for the process of water retting of fibre plants during this early period. The number and location of the retting pits, in relation to the settlement area, indicate the scale and importance of textile fibre production (Andresen & Karg, 2011).

It is said that in the sixteenth century, hemp was so important for day-to-day lives for textile, paper, rope, and oil production that in England, as part of the legislation, King Henry VIII imposed penalties on farmers who failed to produce the crop (Mahapatra, 2018).

Evidence of hemp cultivation in Iceland has also been found. In 1670, Gísli Magnússon, a pioneer in agriculture, wrote a letter to his son where he talked about his cultivation experiments and mentioned that he grew hemp and flax, among other things, and that the plants were growing decently (Vilmundur Hansen, 2019).

By the time hemp was migrated to America by the colonists, it was a crucial industrial plant. In maritime countries, it was used for canvas and cordage production for naval applications (Muthu & Gartdetti, 2020).

Industrial hemp

Industrial hemp is a phrase that has been in use since the 1960s and mainly refers to cannabis cultivars that are farmed primarily for their seeds and fibre as well as for their by-products like oil, seed cake, and hurds (Johnson, 2019).

Today, many countries are taking a growing interest in cultivating this highly environmentally friendly crop. As mentioned earlier, hemp has high CO2 absorption capacities, and almost the whole plant can be used and transformed. According to numbers from the website Statista, the main cultivating countries in the world in 2017 were Canada with 55,000 hectares, China with 46,000 hectares, and in third place, France with 17,000 hectares of confirmed hemp cultivation (Vultaggio, 2019).

Hemp is grown across Europe, and hemp cultivation has increased by 75% in the EU from 19,970 hectares (ha) in 2015 to 34,960 ha in 2019. France is the largest producer, accounting for more than 70% of EU production, followed by the Netherlands (10%) and Austria (4%) (Agriculture and rural development, n.d.).

The European Industrial Hemp Association, often known as EIHA, is an organisation that looks out for the best interests of hemp manufacturing and processing businesses in the industrial sector. It was established in 2005. The association's membership is comprised mostly of farmers, processors, and manufacturers from all 25 member states of the European Union as well as 12 additional nations, including members from North America. The principal goal of the organisation is to keep an eye on the policies that the EU has in place regarding hemp and to offer the EU's decision-makers information that is accurate and trustworthy in a variety of domains of expertise. They are now keeping an eye on the following policies: the CAP reform, the regulation of hemp extracts and novel foods, the THC limitations in feed and food, the Life Cycle Assessment of hemp materials, the CO2 impacts, environmental issues, and cosmetics (EIHA, n.d.).

The fibre hemp industry in Europe is centred on so-called 'technical' hemp fibres, where hemp stems are chopped into short fragments at harvest; this is apt for non-woven fabrics, such as bulk applications of the production of paper, composites and building materials (Vandepitte et al., 2020).

The long hemp fibres cultivated in Europe are moved to China, where the largest processing plants are. For 6,000 years, they have not stopped the production of hemp, so their method is well established (Skoglund, 2021).

Today, Norway is the last industrialised country to still ban the cultivation and research of industrial hemp. The hemp used to be fundamental to Norwegian shipping in the form of ropes and sails, and at one point, Norwegian farmers were required to grow hemp. International producers can grow it and sell food and textile products in Norwegian shops. But still, farmers are not allowed to grow industrial hemp. The reason for the ban is that they chose not to differentiate between different varieties of the cannabis plant in the legislation but define all types as a drug (Shephard, 2022).

Taxonomy

The Integrated Taxonomic Information System (ITIS) classifies Cannabis as one species with two subspecies (ITIS, 2019). Cannabis belongs to the order Rosales, family Cannabaceae, genus Cannabis, species – C. Sativa L., with both industrial hemp C. Sativa L. var. Sativa and narcotic V. Sativa L. var. indica.

Cannabis is divided into several varieties according to its genetic plasticity. The division can be made using different criteria such as origin, length of the vegetation period and content of cannabinoids (THC and CBD). This allows Cannabis to adapt to changing geographical and climate conditions (Strzelczyk, Lochynska & Chudy, 2021). Thanks to this adaptability to various climate conditions and soil structures, the plant spread worldwide (McPartland & Hegman, 2018).

Cannabis sativa is an herbaceous, wind-pollinated annual (Johnson, 2019). Among divergent species of the hemp plant, Cannabis sativa is the one which is used for industrial applications, including fibre production (Muthu & Gartdetti, 2020). Cannabis sativa or industrial hemp can be referred to as hemp and is distinguished from Cannabis indica, containing less than 0.2% of the currently drug-classified cannabinoid THC (Vogel, 2017).

Cannabinoids

Cannabinoids refer to the unique chemical compounds produced in the Cannabis plant, which are known to exhibit a range of psychological and physiological effects. Industrial hemp and marijuana are both varieties of Cannabis and can be distinguished by their chemical and genetic compositions. Genomic research in Canada supports the notion that over thousands of years of cultivation, cannabis farmers have “selectively bred Cannabis sativa into two distinct strains - one for fibre and seed, and one for medicine”. Hemp generally has high levels of CBD to THC, and this metric can be used to differentiate industrial hemp from other cannabis varieties. THC and CBD are among the subclasses of cannabinoids in Cannabis sativa. While some cannabinoids are psychoactive, others, such as CBD, are not considered psychoactive (Johnson, 2019). Below is a list of the subclasses of Cannabinoids for reference.

Cannabinoids

More than 480 natural components are found within the *Cannabis sativa* plant, of which 66 are classified as cannabinoids. Cannabinoids are separated into the following subclasses.

Delta-9 tetrahydrocannabinol (delta-9 THC)	Number of known variants: 9
Delta-8 tetrahydrocannabinol (delta-8 THC)	Number of known variants: 2
Cannabigerol (CBG)	Number of known variants: 6
Cannabichromene (CBC)	Number of known variants: 5
Cannabidiol (CBD)	Number of known variants: 7
Cannabinol (CBN)	Number of known variants: 7
Cannabinodiol (CBND or CBDL)	Number of known variants: 2
Cannabicyclol (CBL)	Number of known variants: 3
Cannabielsoin (CBE)	Number of known variants: 5
Cannabitriol (CBT)	Number of known variants: 9
Other miscellaneous types of cannabinoids	Number of known variants: 11

Source: J. E. Joy et al., eds., *Marijuana and Medicine: Assessing the Science Base*, Institute of Medicine, 1999; and University of Washington, Alcohol and Drug Abuse Institute, "Cannabinoids," June 2013.

Figure 2 Defining Hemp: A Fact Sheet. Congressional Research Service (Johnson, 2019).

Different sexes of the plant

Because hemp is a dioecious plant, it produces both sexes. Individual plants develop female or male reproductive organs. Hemp plants can also be hermaphrodites, with the female and male flowers located on the same plant. Then the hemp plant is Monoecious. Female hemp plants produce bracts, whereas male hemp plants produce little pollen sacs at the nodes of their stems (see figure 2). The female plants' bracts, which gather the pollen discharged by the male, have a wispy, hair-like stigma that grows from them. Hermaphrodite hemp plants can successfully pollinate female plants as well. They can be bred so, or it can be a result of poor seed genetics or stress. Common triggers for the seed to grow into hermaphrodites can be nutrient deficiencies, plant damage from bad weather, or disease. It can also happen when plants are grown inside, from inconsistent lighting or high temperatures. Male and female plants do not flower or age simultaneously. The male plants usually flower earlier and age earlier (Amaducci et al., 2008; Salentijn et al., 2015; Small, 2015).

Figure 3 Hemp plant. A flowering male and B seed-bearing female plant, actual size; 1 male flower, enlarged detail; 2 and 3 pollen sac of same from various angles; 4 pollen grain of same; 5 female flower with cover petal; 6 female flower, cover petal removed; 7 female fruit cluster, longitudinal section; 8 fruit with cover petal; 9 same without cover petal; 10 same; 11 same in cross-section; 12 same in longitudinal section; 13 seed without hull. (Franz Eugen Köhler's Medizinal-Pflantzen. Published and copyrighted by Gera-Untermhaus, FE Köhler in 1887 (1883–1914).) (Cannabis sativa Koehler drawing. 2007).

Regular seeds generate both male and female plants at about a 50/50 ratio, and hemp farmers need to be able to identify the sex of their hemp plants in the field (Johnson, 2019).

When the hemp plant reaches the pre-flower state, at around six weeks of growth, farmers should be able to accurately sex their plants by looking closely at the nodes of the plants' branches (High Grade Hemp Seed, 2020).

Telling which sex a hemp seed will grow into is also possible through genetic testing. A DNA test can be performed when a seedling is a few weeks along. However, this is an expensive solution (Johnson, 2019).

If you want to harvest resin from your hemp crop, which can be processed for its CBD or CBG, you will need a female crop to harvest as much as possible. The resin crop resides in the female plants' flowers. Here farmers must remove their male plants and hermaphrodites to prevent them from pollinating the female plants. Removing the male plant is time-consuming and labour-intensive work for farmers and can eliminate massive quantities of the plant population to preserve the quality of the female plants (Johnson, 2019).

If the goal is to produce hemp fibre, the male hemp plant is used. Male plants have finer fibre which is an advantage for application in textile manufacture. The plant is discouraged from flowering, forcing it to grow taller with less branching (Amaducci et al., 2008; Salentijn et al., 2015; Small, 2015).

Preserving the genetic composition of each variety requires attention to prevent cross-pollination. Cannabis plants are open (e.g., wind and insect-pollinated). And cross-pollination is possible if the crops are grown in proximity which would result in unwanted characteristics (Johnson, 2019).

Plant parts

As mentioned, the Cannabis plant is cultivated as a fibre, flower, and seed crop, depending on the intended use (Johnson, 2019).

Cannabis develops a laterally branched taproot. The root system provides another example of a flexible response in relation to environmental circumstances. One study from 1970 noted that “wild hemp in sandy soils in Illinois seemed able to tolerate dry conditions because the roots penetrated to deep water sources” (Small, 2015).

Hemp consists of two main types of fibres: bast (long outer fibres) and hurd (inner core fibres). Each type of fibre has its functions in different productions (Pallesen, 2016).

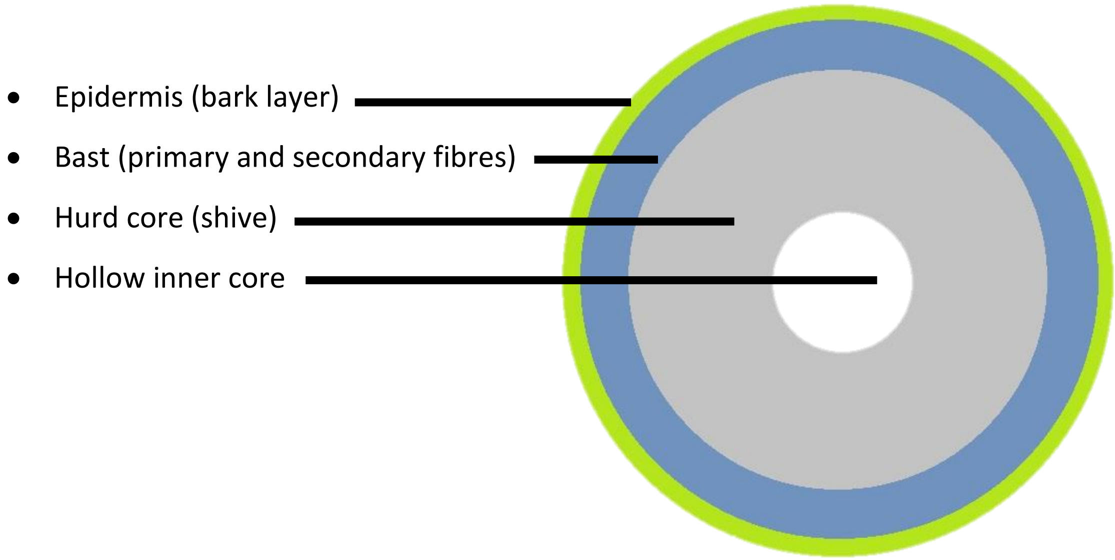

Figure 4 Illustration of hemp stalk cross-section

Seeds

After harvest, the seeds are dried, dehulled and pressed. The oil from the pressed seeds can be used for consumption and processed into beauty products and as fuel. The nutritious seeds are valuable for human and animal diets and are a good source of protein and several Omega-6 and -3 essential fatty acids (Schluttenhofer & Yuan, 2017).

Leaves and flowers

It is possible to make use of both the leaves and the flowers to manufacture medicines, dietary supplements, and essential oil. The hemp plants produce over 100 known cannabinoids, of which the molecules that occur in the most significant proportion are CBD. Although the pharmaceutical use of hemp has been known for more than 5,000 years, new bioactive compounds are still being discovered. So, the potential of this species is still inexhaustible and unfathomable. Currently, clinical trials are investigating CBD for many medical conditions (Schluttenhofer & Yuan, 2017).

Hurd (core fibres)

The stalk from which the fibres are extracted is made up of core fibres and bast fibres. The woody core's inner fibres, the hurd, make up most of the plant's weight. Most hurd goes into animal bedding (Schluttenhofer & Yuan, 2017).

Bast fibres

The bast fibres are the fibres that lie around the hurd as a coat (Holstmark, 2006). These are the fibres that are most interesting for this thesis as these are the ones that can be used for high-quality long-fibre yarns. It is therefore essential to have a good understanding of the development of both fibres (hurd and bast) to preserve the long fibre quality. Bast fibres are primarily used to make high-quality papers and textiles like canvas and rope (Schluttenhofer & Yuan, 2017).

