Evaluation of hemp potential as a raw material in Portugal

Pedro António Albino Zilhão

Dissertação para obtenção do Grau de Mestre em

Engenharia e Gestão de Energia

Orientador: Investigador Ana Filipa da Silva Ferreira

Júri

Presidente: Prof. Edgar Caetano Fernandes
Orientador: Investigador Ana Filipa da Silva Ferreira
Vogal: Prof. Raquel Inês Segurado Correia Lopes da Silva

Outubro 2022

Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Abstract

This thesis studies Cannabis Sativa L (hemp) plant and its applications in order to assess the viability of hemp as a sustainable raw material. Some considerations regarding hemp biorefining in Portugal (where a heavy pulp and paper industry based in eucalyptus globulus plantations exists) are also made.

Based on the technological review and case study analyzed, its environmental impacts are similar to those of other fibers crops. However, when directly compared to eucalyptus globulus it has higher noxious emissions (N_2O NH_3 NO_x NO_3, CO_2) due to the use of fertilizers and farm equipment. Other environmental impacts such carbon uptake, impact on biodiversity, fire hazards and soil erosion were not considered. In economic terms, hemp seems to be a very profitable plant (single crop- 99.05€/hectare.year; dual crop- 648.16€/hectare.year), especially if it used as a dual crop (harvest of straw and seeds)

Applying the analysis to the Portuguese reality, where eucalyptus globulus represents around ¼ (777 800 hectares) of the planted forest stands, hemp can be a good substitute for part of these stands. In particular, for the abandoned ones, that represent the major fire risks and bring no economic return. At the same time, hemp can be used for paper production, so such a replacement doesn't necessarily mean a negative impact in the supply of pulp and paper industry.

Finally, due to the lack of data, final conclusions about establishing a biorefinery in Portugal, could not be achieved. However, a frame for a case study regarding the impacts of an integrated hemp production and biorefinery was laid out and discussed. Hopefully a deeper assessment of this matter will be done in the future.

Key words – *hemp, sustainability, Portugal, eucalyptus globulus, cannabis sativa L*

Resumo

Nesta tese foi feito um estudo sobre a planta *Cannabis Sativa L* (cânhamo) e as suas aplicações, a fim de avaliar se ela é um bom substituto para outras matérias-primas já sob pressão (madeira). Além disso, foram feitas considerações sobre uma bio-refinaria de cânhamo aplicada à realidade portuguesa (indústria pesada da pasta e papel baseada em plantações de *eucalipto globulus*).

O cânhamo é um valioso recurso de biomassa que pode ter um futuro promissor, com estudos e investimentos a ocorrem em todo o mundo. Tem impactos ambientais semelhantes a outras plantações para fibras, contudo, quando comparada diretamente com a cultura do eucalipto, tem mais emissões nocivas provenientes de fertilizantes (N_2O NH_3 NO_x NO_3, CO_2). No entanto, outros impactos ambientais como a absorção de carbono, biodiversidade, risco de incêndio e erosão do solo não foram considerados no caso de estudo. Em termos económicos, o cânhamo parece ser uma planta muito rentável (colheita de caule- 99.05€/hectare.ano; colheita dupla 648.16€/hectare.ano) especialmente se utilizado como cultura dupla (colheita do caule e sementes).

Aplicando à realidade portuguesa, onde o *eucalipto globulus* representa cerca de ¼ (777 800 hectares) dos povoamentos florestais plantados no país, o cânhamo pode ser um bom substituto para parte destes povoamentos. Em particular os abandonados, que representam os maiores riscos de incêndio, sem qualquer aparente retorno económico associado. Ao mesmo tempo, o cânhamo pode ser utilizado para a produção de papel, pelo que a substituição não significa necessariamente um impacto negativo na indústria da pasta e papel.

Finalmente, é também apresentado um esboço para um futuro caso de estudo sobre os impactos de uma instalação integrada de produção e tratamento de cânhamo (bio refinaria) em Portugal, com a esperança de que uma avaliação mais profunda da matéria possa ser feita posteriormente.