The cell wall of the bast fibre contains several essential elements, including pectin and lignin. The pectin forms part of the cell wall, and lignin fills the space between the pectin and the other components of the cell wall, such as cellulose and hemicellulose, which are essential for growth. However, these are undesirable in textile fibre, making it more challenging to process because they make the textile thread stiffer and coarse (Kramer, 2017). The proportion and quality of cellulose is the most important factor in plant fibres. In young plants, the fibres are silky, thin, and very flexible but weak and of uneven quality (Bengtsson, 2009).

The processing of hemp bast fibres creates by-products, such as the shorter fibres that can be used in the manufacturing of animal bedding. Recent technological advances have expanded the use of hemp fibre and hurd to include the production of carbon nanosheets, plastics, 3D-printer filaments, oil-absorbent materials, and construction concrete (Schluttenhofer & Yuan, 2017).

The maturation of the fibres varies with the harvest time, so harvest time should be chosen according to the required fibre quality (Strzelczyk, Lochynska & Chudy, 2021).

Secondary fibres

The secondary fibres comprise 10–30% of the base part and are shorter (approximately 2 mm). Because they have a higher content of lignin, they lower the quality of the primary fibres and make harvesting and processing more difficult. When the internode growing stops, secondary growing starts, and the proportion of the primary fibres decreases. A single fibre matures from outside to inside, developing secondary wall layers (Strzelczyk, Lochynska & Chudy, 2021).

Primary fibres

The primary fibres are the ones that are used for textile production. They make up 70–90% of the base tissue and have a high proportion of cellulose (50–80%) and a low content of lignin (2–7%). The individual cells are between 5–55 mm long, and it is 12 of these fibres that become the high-value raw material for textiles (Bengtsson, 2009; Pallesen, 2016).

The count of the primary fibres does not change during the plant's growing period; however, the fibre length increases with the increasing distance between internodes (Strzelczyk, Lochynska & Chudy, 2021).

The general properties of hemp for textile purposes are the long continuous fibres up to one meter with a high tensile strength of 53-62 cN / tex (cotton 15-55 cN / tex). It has higher moisture absorption than cotton – meaning clothing breathes, is heat conducting, creates smooth fibres and yarns, and has water-repellent properties. The softness versus stiffness depends on the degree of the retting processing (Pallesen, 2021).

Cultivation and harvesting

Ideally, hemp is grown in semi-humid conditions, in well-drained soil. The best yields are attained when hemp is grown with inputs (fertilisers and herbicides) the same as corn and wheat. The plants can survive in conditions around 0°C., and seedlings can tolerate some frost in the spring, though it is best to seed hemp after the danger of a killing frost has passed. After the first stages of growth (i.e., six weeks), it is drought-resistant, but poor conditions can impact the final stem dry matter yield (Duque Schumacher, Pequito, & Pazour, 2020).

Moreover, heavy rainfall can destroy the crop if the soil is too wet for a longer time (Kaiser, Cassady, & Ernst, 2015).

Hemp is usually seeded in a depth of 3-4 cm and in rows at 12-25 cm intervals, but the number of seeds varies greatly depending on what is to be processed and can be in the range of 20 - 120 kg ha. (Þóroddur Sveinsson, 2009). Because of a better root system, hemp is resistant to weeds when planted densely. High plant density is used when growing for fibre (Kaiser, Cassady, & Ernst, 2015).

Hemp is also a fast-growing plant (Kaiser, Cassady, & Ernst, 2015), though not in northern regions such as Iceland (Þóroddur Sveinsson, 2009), that can be cultivated in diverse soil conditions in most environments, and therefore viable conditions are available in large parts of the world (Kaiser, Cassady, & Ernst, 2015).

In Scandinavia, hemp has been commercially grown at latitudes as far north as 65°N and 66°N in the past. The northern limit for hemp production in Europe is currently at 64 to 65°N. In 2003 and 2004, a study was made in Finland to see how different varieties of fibre hemp respond to low temperatures at northern latitudes and day lengths. It showed that; *"*Hemp is sensitive to temperature and day length with a quantitative short-day requirement." However, with optimal growing conditions, late varieties could benefit from long days for fibre production (Pahkala, Pahkala & Syrjälä, 2008), which is of interest for fibre cultivation in Iceland.

In comparison, for seeds to grow into full bloom, it takes about 120 days under the right conditions, but when growing for high-quality fibre, harvesting time is about 90 days (Kaiser, Cassady, & Ernst, 2015), which can be a benefit when growing in Iceland where the growing season is shorter. However, in Iceland, the summers are also cool, and it takes longer for plants to mature.

Processing of fibre hemp

After the hemp has been harvested, the plant must undergo several processing stages before the long bast fibres can be spun into yarn (Zhang et al., 2008). High-quality yarn spinning requires longitudinal processing lines that keep the long, primary fibre bundles intact and aligned during harvesting and eventual fibre extraction (Vandepitte et al., 2020).

The steps required for hemp processing for textiles are:

- Retting
- Decortication / scutching and softening
- Softening
- Combing / hackling
- Spinning

Retting

In the retting process used to extract the bast fibres from the stem, the outside woody covering is rotted away using natural enzymes, which reveal the inner fibres. There have traditionally been two retting methods: Dew retting and water retting. Both are carried out by pectic enzymes secreted by indigenous microflora (Zhang et al., 2008).

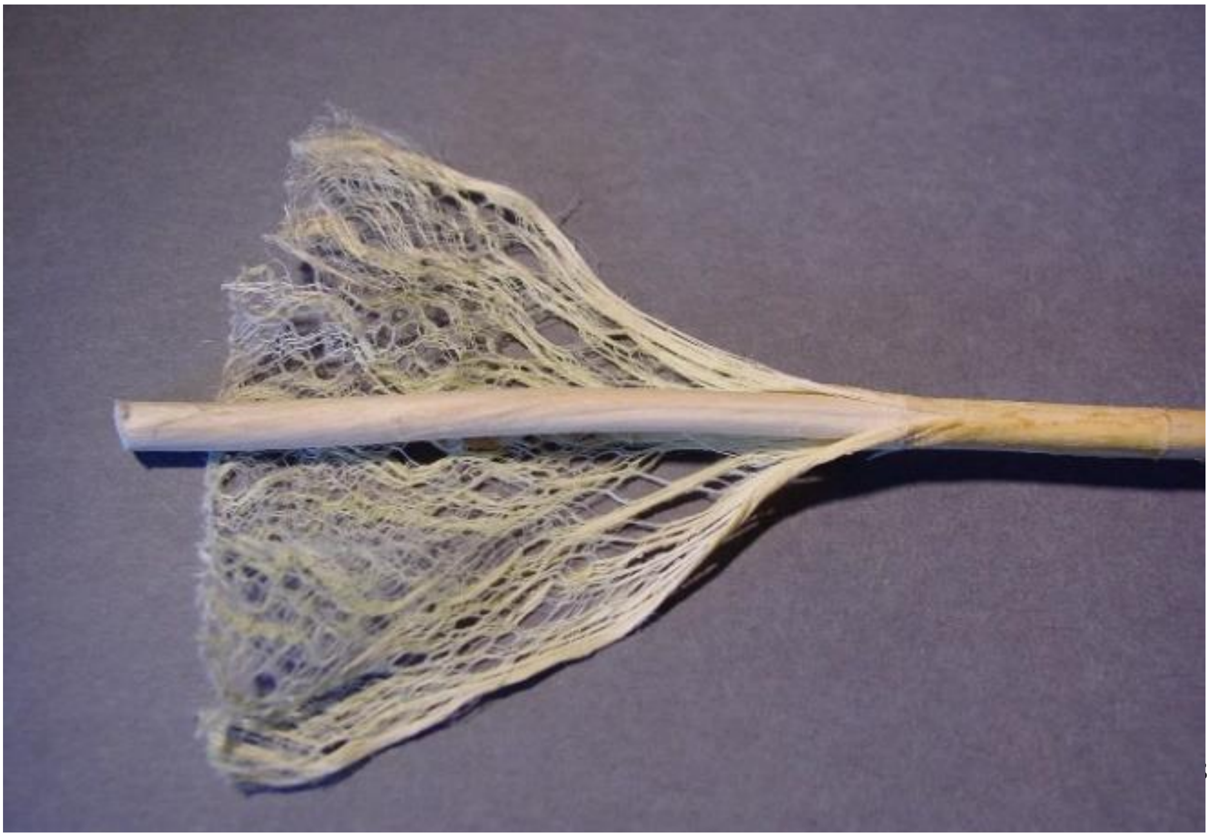

Figure 5 Hemp stem subjected to retting (decomposition of the softer tissues). The fibre in the top portion has been separated from the woody core. Photo by Natrij, released into the public domain (Natrij, 2011).

Decortication & softening

In the process of Decortication, a separation method is used, where the stems are broken through the passing mechanical fluted roller that crushes and breaks it in a sequence of a squeeze, breaks and scutching process. The fibre is separated from the woody core when passing through the last scutching rotary blades. The machine is called a decorticator and comes in commercial and smaller portable sizes for minor operations. It can also be done manually by cutting the leaves, breaking the stems, and beating the broken stems with a stick. The separated fibres are then passed through a hemp softener roller, making them suppler (Mahapatra, 2018).

Hackling

A hackling machine combs out the last of the short, tangled fibres and then aligns the long fibres into a continuous sliver for the spinning process (Mahapatra, 2018).

Spinning

The fibres can now be either dry or wet spun. Dry spinning is cheaper and produces a different yarn appearance than wet spinning. As with flax fibres, the best quality yarn is obtained by wet spinning, which softens the pectin, and produces a more delicate, softer yarn. This is done by passing the fibres through hot water before they are spun, creating a count greater than 12 Nm (Mahapatra, 2018).

Textile fibre quality parameters

Hemp fibre has unique properties. It is among the most durable natural fibres, and by nature, it has long fibres that can be spun into very strong yarns without going through a chemical process (Mahapatra, 2018).

Long hemp fibres are not yet manufactured commercially into fine, thin yarns. One of the difficulties in utilising hemp for textile uses is the procedure of processing and spinning the fibres into yarn without the yarn breaking. The most popular hemp textile on the market today is made from cottonized hemp fibres that are created chemically. A cottonization is a thermal/chemical procedure that "shreds" the lengthy hemp fibres into a few cm by removing all pectin and lignin before spinning them like cotton. The term comes from their resemblance to cotton fibres; they may be spun using techniques designed for cotton-like hemp and are frequently combined with cotton or wool. In contrast to long-fibre hemp, which has incredible strength and is only torn apart in long fibres, the thread in the fabric breaks readily and separates into short fibres when it is tugged (Mahapatra, 2018).

There are different requirements for yarns depending on the different fields in the textile industry. For use in upholstery fabric, strong hemp fibres are essential. Upholstery fabrics must withstand many years of wear and still look nice. It requires high-quality fabric, and according to a report made in Denmark on sustainable textiles, the hemp fibres' unique strength makes them extremely interesting for textile production. Below are the requirement specifications for yarn and fabric from the Danish company Kvadrat. The company was established in 1968 and has had many years of experience producing quality contemporary textiles and textile-related products worldwide (Kvadrat, n.d.).

Requirements Specifications

• Mechanical strength, such as tensile strength, MPa or N, as well as tensile strength (elongation) in%.

Abrasion resistance - Strong fibres that can pass the so-called Martindale test (abrasion resistance test for upholstery fabrics) with up to 45,000 rpm (Martindale) on woven fabrics

Pilling - Fabrics with little tendency to pilling (fluffed with visible small fibrils), Visual rating grade 1-5 (1 is worst). We want 3-4

• Lightfastness - Visual rating grade 1-8 (1 is worst). I wanted 5-6

Rubbing authenticity - Visual rating grade 1-5 (1 is worst). I wanted 3-5

• Yarn qualities (low count) from coarse yarn qualities to finer qualities, of which the finest

can typically be used for knitting

• Shrinkage - max 1 per cent (may vary) for standard washes

• Seam slip - can hold the seam

• Fire properties - depending on the material and use

• Error: max one per. 10 meters

Figure 6 Requirements Specifications (Pallesen, 2021).

For the clothing industry, there are different requirement specifications for processing. According to a report on Sustainable fabrics, “The great focus and expectation for hemp textiles for fashion clothing relate not least to the sustainability aspect, where hemp can be grown without the use of pesticides and fertilisers and irrigation in as opposed to cotton, which is very stressful in terms of pesticide use and irrigation”. Other aspects are that the clothing can last for a long time. There are challenges with hemp fabric as it can change shape after repeated washing, and as is with Linen, it curls more easily (Pallesen, 2021).

Requirements specifications for fabric for the clothing industry.

• Strong fibres that can withstand many years of use of the clothes (and thus high sustainability)

• Suitable yarn qualities for diverse designs, including outerwear

  o Nm 14/1 for weave

  o Nm 24/1 for weave & knit

  o Nm 39/1 for knit

  o for knitwear (ex., t-shirts), the measure is a yarn between Nm 42/1 and Nm 48/1

• Performance requirements: that the clothes do not curl, do not fluff and do not shrink

• Require that the clothes can withstand up to 40 washes

Figure 7 Requirements specifications for fabric for the clothing industry (Pallesen, 2021).

Hemp in Iceland

In Iceland, experiments with hemp cultivation can be traced back to the 17th century in the South. Whereas mentioned above, Gísli Magnússon (Vísi-Gísli), magistrate and pioneer in agriculture, tried a variety of valuable plants at Hlíðarendi in Fljótshlíð in the second half of the 17th century, including hemp. It must be considered very probable that hemp cultivation has been tested in Iceland more than once throughout the times (Þóroddur Sveinsson, 2009), just like flax (Linum usitatissimum) cultivation was in the settlement times (Vilmundur Hansen, 2019).

However, it has been a misunderstanding, though a common belief that the company Hampiðjan, who has been processing Manila hemp since 1934 for use in the fishing industry (Iðnaðarmál, 1955), was hemp (Cannabis Sativa). Incorrectly, the term "hemp" is frequently used in a general sense to refer to fibres derived from a variety of plants, e.g., Manila "Hemp", Sisal "Hemp", Sunn "Hemp", etc. However, these are, in fact, two different species. The Manila Hemp plant (Musa textilis) of the family Musaceae, which is in the banana family, also known as abacá in its native Philippine Islands, has economically significant fibres that are strong and durable. But these are extracted from the leaves that converge at the base to form a false stem. The so-called bast fibres, such as hemp, jute and flax, are derived from the stem (Raven, Eichhorn & Evert, 2013).

In 1974, legislation banned the cultivation and import of hemp in Iceland due to its relation to the narcotic V. Sativa L. var. indica. This legislation was repealed in April 2020. The new article permits the import, handling, and storage of seeds for the cultivation of industrial hemp, so long as the amount of THC in the seeds and the plants they produce does not exceed 0.2%. The imports of the seeds are subject to review by the Icelandic Food Agency. Kjartan Hákonarson, head of communications at the Icelandic Medicines Agency, said, "The goal of the amendment is to allow farmers to cultivate strains of industrial hemp found in the EU plant variety database in Iceland" (Hempindustrydaily, 2020).

According to Hampfélag Íslands, founded in 2019, the interest in growing industrial hemp in this country for use in various industries is growing. For example, in building materials, packaging, food and food supplements. Industrial hemp can replace substances that threaten the environment, such as plastic (Hampfélagið, n.d.).

Also, in the design and textile area in Iceland, the interest is growing, and students are introduced to hemp as a new source of innovative products in school. Students in Hallormsstaðskóli have been attending a workshop where industrial hemp was the key raw material. They researched the potential uses of hemp, in various versions, with the common thread in the studies being sustainability. The students used hemp in cooking, textile processing and more. The schoolmaster at Hallormsstaðskóli expressed that "this skill like working with hemp, is something that definitely needs to be dusted off and revived" (Halla Ólafsdóttir, 2021).

In 2008, an experiment was done in Möðruvellir, where five different recognised industrial hemp varieties were sown in a weed-free grain field at Fjárhústún 8 in May 2008. The layout was a traditional block experiment in three repetitions. The Hemp was harvested on 22 September, plant height and yield were measured, and samples were taken for chemical analysis. The conclusion of this experiment showed that hemp takes a long time to start in the spring, but as the growing season progresses, it can reach a high growth rate if conditions allow. It can produce a decent dry matter crop but does not reach full maturity and does not form seeds in Icelandic field conditions. The dry matter content of hemp is relatively low, which increases the cost of all processing. And due to lacking maturity and thus low dry matter content and high growth (> 2m), it is sensitive to wind in autumn and can then collapse or break (Þóroddur Sveinsson, 2009).

On the farm Gautavík in Berufjörður, a couple started experimental cultivation of three varieties of industrial hemp, 'Felina', 'Futura' and 'Finola' on almost one hectare in the summer of 2019. One of them had taken part in another such experiment in 2013. The purpose of the crop, outdoors and indoors, was primarily to raise awareness of the usefulness of hemp and its potential to greatly increase sustainability in many areas, through the cultivation itself and by experimenting with producing different products from it, such as fibreboard, concrete, paper, ointment, tea, and spices. The information was quickly communicated through social media, presentations, conferences, and meetings. The interest became so great that inquiries flooded them, and many people went to Gautavík to see the cultivation and production, including ministers. The project was funded by both the Ministry of Industry and Innovation and the East Iceland Development Fund (Oddur Freyr Þorsteinsson, 2019).

At Gautavík, they are now experimenting with batteries made from hemp. Pálmi Einarsson, who is also an industrial designer, explains that “it is possible to take the fibres, carbonise them and then we get a very alka-fibre-substance. Just like alkaline batteries” (Rúnar Snær Reynisson, 2021).

Hemp casting houses are also under construction in Iceland, and one of them is being made for the first time, entirely from hemp grown in Iceland. Biobuilding, or Lífhúsið, an experimental project by the Lúdika architectural studio, received a grant from the Design Fund to design a 15 square meter small house made of hemp concrete. The house is planned to be built this spring in Grímsnes to see how well it can withstand Icelandic conditions. One of the owners of the studio behind the project says that the purpose of hemp is to be sustainable.

> The main advantage of hemp concrete is that it is environmentally friendly. The hemp does not just bind carbon dioxide while it grows because the hemp concrete continues to absorb it for decades to come. Hemp concrete also breathes and is insulating and does not burn or mould. (Bergsteinn Sigurðsson, 2022)

She does not think that the wet and windy Icelandic environment is a problem and elaborates that *"The plant is of such a nature that it absorbs water and can release it quickly. It is almost made for these conditions, and we hope to be able to prove it with the house*" (Bergsteinn Sigurðsson, 2022).

In 2021 a group of 3 people received funding for the project: Retting of Icelandic hemp and design of processing equipment. The aim of the project is to design a standard processing process for retting hemp and to develop equipment for water retting, with the goal to maximize the quality of the fibre, with the least possible cost. The hemp fibres from the project will then be used in textile production (Hönnunarmiðstöð, 2021). The experiment is ongoing, and it will be very interesting to see the outcome. I did contact one of the partners, but the project was not far enough in the process for them to elaborate on the experiment.

A growing number of farmers and hobby cultivators were trying out this new crop, and more than a hundred individuals were cultivating it all around Iceland in 2021 (Hamphræktendur og markaðstorg, 2021).

The author of this thesis also tried out cultivation of Hemp this summer on a small plot in south Iceland. July was an unusually cold month in Iceland this year (Ari Páll Karlsson, 2022), and it took a very long time for the hemp to grow, and the plants were small. After harvest the stalks, leaves and flowers were dried, for later processing. The stalks will be retted and processed into yarn later. Flax was also cultivated in the garden in Reykjavik and did very well, growing to about 1 meter. The flax was water retted in a covered water basin in the garden, partially changing the water every other day, and was retted successfully over 7 days, despite of the cold weather. It was then laid out on the ground to dry and is now ready for the braking and combing process before it will be spun into yarn.

Flax – a similar bast fibre plant

Cultivated flax, often known as common flax, is a member of the Linaceae family, which consists of 13 genera and 300 species. Linum usitatissimum L. is the scientific name for this species. The Mediterranean and Southwest Asia are the two regions where the plant was first discovered. It is an annual plant with a straight, herbaceous stem that branches out in a cymose way above the main stem. There are two types of L. usitatissimum that are grown. The linseed type is grown for the oil that is extracted from the seeds. It is a short plant with many secondary branches. The flax type is grown for the fibre extracted from the stem (The Convention on Biological Diversity, 2016).

To grow flax, you do not need much fertiliser or pesticide. The plant will attain a height of 10–15 centimetres eight weeks after it has been seeded, and it will grow several centimetres each day under conditions that are favourable for its growth, reaching 70–80 centimetres after fifteen days. A flax stalk can be anywhere from 0.8 to 1.2 meters in height and has a diameter of between 4 and 5 millimetres (The Convention on Biological Diversity, 2016).

Flax is an annual plant that reproduces by seeds. Flax is a highly self-pollinating species due to the form of its flowers and the "sticky pollen" that they produce, which is difficult for insects to transport to other plants. It only takes the pollen a few hours to lose its viability. As the flower opens, the anthers come together and make a cap over the stigma (The Convention on Biological Diversity, 2016).

Chapter 3

Materials and methods

Literature review with a systematic approach

The data presented in this chapter was obtained from a series of scientific papers. In order to create less bias, a systematic literature review was conducted.

In the pursuit of new research, electronic databases were used, which seemed sufficient, as most articles can be retrieved online these days. Mainly original research and literature reviews we collected.

After writing a list of keywords reflecting the research question, a Boolean search[2] was used, which allows the combination of five different elements to perform a search and utilises a search engine to its fullest potential.

After a few try-outs and adjustments, the keywords utilised were:

Cannabis sativa – industrial hemp – hemp varieties – long fibre – fibre yield – field trial – fibre quality - textile

The databases searched were Science Direct/Elsevier, google scholar, and Leitir.is. (See results at the end of the thesis).

Several field trials and research articles have been conducted in the past decades, focusing on the influence of agronomic factors on the yield and quality of hemp fibre. The search performed provided 208 articles, from which 22 journal articles were initially chosen. After reading the full articles, that number went down to 16 articles of relevance for this thesis. After reading the literature, six topics were identified that were most interesting for answering the research question in this thesis. The topics identified were:

- Photoperiod and cultivars
- Soil preparation
- Plant density

[2] AND, OR, NOT, quotation marks, and parentheses.

- Harvest parameters: Harvest time and quality of hemp grown for fibre
- Retting and processing
- Hemp as a sustainable crop

An addition of two other chapters was added to the result chapter. This was applied after writing the section to get a better perspective of the situation and to be better able to answer the research question that was set out in the beginning. This was justified because of the lack of scientific papers from and about Iceland and Scandinavia. Information was collected from a report from the Danish Environment Agency, written by Bodil Engberg Pallesen, whom I had seen cited in several papers, and who is one of the key speakers for hemp innovation in Denmark. Information from Iceland was collected from reports from Icelandic news sites, local newspapers, and sites related to farming in Iceland. The added topics were:

- Flax in Iceland: A learning curve
- A Danish example

Results

Photoperiod and cultivars

Photoperiod is an important controlling factor for the flowering of numerous plant species, and for hemp phenology, photoperiod is a particularly crucial factor. Hemp has a quantitative short-day requirement, but high yields of suitable quality fibres are possible throughout Europe, even under unfavourable daylength conditions (Sankari & Mela, 1998; Amaducci et al., 2015; Struik et al., 2000).

Genotype selection is also of immense importance. Based on the photoperiod sensitivity of the selected variety, achieving a specific yield in each given environment is possible. There is a significant variation in fibre content among genotypes (Amaducci et al., 2015), and cultivars should be chosen for their specific end application and maturity class (Amaducci, 2008; Amaducci et al., 2015; Struik et al., 2000).

According to research on the phenological development and stem growth of hemp in relation to stem production, accessions of the plant acclimated to low latitudes show delayed blooming and seed maturity when cultivated at higher latitudes. Since they devote less dry matter to the reproductive system, late-flowering hemp cultivars would consequently be preferred for the production of fibre (Sankari & Mela, 1998; Amaducci et al., 2015). Due to the more extended vegetative phase and the fact that fibre synthesis is completed already one month before maturation, a larger stem yield can be obtained (Salentijn et al., 2015).

Amaducci et al. (2015), came to the same conclusion but noted that Inadequate weather conditions for stem drying or uniform retting might coincide with late harvests.

The male plants have superior fibre quality in traditional dioecious hemp varieties (Amaducci et al., 2015). Additionally, it is well acknowledged that dioecious hemp types generate more fibre than monoecious hemp. Still, monoecious cultivars, which are more adapted to the production of both fibre and seeds (dual-purpose crop), have continued to be the focus of current breeding (Amaducci et al., 2015).

However, among some researchers, it is said that the northern monoecious cultivars appear to function better under the prevalent colder, wetter circumstances because they can adapt to the longer growing days before the onset of flowering, according to trials comparing dioecious varieties to monoecious kinds. To address the demands for later-maturing cultivars in Europe's northern latitudes, breeding efforts must be refocused. For example, the monoecious cultivar Beniko has delayed or decreased lignification, which is a significant and advantageous trait, particularly for the wetter and more unpredictable climates of northern Europe. When cutting is put off owing to bad weather, fibre yields are not negatively impacted right away (Bennett, Snell & Wright, 2006).

According to research by Sankari (2000), the earliest developing monoecious cvs. Uso 31, Bialobrzeskie, and Beniko were suggested while comparing cultivar USO 11 to 13 different fibre hemp cultivars in Finland at latitude 60°497 N. Cultivars Uso 31 and Beniko are now on the EU's list of fibre hemp cultivars. The dioecious cultivars in the experiment showed superior or equal qualities to cv. Uso 11 for the majority of the evaluated plant attributes, but they do not grow quickly enough to generate seeds, and the EU's current requirement for hemp subsidies is substantial seed production prior to harvest (Sankari, 2000).

Amaducci et al. (2015), also suggest that the selection of genotypes that are easier to decorticate provides an advantage in terms of fibre quality and a reduction of costs related to fibre extraction. It is a striking feature for this crop how hemp-based products are increasingly being diversified and developed on industry-specific goals, and it means that breeding cultivars for specific end-uses will become critical for the industry (Salentijn et al., 2015).

Soil preparation

According to the research, one of the main agronomic impacts on industrial hemp is soil preparation (Struik et al., 2000; Amaducci et al., 2015).

Springtime seedbed preparation is suggested after autumn or winter ploughing (at a depth of 30 to 40 cm) (Amaducci et al., 2015; Struik et al., 2000). Furthermore, that fertilizer (P and K or organic matter) is administered as a spread treatment prior to final seedbed preparation in the spring. N should then be applied at the same time as or right before sowing (Amaducci et al., 2015). Nitrogen fertilization should be decided depending on soil fertility. The yield response of supplementary nitrogen to hemp was minimal in rich soils (Prade et al., 2011; Struik et al., 2000), while significant yield increases were recorded under nitrogen-limiting circumstances (Struik et al., 2000).