Palavras-chave – *cânhamo, sustentabilidade, Portugal, eucalyptus globulus, cannabis sativa L*

Contents

List of Figures

List of tables

Glossary

Abaca- a species of banana native to the Philippines, grown as a commercial crop
Alkaloids - nitrogenous compounds of low molecular weight
Cannabinoids - group of compounds found in the plant cannabis and human body
Carbon sink resource – is a resource that absorbs more carbon from the atmosphere than releases during its manufacturing
CELPA – Portuguese paper industry Association
Compaction - occurs when soil particles are pressed together, reducing pore space between them
Cultivars - varieties of cannabis strains
Endocannabinoid - endogenous cannabinoids, are cannabinoids made by the human body, very similar to phytocannabinoids
Essential Oils (EO) - a concentrated hydrophobic liquid containing volatile chemical compounds from plants
Inflorescence - complete flower head of a plant including stems, stalks, bracts, and flowers.
FSC - Forest Stewardship Council: non-governmental organization dedicated to promoting responsible management of the world's forests.
GWP_{100} – Global warming potential in 100 years
Nematodes - a worm of the large phylum Nematoda, such as a roundworm or threadworm
Hurd - the coarse parts of flax or hemp that adhere to the fiber in the inner stalk
Lignocellulosic biomass - is plant biomass that consists of cellulose, hemicelluloses, and lignin
Loamy soils - mixture of sand, clay and silt. It contains more moisture, nutrients and humus compared to sandy soil and better drainage compared to clay and silt soil
PEFC - Program for the Endorsement of Forest Certification: international non-profit, non-governmental organization, it's dedicated to promoting sustainable forest management
Phenols - class of organic compounds containing a hydroxyl group and a benzene ring
Phytocannabinoids - are cannabinoids that occur naturally in the cannabis plant
Phytoremediation – the use of plants to clean up contaminated environments
Polyunsaturated fatty acid (PUFA) - fatty acids that contain more than one double bond in their backbone
Retting - the process by which the pectic material, which binds the fibers to the remainder of the stem, is broken down and the fibers are liberated
Strains – sub-families of the plant
Terpenes - naturally occurring chemical compounds found in plants and some animals
Triterpenoids - metabolites of isopentenyl pyrophosphate oligomers
UWF - paper which contains little or no mechanical woodpulp
δ-9-tetrahydrocannabinol (THC) - the main psychoactive ingredient in cannabis plants

1. Introduction

1.1 Framing of the problem

Currently, society deals with a lot of problems. One of them is the sustainability of our actions. From industry to little personal actions, the whole world needs to join efforts to prevent reaching a point of no return in environmental and social issues (global warming, water and resource scarcity, population growth, animal and plant biodiversity, etc..). If it is to be successful in the long run, these efforts need to be sensitive to the economic, environmental and social consequences of human actions. Considering only one of these dimensions may seem to be a good idea in the short term, but it will bring negative impacts in the long term. [1]

At the same time, the needs of modern society are continuously rising, leading to increased demand for natural resources. *Bergh 2003* [2] concludes that the general growth of the world's society (welfare, economics, technological, etc…) cannot be developed by "simply incorporating new elements in existing practices but requires a completely different set of assumptions". Following this logic, if the world is to evolve in a more sustainable way, new materials and processing paths need to be discovered, and applied, in order to fulfil the increasing demand.

One major class of raw materials is biomass "…renewable organic material that comes from plants and animals" [3] A resource used since the dawn of man till the present day. Woody materials (coming from trees in forests and manmade forest stands) represent a heavy share of biomass consumption around the globe. Alternatives must be found in order to avoid putting more stress on the source of those resources (trees). Not just by developing new processes, but also by improving established ones, especially if we take into account the world's shift from fossil fuels to more renewable resources[4], ranging across all sectors, that will inevitably contribute for the increase in demand of biomass, a type of renewable resource.