Requirements for soil are a pH between 6.0 and 7.5, good depth, capillary and aeration richness, nutrient richness, and good water holding (Amaducci et al., 2015).

Studies have shown that hemp needs 500–700 mm of accessible moisture for the best performance of yield and that during the vegetative development stage, 250–300 mm of moisture should be available (Amaducci et al., 2015).

Hemp is less susceptible to potassium (K) and phosphorus (P) fertilization. Hemp has a lower K demand than other crops, with a proposed yearly requirement of 65 kg ha 1. More K is absorbed by late-maturing cultivars than by early ones, with the majority of K adsorbed (70–75%) concentrated in the stems (Amaducci et al., 2015). Though little research has been done on how P affects hemp production, there have been reports that P fertilization has an insignificant impact on stem yield (Amaducci et al., 2015).

Plant density

With sowing densities ranging from 50 to 750 plants m2, fibre production showed the greatest diversity in ideal density for cultivation. Higher rates have been advised for textile destinations of 150-350 plants m2, for the stalks need to grow tall and slim, and lower rates for non-textile destinations, such as 90 plants m2 for paper pulp. Dioecious types for textile use were historically grown in Italy with a goal of 90–100 plants per square meter. In China, plant densities of 120–150 plants per square meter were found to enhance stem, fibre, and bast output (Amaducci et al., 2015).

For two reasons, hemp is typically seeded at a high sowing rate: first, to achieve effective weed control through early canopy closure, and second, to encourage a final denser, shorter crop with thinner stems, which will maximise the yield and quality of the fibre produced (Struik et al., 2000; Bennett, Snell, & Wright, 2006).

The time between emergence and canopy closure is faster at higher plant densities than at lower densities. Flowering is delayed because more nutrients are allocated to the stem and less to the inflorescence and leaves. Due to the fact that SLA (Specific Leaf Area) rises with plant density, dry matter invested in leaves is used more effectively. Because of the increase in bark content, stem quality is increased (Van der Werf, Wijlhuizen, & de Schutter, 1995).

Particularly when hemp is grown for its long fibres, stem height and stem diameter are important crop factors that interact with the harvesting technique and mechanical processing (Amaducci et al., 2015).

Shortly after emergence, plants cultivated in high densities are encouraged by light competition to elongate, creating longer and thinner internodes. This is when plant density begins to affect stem biometrics. At the end of the vegetative phase, plants growing at high density are shorter, thinner, and have fewer nodes because competition after this initial phase inhibits stem development and internode emission (Amaducci et al., 2015).

Along with stem biometry, plant density influences fibre content and fineness, and it is generally believed that higher planting densities are associated with larger yields of fibres that are finer and include a smaller percentage of lignified secondary bast fibres (Amaducci et al., 2008; Amaducci et al., 2015).

However, excessive plant density causes self-thinning, which causes plants to die, slows crop development, and inhibits the formation of stem bark. In contrast to other herbaceous dicots, hemp has a flatter slope of the thinning line, which suggests that, at the same rate of crop growth, hemp has a greater death rate from self-thinning. This is most likely brought on by the quick pace of canopy height growth, which results in a minimal increase in biomass packing during the growing season (Van der Werf, Wijlhuizen, & de Schutter, 1995).

In fibre hemp, the ideal plant density balances the least damaging effects associated with self-thinning with the favourable benefits of high density on crop qualities. The ideal plant density is near to or equal to the greatest plant density that can be achieved. Thus, the self-thinning line of fibre hemp serves as a rough approximation of the link between yield and maximum (optimal) plant density (Van der Werf, Wijlhuizen, & de Schutter, 1995).

It has been shown that, due to the rapid growth in the last stages of the growing season, a late-flowering cultivar produces more yield (Van der Werf, Wijlhuizen, & de Schutter, 1995).

Because interplant competition causes each plant to grow less rapidly at high plant densities, the beneficial effects of having many plants are countered. As a result, in many experiments, the increase in biomass yield is frequently found to stop at a certain plant density. This has been described as the "law of constant final yield" (Van der Werf, Wijlhuizen, & de Schutter, 1995).

Higher plant densities have faster canopy closure, which is advantageous in terms of weed competition and because maximum light interception is attained earlier, resulting in a biomass yield advantage in the early growth stages. This yield advantage is gone after the growing season when there is fierce interplant competition at high seed densities, self-thinning, and biomass loss occur (Amaducci et al., 2015).

Harvest parameters: Harvest time and quality of hemp grown for fibre

Early sowing increases the risk of cold damage at northern latitudes. Thus, to ensure prompt germination and quick crop establishment, the sowing date is typically determined based on soil temperature and water availability. It is also determined based on the photoperiod, which determines the length of the vegetative phase and, ultimately, stem and seed yield (Amaducci et al., 2015).

Hemp is a short-day plant, with shorter days accelerating the commencement of flowering. However, if the variety is cultivated outside of the area where it was produced, the number of days to flowering may differ significantly from that stated in variety registrations. This often translates into later flowering because of longer days in all types in more northern latitudes (Bennett, Snell, & Wright, 2006).

Young hemp stems already contain primary fibre bundles. They can extend nearly the whole length of the plant and run lengthwise along the stem from bottom to top. Before the bundles can be removed, these fibres need to be strong enough. The cellulose-filling level of the cells, which increases from bottom to top and from the outer to the inner section of the stem, is strongly related to the so-called “ripeness” or maturity of the main fibres (Westerhuis et al., 2019; Amaducci et al., 2015).

It is generally acknowledged that significant characteristics of fibre hemp include high stem yield and high bast fibre concentration (Sankari, 2000).

The amount and quality of hemp fibre are thought to be affected by crop management parameters such as sowing density and harvest time (Westerhuis et al., 2009b).

Numerous scientific studies have examined how various harvesting times affect fibre output and fibre properties.

Traditionally, hemp was harvested for fibre when the male plants were fully blooming and the primary bast fibre output reached its peak (Amaducci et al., 2015).

Because of "pre-flowering" in unfavourable environmental circumstances and in some genotypes, determining the start of flowering for harvesting can be misleading (Amaducci et al., 2015).

Given that plant phenology determines when to harvest, a particular environment might be controlled by selecting a genotype with a certain photoperiod sensitivity. When dew retting is done, harvesting should happen when there is a good chance of finding favourable weather conditions. Delaying harvest until the end of the summer may result in decreased fibre output and inferior quality owing to heavy rain in northern and wet areas (Amaducci et al., 2015).

One field trial was conducted with five different hemp varieties, seeded at 150 and 300 seeds per m2, to establish the best time to harvest hemp in order to maximise fibre output and quality. Three cutting periods were set: at the beginning, middle, and end of flowering. After dew-retting in the field, stem fibre was removed to assess the quality and yield of the fibre (Bennett, Snell & Wright, 2006).

Although the initial cut in mid-August produced the maximum yields in most types, there was a significant difference in fibre yields in the five cultivars. It is suggested that the lignification of the fibres that took place following the onset of blooming is the cause of the drop in fibre production that was seen between the first and third cuts. It is also suggested that cultivars with a decreased or delayed beginning of lignification are crucial in the prevailing cooler, wetter climates of the more northerly latitudes, where it is vital to cut hemp early in the fall to avoid lignification of the fibres (Bennett, Snell & Wright, 2006).

The lignification of the fibres that occurs soon after blooming is thought to be the cause of the decreases in total fibre percentage and fibre yields observed at the second and third harvests (Struik et al., 2000). Late-season harvested hemp stems lignify and break during the fibre extraction process, limiting the amount of long fibre (Bennett, Snell & Wright, 2006).

According to another investigation, the time of harvesting should be set at full flowering to optimise fibre yield and fibre homogeneity because fibre maturation at higher internodes was more progressed, and fibre yield was improved by 25% between the beginning and full flowering (Amaducci et al., 2015).

In relation to their use in high-grade composites, hemp fibres' wide variation in mechanical characteristics is problematic (Liu et al., 2015).

Primary and secondary fibres are the two forms of bast fibre found in hemp. In a cross-section of a hemp stem, the inner layer, if existent, is made up of secondary fibres, while the outer fibre bundle layer is made up of primary fibres. The only desirable hemp fibres for making high-quality textile yarns are the primary or “long” fibres (Westerhuis et al., 2019). Numerous factors, including fibre diameter, flaws, chemical composition, and the ratio of these secondary fibres, affect the mechanical characteristics of hemp fibres. After flowering, it has been found that their creation results in a decrease in both fibre quantity and quality (Liu et al., 2015).

The development of bark fibres is a complex process that is closely tied to the growth pattern of the plant (Liu et al., 2015; Da Costa et al., 2001). Primary fibres are first generated and subsequently filled during vegetative growth and up to bloom creation. Secondary fibres are developed with the onset of the generative phase, especially near the stem's base. Peaks in stem and fibre yield at "technical maturity" are likely brought on by an increase in secondary fibre production (Liu et al., 2015; Da Costa et al., 2001). With stem maturity, a statistically significant rise in lignin deposition and a modest decline in pectin in the cell walls of hemp fibre has been shown (Liu et al., 2015).

According to Amaducci et al. (2008), Most of these secondary fibres are found towards the base of the plant stem.

While the primary or long fibres are desired, the secondary or "short" fibres are undesirable because they are too short for spinning, interfere with the production of fine and homogenous yarns, and are technically challenging to separate from the primary fibres during commercial fibre processing (Westerhuis et al., 2019).

Westerhuis et al. (2019), say that it is important to understand how secondary fibre growth above stubble height may be prevented in the raw materials aimed at textile yarn production.

Da Costa et al. (2001), concluded that according to their experiment, dioecious hemp's stem and fibre yield are maximised when harvested at the point of "technical maturity".

Westerhuis et al. (2009a), explored if the effects of sowing density and harvest time are essentially different or whether both impact stem weight, which affects total and long fibre content. It was determined that:

> Sowing density and harvest time affect fibre content in hemp through their effects on stem weight only. In a stem, beyond a certain minimum weight, the increase in dry matter is split up into fibres and wood in a fixed way, which varies with height along the stem. This fibre/wood ratio is highest in the middle part of the stem and lower towards both bottom and top. The long-fibre share in the total fibre fraction does not depend on sowing density and harvest time. The long fibre/total fibre ratio is lowest in the bottom 5 cm of the stems but similar for all other parts. Retting loss percentages decrease as stem parts mature because maturation is associated with increasing amounts of fibres and wood, whereas for each stem part, the amount of material that is lost during retting is constant. (Westerhuis et al., 2009a)

In another study in the Netherlands, it was investigated whether seeding outside of the typical sowing window had an impact on the proportion of wood and fibre yield, as well as what proportion of these fibres were long fibres that could be spun into yarn. A total of 400 stem samples were divided into four fractions: wood, retting losses, tow, and long fibre. The ratios between the fractions were then examined using multiple linear regression analysis (Westerhuis et al., 2009b).

Comparisons were made between a normal sowing date at the end of April and a postponed sowing date at the end of May. The ratio of total fibre to wood was unaffected (Westerhuis et al., 2009b).

> More than 95% of the variance in total fibre was accounted for by the wood weight per stem (55.5%), the variety (+33.3%) and the stem part (+6.5%). The amount of long fibre per stem mainly depended on the amount of the total fibre per stem (95.4% variance was accounted for) and the stem part (+2.0%). (Westerhuis et al., 2009b)

Another experiment was conducted with a single variety to examine the impact of sowing fibre hemp up to 12 weeks later than usual on the amount and quality of the fibres. Retting losses, the ratio of total fibre to wood, and the ratio of long fibre to total fibre were not significantly affected by delaying the planting date by up to 12 weeks (Westerhuis et al., 2009b).

Retting and processing.

Hemp fibre cell walls mostly consist of cellulose, hemicelluloses, lignin, and pectin. A central lamella that is rich in pectin and lignin holds the fibres together. To generate individual fibres and small fibre bundles for high-grade composites, the intermediate lamella fibre bonding must be weakened. Therefore, the stems are often retted before mechanical separation to maximise plant fibre extraction efficiency and decrease fibre breakage. In terms of both the economics and the quality of the fibre, the retting stage is essential for the widespread usage of hemp fibres (Keller et al., 2001; Liu et al., 2015).

According to Bennet, Snell & Wright (2006), When hemp plants are harvested for retting at various periods of the year, there is a noticeable fluctuation in the yield and percentage of fibre. Later maturing types should be harvested in mid-September, whereas early maturing varieties should be harvested in mid-August. However, they do advise in their study that it is crucial to cut the hemp plants early for retting, rather than to wait until September, for all varieties, due to weather unpredictability.

Contrary to cotton, which is made of separate cells that emerge from the cotton seed's epidermis, bast fibres, such as hemp, are bundled together in the stem's bark. As a result, to use hemp for industrial purposes, the entire plant must be separated from the fibres. This is often accomplished by dew or water retting, followed by a mechanical extraction procedure (beating, scutching, and combing), which results in scutched hemp fibres and hemp tow (Keller et al., 2001).

According to Keller et al. (2001), water retting produces wastewater with a high oxygen demand and is thus questionable from an ecological standpoint, whereas dew retting is a weather-dependent and time-consuming procedure that results in inhomogeneous fibre material. Both traditional methods rely heavily on physical labour (Keller et al., 2001).

Due to its low cost, dew retting is still widely utilised (Liu et al., 2015). Hemp is suited to the climatic and soil conditions of many various locations throughout the world (Amaducci et al., 2015), and has been demonstrated to be successfully carried out in many European climates with increased durations (Grégoire et al., 2021).

Plant stems are spread in fields during field retting, where they are attacked mainly by fungi. There the pectin contained in the central lamella areas between fibres can be broken down by the fungi's pectinolytic enzymes (Liu et al., 2015).

In one research by Liu et al. (2015), the decline in fibre quality produced by a lengthy period of field retting was verified and may be connected to an ongoing rise in cellulose degradation. No discernible change in fibre quality was detected during short durations of field retting. More effective and controlled techniques, such as chemical treatment, mechanical defibration, and enzymatic retting, have been researched as a result of the drawbacks of increased scattering of fibre property and the instability of the fibre supply owing to unfavourable weather conditions. However, those methods may result in expensive wastes and high energy input or expensive enzyme costs. While the study concluded that conventional field retting might not be the best pre-treatment for strong fibres, it was suggested that short-period field retting might be used in conjunction with other techniques, such as the use of specific enzymes, chosen microbes or chemicals, to extract fibres more accurately and efficiently (Liu et al., 2015).

Liu et al. (2015), concluded in their trial that:

> Fibres harvested at seed maturity are significantly lignified and thus will be difficult to be extracted from hemp stems compared with fibres from the beginning of flowering. Furthermore, the important reduction in hemp bast mechanical properties with plant maturity may be attributed to the combined effect of the noticeable decrease in cellulose deposition and the formation and increase in the proportion of secondary fibres that caused deterioration of primary fibre quality regarding morphological and chemical characteristics. Highly lignified fibres are not desirable and favourable for retting. Considering the mechanical performance of hemp bast fibres, hemp harvested at the beginning of flowering is recommended for use in strong composites. (Liu et al., 2015)

Amaducci et al. (2015), propose that choosing genotypes that are simpler to decorticate offers benefits in terms of fibre quality and lower costs associated with fibre extraction.

The mechanical decortication of green or pre-retted bast fibres is another method for extracting fibres. Here, breaking the stem—typically accomplished by pairs of profiled spinning rolls—separates the fibres from the woody core. However, this technique produces technical short fibres that are employed as insulation or fillers in composites instead of high-quality fibres (Keller et al., 2001).

To produce fine single fibres, a number of chemical and physical degumming techniques have been developed. The gum materials between the primary fibres are chemically dissolved and removed using these techniques. Physical procedures like steam explosion or ultrasound are used to increase the effectiveness of these chemical processes and to prevent fibre damage. However, these approaches' potential for economic growth is limited by their excessive reliance on chemicals and energy (Keller et al., 2001).

Keller et al. (2001), claim that controlled biological degumming of decorticated bark in bioreactors employing appropriate microorganisms and their enzymes is a more promising technique for producing fine hemp fibres. It takes homogeneous starting material to produce high-quality fibres. The best starting material for degumming is non-retted, green decorticated bark material since after dew retting, the fibre material is uneven. Green bast plant decortication can be done on fresh or dried stems. While fresh decortication often produces higher-quality fibres, dry decortication is reported to be faster and not limited to the harvesting season (Keller et al., 2001).

Keller et al. (2001), found in their experiment that mechanical decortication of non-retted, dried hemp stems was favourable towards the onset of seed maturity, which is around 3–4 weeks after the 'technical maturity'. They found that the tensile strength of the bark was unaffected by the relatively late harvest period, but that decortication damage to the fibres must be avoided to produce high-quality hemp fibres for industrial usage (Keller et al., 2001).

Using specialised flax scutching and hackling equipment, Grégoire et al. (2021), conducted an experiment to determine process parameters that would maximise long-line fibre production.

After scutching and hackling at the laboratory scale, very high long-fibre yields were obtained in the experiment by Grégoire et al. (2021), indicating that hemp can be a very productive source of high-performance fibres. However, it was found that slower scutching and beating speeds were required to be less harsh on the straw and fibres. The outcomes demonstrated tensile qualities that were totally appropriate for both load-bearing composite materials and textile applications.

Additionally, it was shown that hemp could produce as much long fibre per hectare as flax (with tensile properties about 20 % lower than the ones of flax) (Grégoire et al., 2021).

Amaducci et al. (2008), also conducted research in which the effect of an innovative harvesting processing system in which hemp stems are chopped in two pieces of roughly 1 m during harvest to permit processing on contemporary flax scutching lines was examined in terms of its impact on fibre quality. They found that it is possible to promote fibre homogeneity by separating the stem into two pieces and maintaining them separate throughout further processing. They noted that the majority of the fibre is located in the bottom portion, while the top part seems to be finer fibres with less secondary fibre.

Another study investigated the quantity and quality of fibre recovered from field-retted hemp stems using modern machinery for flax.

The field tests were conducted in Belgium, a country with a long history of producing high-quality linen and cultivars from various European origins (USO 31, Dacia Secuieni, Bialobrzeskie, Futura 75, Carmagnola Selezionata, Santhica 27 and Santhica 70) were utilised (Vandepitte et al., 2020).

High processing efficiency was indicated by the quantity of total fibre retrieved (i.e., long fibre + tow). The extraction of tow and long fibre was almost equal. Although there was a significant difference in yield across cultivars, the amount of long fibre removed remained almost consistent. The long hemp had a high total fibre tenacity that was equivalent to flax (Vandepitte et al., 2020).

According to the findings, field-retted hemp has the ability to be processed into high-quality fibre on an industrial flax line, and genotype selection is probably a good way to increase fibre production further. This strategy requires harvest mechanisation in order to gather parallel hemp stem pieces that are the right length for the flax scutching line (about 1 m). To fully explore the potential of long hemp as a flax supplement for textile applications, more studies on the fibre characteristics after hackling and wet spinning will be required (Vandepitte et al., 2020).

Although hemp fibre yield appears to be somewhat lower than that of flax, given the wide range of hemp genotypes studied, it is possible that genotype selection can increase fibre yield. The primary fibre content and long fibre output of hemp stems may also be improved by agronomic techniques aimed at maximising plant diameter, such as modifying plant population density (Westerhuis et al., 2019; Vandepitte et al., 2020).

According to Vandepitte et al. (2020), harvest mechanisation of hemp stems is urgently crucial in order to cut labour costs and make this production chain economically feasible. Therefore, it would seem wise to automate the cutting and collection of segments of parallel-lying hemp stem that are about one meter long, as this is the right size to feed the present flax line. To reduce variance and give farmers clear, actionable field guidance, more studies on the impact of field retting conditions on fibre quality across harvest years and geographies would likely be necessary.

Westerhuis et al. (2009b), argue out that "the limited market for high-quality hemp yarns does not justify the development of specialised hemp scutching and hackling lines. Hence existing flax processing lines should be used". They looked at the prospect of lowering the vegetative development phase by delaying the planting date as a natural technique to shorten the plant's height. Suggesting that after the shift to the generative phase is complete, stem elongation slows down or ends. They came to the conclusion that, theoretically, two hemp crops might be grown in quick succession. However, it remained to be seen if it should be favoured over a crop with a lengthy growing season and urged for more research (Westerhuis et al., 2009b).

Sustainable aspect of hemp

Cannabis sativa is a great crop for organic farming. Because of its small need for fertilisers and quick growth following emergence, hemp is, under optimal conditions, very competitive with weeds. It also typically does not require pesticides (Amaducci et al., 2015; De Vos et al., 2022).

It can thrive in a variety of soil types and has demonstrated the ability to withstand heavy metal pollution thanks to mechanisms specific to the plants (De Vos et al., 2022). As a result, it holds promise as a phytoremediation crop for the removal of heavy metal pollution, with several genotypes exhibiting distinct variations in its capacity to tolerate and accumulate heavy metals (Salentijn et al., 2015).

The technique of phytoremediation, using plants to rid the soil of heavy metals and organic pollutants, is a sustainable and affordable soil remediation technique. The high biomass yields produced by hemp are commercially valuable for a variety of non-food industrial uses (De Vos et al., 2022).

Previous studies demonstrated that, when compared to hemp grown on the non-contaminated ground, heavy metal absorption in hemp does not or very minimally, mainly in the leaf region, impair biomass production and does not alter fibre quality. It was shown that the early cultivar USO31 was a promising option for the climate in North and Central Europe when the parameters of fibre quality and climatic adaptability were added to the earlier findings. In order to combine the secure production of hemp fibres as a raw material for the textile industry with the valorisation of the contaminated land, the study demonstrates encouraging findings toward the growth of fibre hemp on heavy metal polluted soil within a phytoattenuation approach (De Vos et al., 2022).

Flax in Iceland: A learning curve

While there is not much history of hemp production in Iceland to draw experience from, when it comes to the production of long fibre for textile applications in recent times, there might be from flax production.

Flax cultivation is an ancient industry in Europe (Egol, 2004). Around the time Iceland was settled, the cultivation of flax was common in northern Europe and Scandinavia. And at the beginning of settlement times, it was also cultivated in Iceland (Vilmundur Hansen, 2019).

In the 1950s and 1960s, experiments were carried out with flax cultivation in Iceland. Among other places, cultivation took place at Bessastaðir in Álftanes and Hvanneyri. Part of the harvest was sent to Denmark, where the quality of the linen was studied. The linen from

Hvanneyri was rated fair but very good from Bessastaðir. A cloth woven from the linen from Bessastaðir was and perhaps still is on the altar of Bessastaðir Church (Vilmundur Hansen, 2019).

Early in this century, a company called Feyging ehf. Started a linen factory in Þorlákshöfn. The largest owners of Feygingar ehf. were Orkuveita Reykjavíkur, Ölfushreppur, Eignarhaldsfélag Suðurland and Byggðastofnun (Vilmundur Hansen, 2019). The Flax was supposed to be used to produce Icelandic linen for export. Approximately 340 million ISK was invested in the company (Búnaðarsamband Suðurlands, n.d.).

The company's operation soon collapsed, and nothing came of the linen processing in Þorlákshöfn despite the huge costs that were put into the operation (Vilmundur Hansen, 2019). But there might still be something to learn from this experience.

Flax is grown in the fields, and the plant is then left to mature there for a few weeks to ret. It is the same traditional process as has been used for hemp, where the stem bark rots away from the fibre, which is the sought-after part of the plant. It is the weather and winds that take care of the retting process, which results in an uneven and variated quality of the production from year to year (Egol, 2004).

As has been discovered in this thesis, it is the same process that has traditionally been used for hemp, and with the same complications in the retting process.

However, in the plant in Þorlákshöfn, so-called water flushing was utilised, in which geothermal heat was used to separate the fibres from the skin. According to one of the owners of the company, the process was thought to deliver a much more even and better production than foreign manufacturers were offering at the time, and the company believed that if they could get the desired grip on production in Iceland, Icelandic linen prices would be 15-20% higher than foreign linen prices (Egol, 2004).

But there were complications in the production process in the factory, and the farmers also had difficulties with the cultivation. The company should have had 8-12 people working at the factory when the business was fully operational and would then have been able to process 40-50 round-bales a day. But the operation was never fully operational. For three years farmers were cultivating flax, and at one point, around 10.000 round-bales of plucked flax around the country were waiting for processing (Egol, 2004), but the company had a lot of problems developing and designing the drying systems that were to be used in the processing of the Flax (Hörvinnsla tefst enn í Þorlákshöfn, 2010).

In an article in Morgunblaðið, it was mentioned that some farmers "just weren't ready for it", and many of the farmers had difficulties "getting a hang of the crop". One of the main problems was that there had not been any fertiliser experiments done in Iceland prior to the beginning of the cultivation, and the farmers didn't know what kind of fertiliser was best to use or in what quantity. And fertiliser experiments on flax cultivation were only done later, on an initiative by the farmers in the West, in cooperation with the Agricultural University in Hvanneyri (Egol, 2004).

Other problems were due to the lack of guidance in harvest parameters. Flax is first plucked when the stalks have turned yellow, and the fibre is mature, and that was not done properly, which would have influenced the quality of the production. Davíð Guðmundsson, who took over as Feygingar's managing director, admits that it wasn't certain that all linen in old bales was usable but that it was necessary to give farmers plenty of time to develop the crops (Egol, 2004). He also mentioned that there was a very good market for the production, with buyers just waiting impatiently for the product, and that the results of all the hard work were right within their reach (Egol, 2004).

In an article on the website, Búnaðarsambands Suðurlands, one of the farmers who had been cultivating flax in these three years and had acquired equipment for flax production worth 5 million ISK, said: "It will be a big blow to me if they decide to shut down the factory". He also said that:

> If the factory is dismantled, and sold for nothing, then in my opinion it is a blow to the credibility of the institutions that were involved in the professional aspect, including the Institute of Industrial Technology and RALA [the Agricultural Research Institute]. I would like to hear where they stand regarding the demolition of a project that is almost ready. (Búnaðarsamband Suðurlands n.d.)

There were many who believed that the only thing missing was the determination to bring it to completion. In the end, all the machinery and equipment in the company were put up for sale (Búnaðarsamband Suðurlands n.d.).

A Danish example

In September 2021, a report from the Danish Environmental Agency came out, covering the project, Sustainable hemp textiles: Development of a concept for the production of sustainable hemp textiles (Pallesen, 2021).

The report is very extensive and covers the process of hemp from cradle to cradle. In this chapter, I will review some of the key areas of fibre hemp production relating to this thesis.

The aim of the Danish project was to go a step further towards being able to produce textile raw material from Danish-grown hemp and creating the basis for a new business area with great growth potential, such as sustainable textiles for an industry that is environmentally burdened in many areas (Pallesen, 2021).

The main task was to rethink and streamline the processing processes in the entire value chain from the field to the final product – and link the relevant companies and actors together in a joint consortium that aims to solve the challenges (Pallesen, 2021).

The project consortium included partners from the entire hemp value chain, and the participating project partners worked with hemp from different angles and together to form a strong project network to cover the entire value chain (Pallesen, 2021).