1.2 Goals of the thesis

In this thesis, hemp (*cannabis sativa L*) is presented as an alternative raw material. Not just as a substitute for woody materials in fibre production (used in pulp and paper) and energy, but also for applications in other fields such as: biomaterials (bioplastics, bio-composites), food supplement, construction material, pharmaceutical, etc… At the same time, the hypothesis of establishing a hemp biorefinery in Portugal is considered and analysed. So, the thesis two main goals are:

- Assessing the viability of hemp as a sustainable raw material
- Making some considerations regarding establishing a hemp biorefinery in Portugal

In order to reach the first goal, an extensive literature review was undertaken gathering information regarding hemp and its known applications; an analysis of a case study assessing hemp plantation environmental impacts was also conducted.

In order to reach the second goal, two separate steps were undertaken. First, the benchmarking between a *eucalyptus globulus* plantation (a very used tree crop in Portugal) and a hemp plantation, to assess their respective environmental and economic impacts. Unfortunately, due to the lack of real data, the second step, evaluation of a biorefinery, where not only the pulp and paper production would be considered (due to the size of these industries in Portugal), but also the production and selling of other by-products, could not be undertaken. Nevertheless, with the goal of trying to assess the viability of such a project, several comparisons and examples taken from the literature are given to try to assess the economic and environmental impacts that it would have.

1.3 Structure of the thesis

The thesis is organized in 6 chapters.

Chapter 1: Introduction - In the Introduction an explanation of the problematic in hands, and the goal of the thesis are done. Finally, a section explaining the structure of the thesis is presented at the end.

Chapter 2: State of the art – Here a scientific review about the main topics is done. The characterization of *cannabis sativa L* is done, not just of the plants itself, but also of the plantations and their impacts. What is a biorefinery and the status of hemp biorefineries around the globe. Focusing on Portugal, a quick summary of the pulp and paper industry is done, as well of the *eucalyptus globulus* crop.

Chapter 3: Plantation Life cycle analysis: case studies – In this chapter two case studies are analyzed and compared. First of a *Cannabis Sativa L* plantation in a typical European situation, and second of a *eucalyptus globulus* plantation in Alcochete, Portugal. Both case studies are assessed in economic and environmental terms. Regarding social impacts, considerations are also done.

Chapter 4: Discussion of the Results – Here, the results and conclusion obtain in the previous chapter are discussed and evaluated. Is tried a direct comparison of the 2 plantations, in terms of the economic and environmental impacts. But also benchmarking with others similar crops (pines for eucalyptus and other fibers crops for hemp)

Chapter 5: Hemp biorefinery in Portugal – In the fifth chapter, based on the literature review and previous case studies, considerations about a hemp biorefinery in Portugal are made. Also, a work frame for a future case study is considered with the hopes of a deeper assessment in the future.

Chapter 6: Final Conclusions and Considerations – Here the final conclusions about the topic of the thesis are presented, as the main issues regarding the making of the thesis.

2 Literature review

In this chapter an overview of the current literature is done, in order to give a solid background for the assumptions and conclusions taken during this thesis. A deep characterization of hemp is made, and its applications. The concept of biorefinery and in particularly hemp biorefinery are also investigated, and a brief resume of the state of the paper and pulp industries around the world and in Portugal.