Among other things, enzymatic methods to expose hemp fibres to textile fibres and hydrothermal methods were tested as a starting point for the development of the concept (Pallesen, 2021).

Development goals no. 9. Industrial innovation and infrastructure, no. 11 Sustainable cities and local communities, no. 12. Responsible consumption and production and no. 13 Climate action, from the UN's 17 global goals for sustainable development, were all goals addressed in the project to accommodate the demand from the large textile companies where CSR (Corporate social responsibility) efforts are high on the agenda (Pallesen, 2021).

Studies were carried out with the cultivation of hemp at Vittenbjerggård (where they since 1998 have grown industrial hemp (Vittenbjerggaard, n.d.)), with tests of varying seed quantities and harvest time, and subsequent analysis of the parameters' impact on the quality of the raw material. All the trials during the trial period were carried out with Futura 75, which is a well-regarded and suitable textile variety, though a little late in development compared to other varieties, such as Uso, Felina etc. (Pallesen, 2021).

Investigation of seed quantity

As an important part of the concept of finding the best cultivation conditions that produce quality fibre, an experiment with varying seed rates was made to find the most optimal seed rate. Seed quantities of 25 kg, 40 kg, and 60 kg per ha with the cv Futura 75 were tested (Pallesen, 2021).

The hemp was sown on 8 May 2018, and it was reported that the thickness of the stem was reduced at a higher seed rate, which means a higher fibre yield in the individual stem, as the proportion of straight versus crooked becomes higher (Pallesen, 2021).

The height of the plants varied from 2.5 – 3 m. The dense plant population at 60 kg/ha produced long and slender stems average diameter of 0.75 cm. Plants sown with 25 kg/ha, which is normally the seed quantity for, e.g., short fibres and bedding purposes, gave diameters for the stems of 1 – 1.25 cm or more. The extracted raw material was then included in retting experiments with enzymes and hydrothermal treatment (Pallesen, 2021).

Retting experiments

They successfully developed a concept for a controlled retting of hemp stalks using enzymes and hydrothermal treatment on a lab-scale level, where it was possible to separate the fibres from crooked stems without problems (Pallesen, 2021).

They also reported a good effect of retting with enzymes from Novozymes, i.e., BioPrep. Here it was concluded that a processing time between 16 and 24 hours was best. The process loss was between 5 and 8% for unreddened as well as retted hemp stalks and the greatest loss was seen for the un-retted hemp quality (Pallesen, 2021).

On the other hand, hemp pre-treated with lactic acid, i.e., ensiled hemp, had a large dry matter loss from the enzyme process, and the strength was severely weakened. And an undesirable high degree of breakdown of the cellulose was reported (Pallesen, 2021).

The hydrothermal treatment also showed a clear effect. Here treatment with pH regulation, either by soaking stems in thin acetic acid prior to treatment or equivalent with NaOH (Sodium hydroxide), also in a thin solution, was used to give a positive outcome regarding releasing the fibre bundles (Pallesen, 2021).

Differences in the results were found due to raw material quality, harvest time and annual variation. In particular, the time of harvest had an influence on the degree of retting and the quality of the hemp fibres exposed to the controlled retting methods (Pallesen, 2021).

According to Pallesen (2021), the work of developing an alternative retting concept is not yet completed, but there was a clear trend which showed that the treatments gave the fibres the desired properties.

The results of the retting experiment, together with measured strength properties, showed that the release of fibres was achieved to some degree, and the quality of the fibres for use as textiles was on par with cottonized hemp fibres (shortened hemp fibres, spun similarly to cotton) or better (Pallesen, 2021).

According to Pallesen (2021), the Hemp4tex project will try to solve the identified challenges in being able to produce Danish hemp for strong yarns and high-quality goods by the meter, using new methods and technologies. The project in this report resulted in the clarification of the many links in the chain that must work together to successfully establish a hemp textile industry in Denmark, and the project's outcomes will be further developed in the Hemp4tex project. Pallesen mentions that there is also a focus on the development of long-fibre fine threads in Europe, but so far, it has not proven successful. Hemp still needs to be imported from China in order to be used as a raw material for textiles, and the material is not yet of a high enough grade to be spun into fine threads.

Chapter 4

Discussion

Here the essential and controlling factors of cultivating hemp for long fibre yield in northern latitudes will be discussed.

This thesis aimed to explore the possibility of cultivating hemp for long fibre yield in Iceland and the necessary methods of processing it to use in high-quality yarns for textiles.

The research question was,

"Cultivation of Industrial fibre hemp (Cannabis sativa L.) in Iceland. How can we produce high-quality long fibre for use in textile applications?"

While there were a lot of scientific reports on the cultivation of hemp, papers focussing on long fibre yield in northern latitudes were few.

It was attempted to give an overview of the process involved with cultivating for high-quality long-fibre yield and identify cultivars that could be suggested for Iceland for long-fibre yield.

All the papers from which the data was retrieved differed in their focus of research. But as a common feature, all articles have been conducted in the past decades, focusing on the influence of agronomic factors on the yield and quality of hemp fibre in northern latitudes or of interest for the cultivation of long fibre yield.

Cultivars and sexes

In this thesis, we have learned that in hemp phenology, photoperiod is a particularly crucial factor. The day-length conditions in Iceland are very long during the summer period, and hemp has a quantitative short-day requirement. However, as several authors have pointed out, high yields of suitable quality fibres are possible throughout Europe, even under unfavourable day-length conditions (Sankari & Mela, 1998; Amaducci et al., 2015; Struik et al., 2000), and achieving a specific yield in each given environment is possible based on the photoperiod sensitivity of a selected variety. Amaducci et al. (2015) also point out that the fibre content among genotypes has significant variations, which should be considered when choosing varieties for cultivation in Iceland. In Denmark, the cv Futura 75 was cultivated with success as a suitable textile variety (Pallesen, 2021). Pallesen (2021) does mention that it was a little late in development compared to other cultivars.

The result section in chapter 3 of this thesis reveals that the fibre formation in hemp finishes already a month before ripening; late cultivars are often grown in northern regions to produce stem and high-quality fibres, which is of interest for cultivation in Iceland.

According to Salentijn et al. (2015), late flowering cultivars have a prolonged vegetative phase and a higher stem yield in the northern regions. And (Sankari & Mela, 1998) suggests Late-flowering hemp cultivars, therefore, are to be favoured to produce fibre since they invest less dry matter in reproductive organs, which could mean that late-flowering cultivars can be one of the advantages when planning cultivation in Iceland.

However, as mentioned by Amaducci et al. (2015), late harvesting could coincide with wet and cold periods that are not favourable for stem drying or homogenous retting and in Iceland, September is one of the wettest months of the year (World data, n.d.).

This thesis also revealed that there is a debate among researchers about whether dioecious varieties or monoecious varieties are more suitable for fibre cultivation in the more northern latitudes. Though generally, it is accepted that dioecious hemp varieties are higher in fibre yield than monoecious varieties (Amaducci et al., 2015; Sankari, 2000).

In traditional dioecious hemp varieties, the male plants have superior fibre quality characteristics, and historically farmers hand-pulled male plants to use their fibre for fine textile applications while female plants were used for coarse fabrics (Amaducci et al., 2015).

But, the results from several experiments comparing the dioecious to the monoecious varieties (Sankari, 2000; Bennett, 2006), suggest that in more northern latitudes, this may not be true due to the longer days during the growing season and that the northern monoecious varieties perform better under the prevailing cooler, wetter conditions as they are able to respond to the longer growing days prior to the commencement of flowering (Bennett, 2006).

Bennet (2006), points to the monoecious Polish varieties Beniko and Bialobrzeski having higher fibre yields and fibre percentages in his experiment, explaining that the delayed or reduced lignification that occurs in Beniko is an important and useful characteristic, especially for the wetter and more unpredictable climates of northern Europe. If cutting is delayed because of wet weather conditions, then fibre yields are not so rapidly adversely affected.

Another study by Sankari (2000), in Finland, at latitude 60°497 N, Ukrainian monoecious cv. USO 11 was compared to 13 other fibre hemp cultivars, and it was concluded that cv. Uso 11 is the best cultivar for cultivation in the long-day growth conditions in Finland as an early maturing cultivar with a relatively high stem yield. Nevertheless, if fibre content and fibre yield are considered as well, the earliest maturing monoecious cvs. Uso 31, Bialobrzeskie and Beniko were also recommended, which is worth mentioning for this thesis and suggests that field trials of both monoecious and dioecious varieties should be conducted to see how they perform differently in Iceland.

The results, however, also showed that in regard to most of the plant properties studied, the dioecious cultivars exhibited better or equivalent properties for cv. Uso 11 but did not mature fast enough to produce seeds (Sankari, 2000). For this thesis, where the focus is on fibre yield and not a dual crop with both fibre and seeds, this information is of more interest as it suggests that the dioecious cultivars would then perform better in Iceland.

Iceland and Finland are similar in climate, with Finland having one more hour of daily sun but being 2,5 Celsius colder on average (World data, n.d.), and it is probable to assume that these varieties could show similar behaviour here in Iceland.

Amaducci et al. (2015), also mention that the selection of genotypes that are easier to decorticate provides an advantage in terms of fibre quality and a reduction of costs related to fibre extraction.

Soil preparation

As mentioned earlier, soil preparation for hemp cultivation is essential, and it resembles other break crops (pulse or oilseed crop) with ploughing in autumn or winter and Phosphoros (P) and potassium (K) or organic matter administered prior to final seedbed preparation. According to the results of one experiment, hemp has a lower K demand than other crops, with a proposed yearly requirement of 65 kg per hectare. However, more K is absorbed by late-maturing cultivars than by early ones, with the majority of K adsorbed (70–75%) concentrated in the stems (Amaducci et al., 2015). As discussed above, later cultivars are recommended for northern latitudes, so this could be of relevance for cultivation in Iceland. Though not much is known about how P affects hemp production, it was mentioned by Amaducci et al. (2015), that P fertilisation has an insignificant impact on stem yield, so it is probably not necessary to use P in Iceland for fibre crops.

Nitrogen (N) is typically applied at the same time as or right before sowing (Amaducci et al., 2015). It should, though, be mentioned that the yield response of additional nitrogen to hemp has been reported to be minimal in rich soils (Prade et al., 2011; Struik et al., 2000), while significant yield increases were recorded under nitrogen-limiting circumstances, and nitrogen fertilisation should be decided depending on soil fertility (Struik et al., 2000).

Plant density

When sowing hemp for fibre, it is generally considered that a higher planting density resembles a higher yield of fibres that are finer and with a lower proportion of lignified secondary bast fibres (Amaducci et al., 2015; Bennett, Snell & Wright, 2006). Furthermore, as it has been revealed in this thesis, that the main concern in long fibre production is to avoid that secondary fibre formation, which develops in the stalks during the growing season. Van der Werf, Wijlhuizen, & de Schutter (1995), explains that because more assimilates are partitioned to the stem and less to the inflorescence and the leaves, and flowering is delayed, the stem quality is improved because bark content increases. Stem height and stem diameter are relevant to crop parameters, especially when hemp is cultivated to produce long fibres (Amaducci et al., 2015).

Pallesen (2021), also concluded in the Danish field trials that the thickness of the stem was reduced at a higher seed rate and a dense plant population at 60 kg/ha, which produced long and slender stems with an average diameter of 0.75 cm. in their trial, was recommended for long fibre yield.

Dioecious cultivars for textile use have historically been grown in Italy with a goal of 90–100 plants per square meter. In China, plant densities of 120–150 plants per square meter were found to enhance stem, fibre, and bast output. However, seeding densities of 50 to 750 plants per square meter have been seen, with higher rates recommended for textile destinations (Amaducci et al., 2015). This seems to indicate that finding the maximum plant density for each environment is required.

When plant density is too high, plants self-thin and die, crop development is slowed down, and the amount of bark in the stem stops increasing. Its self-thinning line consequently roughly approximates the connection between yield and maximum plant density in hemp used for fibre (Van der Werf, Wijlhuizen, & de Schutter, 1995). Research on maximum plant density for different varieties is recommended to be carried out in Iceland to optimise fibre yield when cultivating fibre hemp for long fibre yield.

Sowing and harvest parameters

Bennett, Snell, & Wright (2006), writes that when a variety of hemp is grown away from the region where it was developed, the number of days to flowering can vary significantly from what is published in cultivar registrations, which they mention, generally means later flowering due to longer days in all varieties in northerly latitudes.

Amaducci et al. (2008; 2015), write that to ensure speedy germination and crop establishment, the sowing date is determined by the photoperiod, which governs the duration of the vegetative phase, soil temperature, and water availability. Early sowings increase the danger of cold damage in northern latitudes (Amaducci et al., 2015); thus, in Iceland, it is imperative that the sowing date is postponed until weather conditions are right, which in some years can be as late as June which possible could be too late if it is a particularly cold year as the summer was in 2022 (Ari Páll Karlsson, 2022).

When there is a good chance of finding favourable weather circumstances, harvesting should be done. Especially if dew retting is used after harvest, delaying harvest till the end of summer in northern and humid climates may result in reduced fibre output and poor quality owing to heavy rain (Bennet, Snell, & Wright, 2006; Amaducci et al., 2015). This suggests that dew retting might not be a sustainable solution in Iceland due to the rainfall in September.

The Icelandic field trial in 2008 reported that hemp took a long time to start growing but, when established, did quite well (Þóroddur Sveinsson, 2009), but the experiment was not specifically for fibre yield, and so much more data is still needed from trials in Iceland.

One field study in Europe, in which five hemp types were grown at two seed rates: 150 and 300 seeds/m2, was conducted to find the best time to harvest hemp for maximum fibre yield and quality. Following dew-retting in the field, fibre from the stems was collected to evaluate fibre yield and quality. Three cutting times were implemented from the start of flowering, mid-point of flowering, and end of flowering, and fibre yield and quality were determined (Bennett, Snell, & Wright, 2006).

Although there was a significant difference in fibre yields amongst the five types, the majority of the varieties produced their maximum yields when the first cut was made in the middle of August. From the first to the third cut, there was a decrease in the amount of fibre that was harvested, and it is hypothesised that this was due to the lignification of the fibres that took place following the beginning of blooming (Bennett, Snell, & Wright, 2006).

Westerhuis et al. (2019), mentioned that during the course of the growing season, there is evidence to suggest that the height up to which secondary fibres are present travels upward along the stem and that this movement is accompanied by a quickening of the process around flowering.

Bennett, Snell, and Wright (2006), believe that cultivars with decreased or delayed development of lignification are significant in the cooler and wetter climates of the more northerly latitudes because of this.

When fibre is extracted from hemp stems collected later in the season, the stems are lignified and break, which results in a lower yield of long fibre (Bennett, Snell, & Wright, 2006; Keller et al., 2001; Amaducci et al., 2015).

And Liu et al. (2015) say there is a significant variation in the mechanical characteristics of hemp fibres, which presents a challenge when it comes to using these fibres in high-grade composites.

Amaducci et al. (2015), identified that the time of harvesting needs to be placed at full flowering in order to optimise not only fibre yield but also fibre homogeneity. This was due to the fact that fibre maturation at higher internodes was farther along than it was at lower internodes. In contrast, Da Costa et al. (2001), came to the conclusion, in their experiment, that the best way to maximise stem and fibre output was to harvest dioecious hemp at the beginning of the flowering phase. The contrasting results from these different field trials indicate the importance of field trials of harvesting time, done of various varieties in the environment in Iceland.

In a different experiment, it was investigated whether sowing beyond the average sowing period in the Netherlands influences the ratio in which fibres and wood are produced, as well as what proportion of these fibres are long fibres suitable for long fibre spinning. The results of this trial showed that sowing beyond the average sowing period did not influence the ratio. About 400 stem samples were fractioned into retting losses, wood, tow, and long fibre, and multiple linear regression analyses were used to analyse the ratios between the different stem fractions (Westerhuis et al., 2009b).

The normal sowing date, which takes place at the end of April, was paired with a sowing date that was pushed back to the end of May. The ratio of total fibre to wood was not impacted in any way (Westerhuis et al., 2009b). Since sowing time in Iceland is always delayed compared to other environments in Europe, this is a positive outcome for fibre cultivation here.

The effect of sowing fibre hemp up to 12 weeks later than usual on the amount and quality of the resulting fibres was investigated in a separate experiment using one of the available varieties. There were no significant changes seen in retting losses, the total fibre/wood ratio, or the long fibre/total fibre ratio as a result of delaying the planting date by up to 12 weeks (Westerhuis et al., 2009b).

Nevertheless, Bennet, Snell & Wright (2006), suggest in their trial that for all varieties, it is essential to cut the hemp plants early for retting rather than delay.

Retting

The process of retting traditionally consisted of dew or water retting (Keller et al., 2001). But although hemp is adapted to the climatic and soil conditions of many places around the world (Amaducci et al., 2015), the possibility to perform dew retting advantageously is more favourably conducted in mild and humid areas, even though it has been shown that it can be performed in many different European climates (Grégoire et al., 2021).

Other than being climate-dependent, dew retting is also a lengthy process that leads to the inhomogeneous fibre material. And water retting method causes wastewater with a high oxygen demand and is therefore environmentally questionable. Both traditional processes are based on a significant amount of manual labour, and because of this, these processes are not utilised in Western Europe (Keller et al., 2001).

Also, a study done by Liu et al. (2015), confirmed that a long period of field retting causes a noticeable decrease in the quality of the fibres produced by the plant. This decrease in quality may be related to a continuous increase in the amount of cellulose that is degraded over time. On the other hand, a short period of field retting did not cause any noticeable change in the quality of the fibres produced by the plant. But after coming to the conclusion that traditional field retting might not be the best pre-treatment for strong fibres, they proposed that a short-period field retting might be used to extract fibres more efficiently and accurately in combination with other methods, such as the application of targeted enzymes, selected microbes, or chemicals (Liu et al., 2015).

Keller et al. (2015), suggested a solution for separating the fibres that showed to be a more promising way to get fine hemp fibres than any other methods in use at the time of the research was the use of Bioreactors to control the biological degumming of peeled bark employing appropriate microorganisms and their enzymes. Here it is necessary to begin with a material that is homogenous if one wants to produce fibres of a high grade.

Because the material that remains in the fibres after dew retting is not homogenous, the non-retted, green bark material that has been decorticated is the best beginning material for the degumming process. The decortication process can be performed on fresh or dried stems of green bast plants. Dry decortication is said to be faster and is not constrained to the harvesting season, although fresh decortication often results in the production of fibres that are of higher quality (Keller et al., 2001).

Opposite to what was discussed in the chapter above about harvesting time, Keller et al. (2001), concluded in their study on the "Influence of the growth stage of industrial hemp on chemical and physical properties of the fibre" that the best time to harvest is roughly three to four weeks after "technical maturity," when the seeds are just starting to become mature. This time frame was advantageous for the mechanical decortication of non-retted, dried hemp stems. In the study conducted by Keller et al. (2001), on the influence of the growth stage of industrial hemp, the tensile strength of the bark was not negatively impacted by the unusually late harvest period (Keller et al., 2001).

In the Danish paper, Pallesen (2021) said that they successfully established a concept for the controlled retting of hemp stalks utilising enzymes and hydrothermal treatment, where it was managed to separate the fibres from crooked stems without difficulty (Pallesen, 2021).

They conducted several retting tests, some of which were effective while others were not. The hemp that had been pre-treated with lactic acid exhibited an unfavourable level of cellulose degradation and a substantial loss of dry matter as a result of the enzyme process, as well as a significant reduction in strength (Pallesen, 2021). However, they found good results when retting with Novozymes enzymes, where the process loss was between 5 and 8% for both unreddened and retted hemp stalks, with the maximum loss noted for the un-retted hemp quality at a process duration of 16 to 24 hours (Pallesen, 2021).

The hydrothermal treatment with pH regulation, conducted either by soaking stems in acetic acid prior to treatment or equivalently with NaOH (Sodium hydroxide), both in a dilute solution, had a clear effect on releasing the fibre bundles (Pallesen, 2021).

Pallesen (2021), claimed that the release of fibres was achieved to some degree and evaluating the strength qualities revealed that the quality of the fibres for use in textiles was comparable to or better than that of cottonized hemp fibres (Pallesen, 2021).

It is clear that many researchers are working on finding a solution to releasing the fibres, but there doesn’t seem to be any final conclusion yet as to what method is best for high quality long-fibres, and this area needs follow-up, to see what developments will take place in the future, in the countries that will be targeting long fibre production.

Postharvest

As the thesis has revealed, there is no processing system for the long fibre yield of hemp in Europe at this point. Westerhuis et al. (2009b), argue that "the limited market for high-quality hemp yarns does not justify the development of specialised hemp scutching and hackling lines; hence existing flax processing lines should be used".

Grégoire et al. (2021), conducted an experiment to establish process parameters maximising the long fibre yield using flax-dedicated scutching and hackling devices at a laboratory scale. The results showed tensile properties completely suitable for textile use as well as for load-bearing composite materials (Grégoire et al., 2021).

It was also demonstrated that hemp has the potential to provide equivalent amounts of long fibres per hectare as flax (with tensile properties about 20 % lower than the ones of flax) (Grégoire et al., 2021).

Amaducci et al. (2008), also carried out research where in order to enable processing on present flax scutching lines, hemp stems are cut into two pieces during harvest that is each about 1 m long. The research of distinct stem sections was conducted to ascertain the impact on fibre quality of this innovative harvesting and processing technology. With most of the fibre concentration in the bottom portion, but the top part is finer with less secondary fibre, they reported that it seems possible to increase fibre homogeneity by dividing the stem into two portions and keeping them separate during further processing.

Vandepitte et al. (2020), concluded in their studies that field-retted hemp has the potential to be processed into quality fibre on the industrial flax line and that fibre yield can likely further be improved by genotype selection. Harvest mechanisation focused on the collection of parallel hemp stem portions of appropriate length for the flax scutching line of 1 meter seems warranted to make this approach economically viable. Adding that additional research on the influence of field retting conditions between harvest years and on the fibre properties, followed by hackling and wet spinning, will be needed to fully explore the potentiality of long hemp as a flax supplement for textile applications (Vandepitte et al., 2020).

As was discovered, Flax cultivation is also possible in Iceland, and though there is no flax production here today, there has been an interest in setting up a mill to process flax here, which almost succeeded but unfortunately was closed down before production was able to start. However, there is an opportunity there to start a combined production of flax and hemp.

A sustainable crop

Production of Hemp does present the possibility of meeting many of the UN's 17 global goals for sustainable development, as mentioned by Pallesen (2021). In their project, several goals were addressed to accommodate the demand from the large textile companies where CSR efforts are high on the agenda. Some of these goals are no. 9. Industrial innovation and infrastructure, no. 11 Sustainable cities and local communities, no. 12. Responsible consumption and production and no. 13 Climate action (Pallesen, 2021).

Hemp can thrive in various soil types and is an excellent crop for organic farming. Because of its limited need for fertilisers and fast growth following emergence, hemp is very competitive with weeds (Amaducci et al., 2015; De Vos et al., 2022). But as mentioned by Þóroddur Sveinsson (2009), the plant develops slower in Iceland because of the cooler climate here, and thus it is probable that more fertilisers will be needed.

The hemp plant is also a sustainable and affordable soil remediation plant. According to studies by De Vos et al. (2022), hemp has demonstrated the ability to withstand heavy metal pollution thanks to mechanisms specific to the plant. This does not impair biomass production and does not alter fibre quality. In the research, the study demonstrated encouraging findings toward the growth of fibre hemp on heavy metal-polluted soil with fibres as a raw material for the textile industry with the valorisation of the contaminated land. Using plants to rid the soil of heavy metals and organic pollutants is called phytoremediation (De Vos et al., 2022). This is very interesting as a sustainable solution for the valorisation of contaminated land in Iceland and could be of great interest for projects on that subject and therefore deserves mentioning for possible future research where the combination of fibre hemp and sustainability is the topic.

Flax in Iceland vs. A Danish example

Quality-specific requirements for textile applications were not introduced in the articles but were mentioned in chapter 2 in the background section.

Precise specifications are required to build operations for producing high-quality, high-value fibre. These are currently difficult to find because there needs to be a bigger market for hemp fibre. And due to the long ban in the western world on hemp cultivation, hemp has not been emphasised enough, and therefore there has been a stop in development and innovative solutions in the field (Pallesen, 2021).

Hemp fibres can fit fine fabrics based on length, strength, and surface friction. However, these same parameters also make it challenging to process the fibre in conventional spinning mills. Especially an effective retting method that keep the quality of the fibre intact and is homogeneous still needs to be perfected (Pallesen, 2021), as has been revealed in this thesis.

For producers to dare to invest land and money in hemp, they need to know that someone buys and refines the product. To create a value chain, actors need to come together and invest together, thus being clear about which fibre qualities are desirable and achievable (Pallesen, 2021). With many stakeholders involved (including growers and textile designers), there may be a good chance of creating one functioning value chain from which many more can benefit.

The Danish project is a good example of how many links in the process come together before actual production is set in motion.

I argue that the strength of the Danish project, "Sustainable Hemp Textiles", is that they linked all the relevant actors and companies in the research phase to solve the challenges. And thus, creating a strong project network with partners working on the hemp from different angles. The project is still in progress and is entering its next phase, where among other things, the right retting treatment is being further developed (Pallesen, 2021).

Whereas the Icelandic flax company didn't seem to have had enough dialogue with the farmers in relation to cultivation and harvesting parameters, and farmers expressed that they didn't know the right fertiliser requirements or the right time to harvest the plants

(Egol, 2004). The company didn't start at the right end. No experiments were done before the factory was built to look at the key factors of fertiliser amount, the amount of sowing and the time of harvest, all of which would affect the quality of the linen. Examining the effect of the retting process on the quality of the linen would also have been an important part of the process.

Of course, the biggest downfall was that they hadn’t finished the development of the facilities. Hence the company didn’t succeed (Vilmundur Hansen, 2019), which shows the importance of the research phase.

Conclusions

When I started drafting this thesis, I wanted to create a knowledge base to start a production centre for processing long-fibre hemp that is compatible with spinning mills. It is now clear that more research is needed on genotype choice, plant density, harvesting time, and especially on the retting process.

Obtaining a good quality hemp fibre for textile applications requires good planning from choosing the right cultivar to the postharvest processing of the fibre. This includes practices throughout the cultivation period, being up to date with the plant strand development, harvesting at the very right moment and finally choosing an appropriate retting method, all in order to produce a fibre with the desired characteristics for yarn spinning.

This research has revealed that even though photoperiod is a crucial factor for hemp cultivation, and hemp has a quantitative short-day requirement, hemp can still be cultivated in Iceland, despite our very long days during the summer, with a careful selection of cultivars. Cultivars for cultivating long fibre in Iceland should be chosen based on their photoperiod sensitivity, fibre content, and possibly whether they are easily decorticated.

Late cultivars are suggested for high-quality fibre yield because, in the prolonged vegetative phase, they invest less dry matter in reproductive organs resulting in a higher stem yield when cultivated in northern regions.