2.1 Hemp characterization

Hemp is in fact cannabis! Classified into the family Cannabaceae, cannabis has three main sub-species/strains: *C. sativa, C. indica,* and *C. ruderalis*. (fig. 1) [5] However, each subspecies can have hundreds, or even thousands of cultivars. Industrial hemp is *Cannabis Sativa*, in particular*, cannabis sativa L.* and is characterized by a concentration of δ-9-tetrahydrocannabinol (THC) content lower than 0.3% in the US. [6] In the EU, currently the maximum is 0.2%, but a new Common Agricultural Policy was approved in 2021, increasing the maximum THC content to 0.3%, starting in 2023, increasing the varieties of cultivars that can be used in the old continent. [7]. These percentages make impossible to use hemp as a psychotropic drug [6], while marijuana THC content normally falls between 10–30%. [8] Nevertheless, hemp it still is rich in other chemicals called terpenes, phenols, and cannabinoids like (CBD), (CBG), (CBC), (CBDV), (THCV). These compounds occur almost uniquely in hemp and marijuana plants (cannabis plants). In total, cannabis contains about 60 cannabinoids, holding pharmacological properties. [9] In fact, mammals (therefore humans) have an endocannabinoid system (ECS), a complex endogenous biological system, that regulates body functions including cognition, sleep, mood and behavior, stress response, energy metabolism, pain control, learning and memory, reproduction, food intake, immune response, cancer progression, and much more. This system is yet not fully understood but has gathered great attention as a potential therapeutic avenue in several pathological conditions, including neuropsychological disorders and neurodegenerative diseases. [10,11]

Physically, the plant is characterized by long, thin flowers and spiky leaves [5] and it's impossible to distinguish between marijuana (when is also from sativa strain) and industrial hemp purely by looking at the plant [6]. Unlike other strains, *C. Sativa* strain spread throughout harsher and moderate climates, making it stronger and ideal to industrial applications.

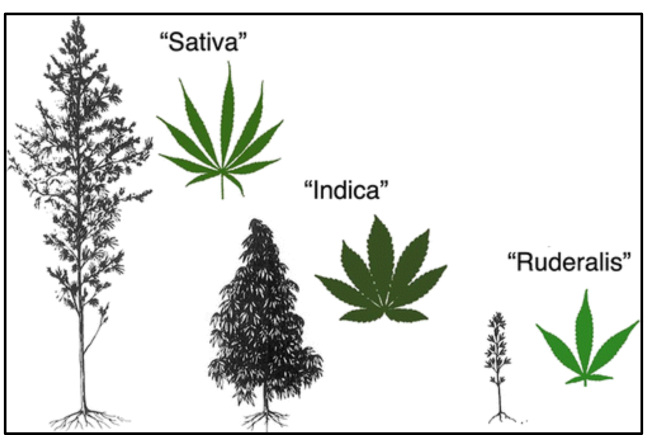

Figure 1 Cannabis strains and their taxonomy. [97]

2.1.1 Hemp history

Throughout history, hemp has been a very important plant acting as a crucial raw material. It is thought that is native from Western and Central Asia, where it grows wild. [40] Evidence dating back to 8000 BC show rests of hemp fabrics in ancient tombs. From then on, evidence of hemp being used for almost everything (clothing, paper, food, medicines, sails, ropes) exists around the world. [8] Some of the most common examples of the importance of hemp in the ancient days are: from the ancient Egypt's to the first Gutenberg bible and US declaration of independence, hemp paper was used. The Vikings in the first millennium, to the Portuguese in the discovering age, used ropes and sails made with hemp fibers. There were times in history, where hemp crops were even incentivized/mandatory in times of need in some countries (in England in the 16th century, and even during the WWII in the USA). With the development of technology, even the car industry used hemp, with the Ford Model T having body parts made with hemp composites. [6,8,12–14]

In the end of the 19th and beginning of the 20th century the relationship between Man and Hemp deteriorated. Productions started to decrease in Europe and Americas in the late 19th century due to several economic and technological factors: the replacement of sail ships with steamships, the availability of abaca fibers and ropes, the development of the paper industry using wood pulp[15], and the availability of other less expensive and softer fibers such as cotton, (during the 18th century the cotton industry had come across major breakthroughs). In addition, synthetic fibers such as polyester, nylon, and acrylic were invented in the 1930s and 1940s, becoming major fiber competitors after WWII [14]. In 1937 the American government banned Hemp nationwide, due to its association with marijuana, stating that Hemp was "a drug for recreational purposes, implying violent behavior, crime affinity and insanity when exposed to it". [12] During WW2 hemp crops were desperately needed again for war supply, so, for that period, the cultivation of hemp was strongly encouraged under the slogan "Hemp for Victory". However, the plant was banned once again after the war and the negative image campaign against hemp resumed. [14] The hellish view towards Hemp rapidly spread to Europe and in 1961 the UN achieved the complete prohibition in all member states, by "The Single Convention on Narcotic Drugs".[16] In a space of less than 100 years, Hemp went from one of the major crops worldwide, to be ostracized in the western world and almost forgotten.