Though there is a debate about whether dioecious or monoecious varieties are more suitable for fibre cultivation in more northern latitudes, depending on what retting and processing method is chosen, this thesis concludes that dioecious varieties are best suited. It was argued in the material that the dioecious male plants have superior fibre quality characteristics when only fibre yield was considered and exhibited better or equivalent properties to the most suitable monoecious varieties.

Still, it would be interesting to experiment with the monoecious variants that shoved delayed or reduced lignification, resulting in fibre yields not being so rapidly adversely affected if the cutting is delayed because of wet weather conditions. This could be a very useful characteristic for the unpredictable weather conditions in Iceland around harvesting time.

It was revealed that fibre hemp could be cultivated, under good conditions, with little to no fertilisers and need only small amounts of Nitrogen depending on soil fertility and Potassium if late maturing variants are chosen since they absorb more Potassium to the stems. However, due to both colder and longer days in Iceland, this conclusion might not apply here.

A high plant density should be applied when sowing to attain a higher fibre yield, with finer primary fibres and with a lower proportion of lignified secondary bast fibres. But field trials should be conducted to find the self-thinning line of the cultivar chosen to reveal the maximum plant density.

The timing of sowing and harvesting affects both production and fibre quality. Early sowing is not possible in Iceland due to the risk of cold damage, and hence sowing date should be postponed until conditions are right, which is usually in late May or the beginning of June. But if variety and time are carefully considered, much may be gained.

Normally the result of early flowering is a larger proportion of secondary fibres brought on by the increased plant mass, which is unwanted for the processing and quality of long fibres. But generally, all varieties, when sown in northerly latitudes, have later flowering due to longer days, which is great for long-fibre cultivation in Iceland.

But late harvesting should also be avoided, which could coincide with wet and cold periods, which lower fibre yield and is unfavourable for stem drying or homogenous retting if field retting is applied. September is one of the wettest months of the year, so harvesting is recommended by the end of August.

The retting process is probably the trickiest part of the processing steps and needs more research. In the material, it was argued what the best method of retting is while still obtaining good quality long fibres. A combined method was suggested where short-period field retting may be adapted to extract fibres more efficiently and accurately combined with other methods, including the use of targeted enzymes, selected microbes, or chemicals. But all papers called for more research on the matter of the retting process.

As there is no processing system for the long fibre yield of hemp at this point, existing flax processing lines should be used. This seems like an even better solution for Iceland, where the scale of cultivation is small, so combining it with flax processing would open more possibilities for farmers here.

Hemp has the potential to be processed into quality fibre on the industrial flax line. Harvest mechanisation focused on the collection of parallel hemp stem portions of appropriate length for the flax scutching line (about 1 m) is needed to make this approach economically viable.

Fibre hemp also has the potential of being a sustainable crop in Iceland, but a rather elaborate finishing of the fibres follows, and if there is neither machinery for harvesting and processing nor industry to take the harvested fibres, there is still a long way to go. However, I still believe that hemp's good properties in agriculture and as a textile fibre are a great argument for the cultivation of fibre hemp in Iceland. We have only just begone the exploration of hemp cultivation and processing in Iceland, and with time, I believe that setting up a combination of hemp and flax processing would be the right step to take, creating diversity both in the field and market.

The reason why I find hemp to be so interesting is its ability to be a particularly sustainable crop to grow. The whole plant can be used; both seeds, leaves and the part of the stems that are not textile fibres can be used for a wide range of technical purposes for paper, composites, building materials etc., in addition to animal bedding.

With its heat-insulating properties, hemp could also be a potential blend material with wool for warm textiles, which can open a market here in Iceland, where wool has an established market which could be built on. The fibre strength in the long fibres is why hemp is so durable and would therefore give the fabrics produced from it long durability.

Even though several quality parameters of hemp fibre can be influenced by cultivation practices, the fine fibre quality required by the industry for the fabrication of garment textiles, defined in chapter 2, is largely a matter of postharvest processing techniques.

What is missing in Iceland today are suitable harvesting machines, drying facilities and processing plants, which play a major role in ensuring that the finished hemp textile fibres can be delivered to the textile industry. Access to these machines probably plays a big role in whether growers dare to invest money and set aside market space for long-fibre hemp production. A possible way to go is a collective investment in a proper processing plant for hemp and flax fibre to broaden the market. But first, much more research in Iceland on all the factors of the whole process is needed.

The mistakes made during the flax company adventure in Þorlákshöfn are critical for us to learn from. There needs to be a long-term vision to make sure the farmers can develop the crop. Supported research and development planning are thus key initiatives for farmers and researchers in the field, so the risk is not as significant as in the Þorlákshöfn case, if we are to succeed in creating an industry.

Despite hemp fibre being slightly tricky to process, hemp has great potential in meeting future demands of crops and growing practices adapted to be more environmentally friendly.

Implementing everything that I have learned from writing this thesis, I am confident and look forward to setting up a field trial with cultivating hemp for fibre yield next year.

Recommendations for cultivation experiments in Iceland

- Trials of different genotypes should be done for photoperiod sensitivity, fibre content, and possibly whether they are easily decorticated.

- It is suggested that field trials of both monoecious and dioecious varieties should be conducted to see how they perform differently in Iceland.
- Fertiliser experiments are recommended due to the climate in Iceland.
- Research on maximum plant density for different varieties is recommended to be carried out in Iceland to optimise fibre yield when cultivating fibre hemp for long fibre yield. Finding the maximum plant density for the specific environment will also be required.
- The contrasting results on harvesting time, from different field trials in the research indicate the importance of field trials of harvesting time, done of various varieties in the environment in Iceland.
- An effective retting method, that keep the quality of the fibre intact and is homogeneous, still needs to be perfected. Research in this field is crucial for the production of Hemp fibre for high-quality yarns. Though researchers are working on finding a solution to releasing the fibres, still there doesn't seem to be any final conclusion yet to what method is best for high quality long fibres, and this area needs follow-up, to see what developments will take place in the future, in the countries that will be targeting long fibre production.

A summary of the conclusion

- Achieving a specific yield in each environment is possible based on the photoperiod sensitivity of a selected variety.
- Fibre content among genotypes has significant variations, which should be considered when choosing varieties for the cultivation.
- In Northern regions late cultivars are often favoured to produce fibre since they invest less dry matter in reproductive organs.
- The dioecious cultivars have exhibited better or equivalent properties to the monoecious varieties in most plant properties studied.
- It has been suggested that during the growing season in northern latitudes, the northern monoecious varieties perform better under the prevailing cooler, wetter conditions as they are able to respond to the longer growing days prior to the commencement of flowering with delayed or reduced lignification.

- Phosphoros (P) and potassium (K) or organic matter is administered prior to final seedbed preparation.
- Hemp has a lower K demand than other crops, but more K is absorbed by late-maturing cultivars than by early ones, with the majority of K adsorbed concentrated in the stems.
- Not much is known about how P affects hemp production, but it was mentioned that P fertilisation has an insignificant impact on stem yield.
- Nitrogen (N) is applied at the same time as or right before sowing, and should be decided depending on soil fertility. The yield response of additional nitrogen to hemp has been reported to be minimal in rich soils, while significant yield increases were recorded under nitrogen-limiting circumstances.
- Thickness of the stem is reduced at a higher seed rate, and higher planting density resembles a higher yield of fibres. With longer and slender stems where fibres are finer and with a lower proportion of lignified secondary fibres.
- When plant density is too high, plants self-thin and die, crop development is slowed down, and the amount of bark in the stem stops increasing. The self-thinning line roughly approximates the connection between yield and ideal plant density in hemp when used for fibre.
- The sowing date is determined by the photoperiod, which governs the duration of the vegetative phase, soil temperature, and water availability.
- Early sowings increase the danger of cold damage in northern latitudes.
- The results of a trial of delayed sowing showed that sowing beyond the average sowing period did not influence the ratio, in which fibres and wood are produced, as well as what proportion of these fibres are long fibres suitable for long fibre spinning.
- In the Icelandic field trial, hemp took a long time to start growing but, when established, did quite well.
- It was concluded by some researchers that the best way to maximise stem and fibre output was to harvest dioecious hemp at the beginning of the flowering phase.
- Other researchers identified that the time of harvesting needs to be placed at full flowering in order to optimise not only fibre yield but also fibre homogeneity due to

the fact that fibre maturation at higher internodes was farther along than it was at lower internodes.

- Late harvest at the end of summer in northern and wet climates may result in reduced fibre output and poor-quality owing to heavy rain that are not favourable for stem drying or homogenous retting.
- Evidence suggests that the height up to which secondary fibres are present travels upward along the stem, accompanied by a quickening of the process around flowering. Because of this, cultivars with decreased or delayed development of lignification are significant in the cooler and wetter climates of the more northerly latitudes.
- All varieties of hemp developed in lower latitudes generally result in later flowering in northern latitudes due to longer days.
- When fibre is extracted from hemp stems collected late in the season, the stems are lignified and break, which results in a lower yield of long fibre.
- The selection of genotypes that are easier to decorticate provides an advantage in terms of fibre quality and a reduction of costs related to fibre extraction.
- Both traditional retting processes, dew, and water retting, are based on a significant amount of manual labour, and these processes are not utilised in Western Europe. Dew retting is climate-dependent and leads to inhomogeneous fibre material. Water retting causes wastewater with a high oxygen demand and is environmentally questionable.
- A short period of field retting does not cause any noticeable change in the quality of the fibres.
- It was proposed that short-period field retting might be used to extract fibres more efficiently and accurately in combination with other methods, such as the application of targeted enzymes, selected microbes, or chemicals.
- The use of Bioreactors to control the biological degumming of peeled bark employing appropriate microorganisms and their enzymes was suggested as a promising solution, beginning with a homogenous material for the production of fibres of a high grade. Non-retted, green bark material that has been decorticated was the best beginning material for the degumming process.

- Dry decortication is said to be faster and is not constrained to the harvesting season, although fresh decortication often results in the production of fibres that are of higher quality.
- When used as non-retted, dried stems for mechanical decortication, the best time to harvest is roughly three to four weeks after "technical maturity", when the seeds are just starting to mature. One study concluded that the tensile strength of the bark wasn't negatively impacted by the unusually late harvest period.
- It is also possible to separate the fibres from crooked stems without difficulty by utilising enzymes and hydrothermal treatment.
- Good results were also found when retting both unreddened and retted hemp stalks with Novozymes enzymes, at a process duration of 16 to 24 hours, with the maximum loss noted for the un-retted hemp quality.
- Hydrothermal treatment with pH regulation, conducted either by soaking stems in acetic acid prior to treatment or equivalently with NaOH (Sodium hydroxide), both in a dilute solution, also had a clear effect on releasing the fibre bundles.
- The quality of the fibres in the Danish experiments for use in textiles was comparable to or better than that of cottonized hemp fibres after the processes of retting.
- Hemp that has been pre-treated with lactic acid exhibited an unfavourable level of cellulose degradation and a substantial loss of dry matter due to the enzyme process, as well as a significant reduction in strength.
- There is no processing system for the long fibre yield of hemp in Europe at this point.
- It is argued that "the limited market for high-quality hemp yarns does not justify the development of specialised hemp scutching and hackling lines, and hence existing flax processing lines should be used".
- Hemp has the potential to provide equivalent amounts of long fibres per hectare as flax and has the potential to be processed into quality fibre on the industrial flax line, with fibre yield improved by genotype selection.
- Results from an experiment to establish process parameters maximising the long fibre yield using flax-dedicated scutching and hackling devices at laboratory scale

showed tensile properties entirely suitable for textile use as well as for load-bearing composite materials.

- Hemp stems should be cut into two pieces during harvest that is each about 1 m long in order to enable processing on present flax scutching lines.
- With most of the fibre concentration in the bottom portion but the top part being finer with less secondary fibre, it was reported possible to increase fibre homogeneity by dividing the stem into two portions and keeping them separate during further processing.
- Flax cultivation is also possible in Iceland, which presents an opportunity for a combined production of both hemp and flax.
- On the subject of sustainability, the production of hemp does present the possibility of meeting many of the UN's 17 global goals for sustainable development.
- The hemp plant is a sustainable and affordable soil remediation plant.
- Hemp has demonstrated the ability to withstand heavy metal pollution thanks to mechanisms specific to the plant that does not impair biomass production and does not alter fibre quality.

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Completed search & literature list

Database: Science Direct, Google Scholar, Leitir.is

16 in total chosen articles from 3 different search machines. Most papers found on the Google Scholar and Leitir were also on Elsevier. Of the 16 papers, almost all of them were field trial research.

Database	Search number:	Search words	Result	Filter	Titles read	Abstract reviewed	Chosen articles
Science Direct / Elsevier	#1	"Cannabis Sativa" AND "industrial hemp" AND "hemp varieties" AND "long fibre" OR "long fiber" AND "fibre yield" OR „fiber yield“ AND "field trial" AND "fibre quality" OR „fiber quality“ AND "textile"	(1283) 194 after using filter (09.10.2022)	Article type: Research articles, Publication type: Industrial crops and products (167), Field crops research (27)	194	41	13
Google Scholar	#2	"Cannabis Sativa " AND "industrial hemp" AND "hemp varieties" AND "long fibre" OR "long fiber"	12 (included articles from search in Science Direct)	Boolean connectors,	12	12	(5)

		AND "fibre yield" OR „fiber yield“ AND "field trial" AND "fibre quality" OR „fiber quality“ AND "textile"					
Leitir.is	#3	"Cannabis Sativa" AND "long fibre" OR "long fiber" AND "fibre yield" OR „fiber yield“ AND "fibre quality" OR „fiber quality“	20 (included articles from search in Science Direct)	Advanced Search	20	11	3 (8)

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