In the nineties (1992) the EU changed its regulations and the prohibition of cultivating industrial hemp was abandoned. Steady but slowly the investigation of Hemp has resumed, and many new properties have been discovered since, especially in medicine, composites and biomaterials, and civil engineering.[12] Even the US, historically the grate adversary of Hemp, has legalized industrial hemp in 2018 through the 2018 Farm Bill. [6,17]

2.1.2 Hemp constituents

The hemp plant is sometimes referred as a “natural biorefinery” due to the fact that from the different constituents of the plant, thousands of different applications can be used. The most important components of the plant are the stalk, the seeds, and the flowers, however, the roots, the stems and the leaves also represent valuable opportunities and applications. In figure 2, is possible to see a general scheme of hemp constituents and applications.

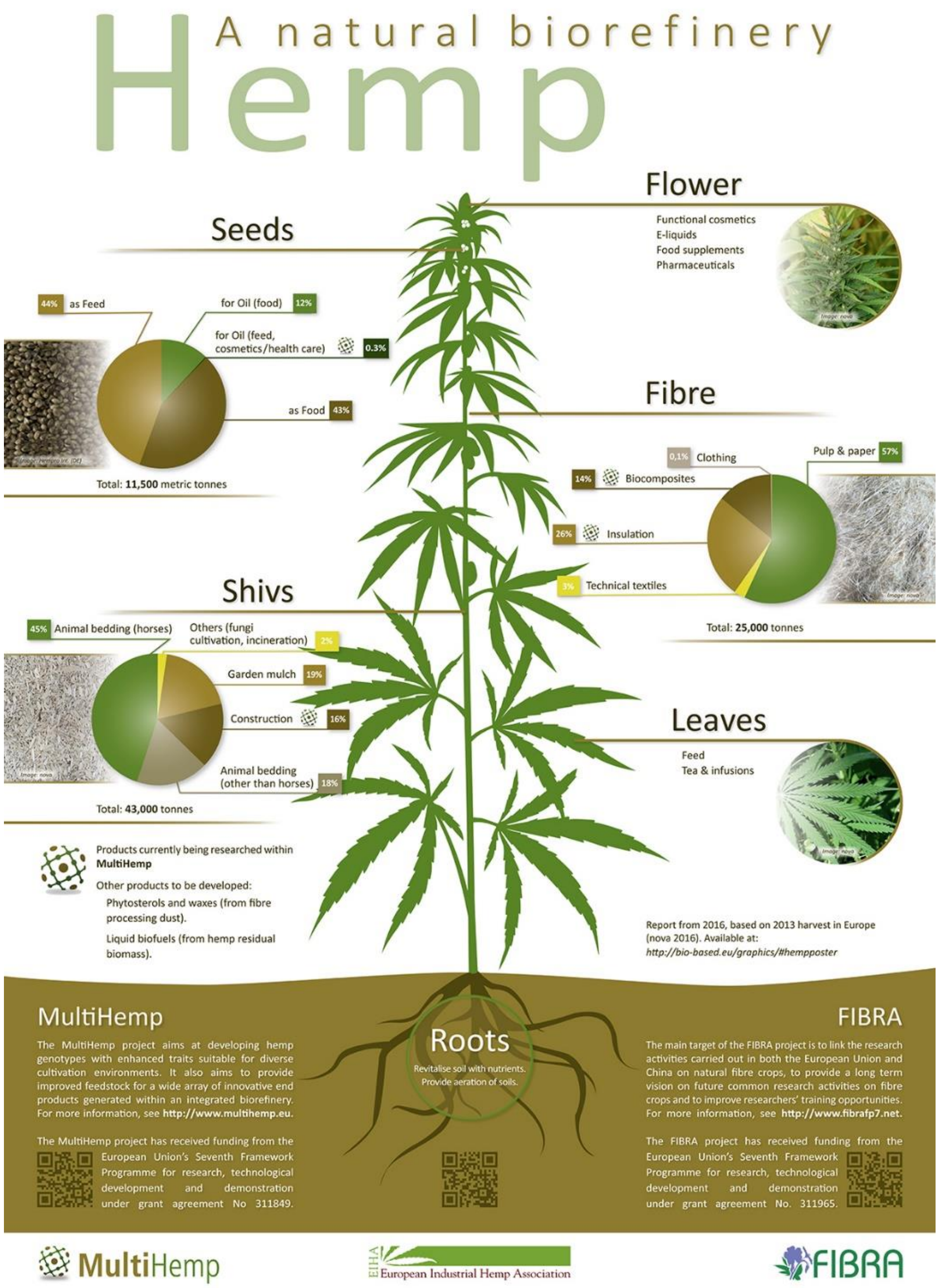

Figure 2 Schematic of hemp different constituents and their applications [98]

Roots- The cannabis roots (fig. 3) can go up to 1.5m in depth and have an average thickness of around 200μm.[18] Studies has showed that hemp roots have reclamation and anti-erosion influence, and it can drain soils from poisonous substances (even radiation) and heavy metals. [19]. After harvesting, the roots have therapeutic applications and are used as a popular medicine for inflammation, fever, gout, and pains for thousands of years. Despite not being as rich in cannabinoids and terpenes they are rich in other compounds, including the triterpenoids, like friedelin and epifriedelanol; alkaloids, (ex: cannabisativine or anhydrocannabisativine); and other compounds that have medical properties.[20] Besides, they can also be used as fertilizer (biomass residue).

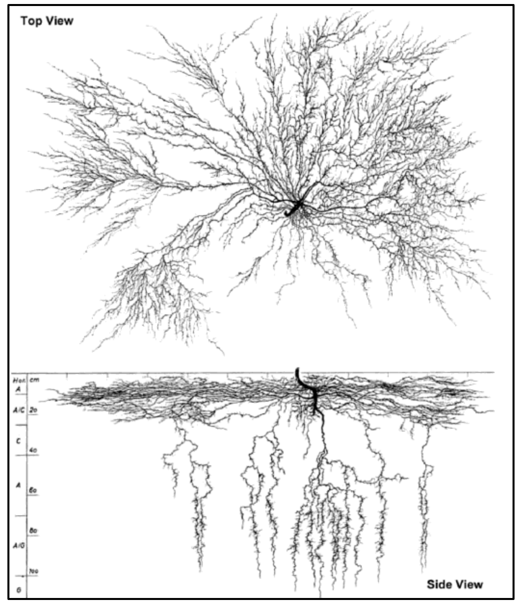

Figure 3 Schematic of hemp root system [99]

Stalk- The stalk of Hemp is composed of several different parts. The two main constituents and with interest are: the hurd or shiv, the inner woody part of the stalk, and the fibers, the more exterior part of the stalk, before the epidermis. They are organized in a concentric way and inside, the stalk is hollow, as it can be seen in the schematic on the right. (fig. 4)

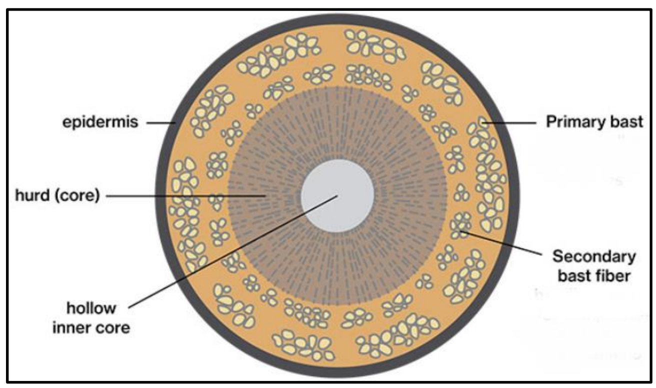

Figure 4 Scheme of hemp stalk [100]

Regarding bast fibers, the array of compositions can vary between 20 – 40% of the stalk weigh, depending on the cultivar [21]. Are generally composed of 55-90% cellulose, 4-18% hemicellulose, 1-17% pectin, and 1-21% lignin. [21,22] There are the primary fibers, longer and thicker (20 mm long and 10 –40 μm in diameter) than the secondary fibers (2 mm long and approx. 15 μm in diameter). For example, the primary fibers with a greater cell length and higher crystalline cellulose content levels are preferred to secondary fibers for composite reinforcement, however the separation of the two fiber types is difficult and secondary fibers remain attached to the primary fibers thereby affecting the overall quality of the harvested material. The amount of secondary fibers varies according to the position in the plant stalk/stem (greater at the base) and increases with plant age.[23]. Hemp fibers can be used for textiles, paper, building material, energy generation, bio-composites and an array of industrial products. [24]

Just for a quick comparison, as a fiber crop, hemp provides a high yield; it produces 250% more fiber than cotton and 600% more fiber than flax, from the same acreage [14]. Because it grows fast and surpasses weeds, it doesn't need no herbicides after sowing, and few pesticides.[25]

Due to the capability of Hemp being a carbon sink resource, the use of its fibers in composites can generate carbon negative material. On top, if we compare with the production of artificial fibers (glass fibers or carbon fibers), that not only require a lot of energy to produce, but also emits carbon, and other noxious substances for the environment and public health, [26,27], hemp fibers seem more sustainable. However, the main problem associated with natural fibers is the lack of homogeneity and high hydrophily of natural fibers resulting in high moisture absorption. [22]

Hemp hurds (taken form the inner stalk) represents the rest of the weight of the stalk (60-80%) contains 40-48% α-cellulose, 18-24% of hemicellulose and 21%–24% lignin as major components, along with 4.0% extractives (oil, proteins, amino acids, pectin) and 1.2% ash.[22,28]. The hurd is the least valuable part, chemically similar to wood. Nevertheless, it can also be used for paper making [15] and interesting thermal and acoustic isolation properties are being investigated, not only for animal bedding but also for construction material, such as hempcrete, a lighter material, therefore with less structural strength, but with better thermal and acoustic isolation capabilities. While being a carbon negative material.[29] Others inheriting properties of hemp hurds are: low density, aseptic, biodegradability, low costs and ecological suitability of this raw material are also aspects to take into account. [22]

Seeds- Hemp seeds have a lot of potential. Are composed of a shell and the nut. At the same time from the whole seed hemp oil can be obtained (fig. 5).

The nut is fitted to be consumed by people, and also animals, and are an important source of easily digestible protein (20–25%), polyunsaturated fatty acid (PUFA) abundant lipids (25–35%), carbohydrates (20–30%) and high in insoluble fibers. Besides, they have present in smaller amounts carotene, phosphorus, potassium, magnesium, sulfur, calcium, iron and zinc as well as vitamin E,C,B1,B2, B3, B6. [30] They deliver a desirable ratio of omega-6 to omega-3 PUFA, which can improve cardiovascular health, reduce osteoporosis symptoms, and diminish eczema conditions. [14]

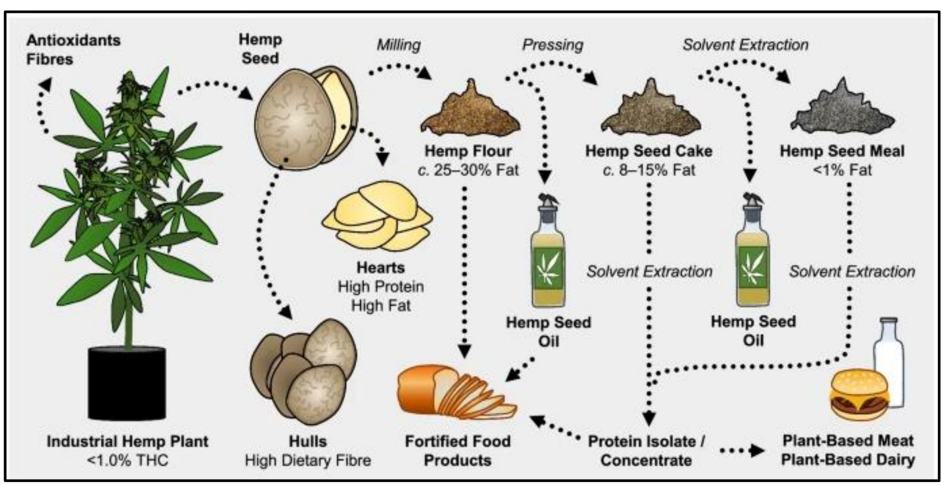

Figure 5 Flow chart of hemp seeds applications [101]

At the same time, despite having lower levels compared with the flowers, the seeds also contain valuable phytocannabinoids, (THC, CBD, cannabigerol (CBG), cannabichromene (CBC), etc..) which are naturally occurring cannabinoids that are unique to the Cannabis plant. These compounds interactions with the endocannabinoid system is not yet fully understood and seems complicated however, has shown potential therapeutic properties that make it a potential therapeutic future agent for central nervous system diseases, such as epilepsy, neurodegenerative diseases, and multiple sclerosis. [14] The oil is also rich in important compounds like tocopherols, a natural antioxidant that can reduce the risk of oxidative degeneration related disorders. Terpenes and polyphenols, which contribute to the odor/flavor and intrinsic antioxidant activity.[14] And phenolic compounds, that promotes the anti-inflammation capacity on human beings [31], like flavanones, flavanols, flavanols, and isoflavones.[14]. Application in dermatology and as cosmetic ingredients are also very promising[32] and are already in use in some products/countries. The cake, a byproduct of oil manufacturing, is suitable for animal food and organic compost; however, studies are being made to add value to this resource [33].

The hemp seed oil, besides food and medical applications, can also be use to manufacture industrial materials as solvents, varnishes and fuel as a bio-diesel. Depending on the production method and blends, different results occur, but studies are being made and show promising results. Not just in emissions and production methods, but also in efficiency of the fuel itself. [34,35]

Flower

Cannabis flowers are small and bushy (fig.6). In marijuana plants, this is the most valuable resource of the plant, where the THC and other cannabinoids content is higher. In hemp, THC is present in negligible quantities (<0.3%), but all the other important chemicals are still present like (CBD), (CBG), (CBC), (CBDV), (THCV), terpenes and flavonoids that are beneficial for health. Depending on the cultivar, the exact percentages vary. So, in plantations where the creation of medical hemp products is the goal, flower and seeds are the main resource due to the high content of cannabinoids. [17] Nevertheless, in hemp plantations where they are not the main goal, they are often discarded as a residue for burning or composting. [36]

Figure 6 Cannabis flower

Nowadays, medicinal hemp has an array of already known medical uses such as: anti-inflammatory, analgesic, appetite-stimulating, anti-emetic, and anti-proliferative agent in terms of tumor cells. CBD based medicines (syrup, supplements, drops, etc.…) are more common and spreading rapidly and are used as an anti-psychotic, anti-nausea, neuroprotective, anti-cancer, and anti-diabetic agent, all without resulting in strong side effects. Other components such as CBG, terpenes and terpenoids can also be found in hemp and studies have reported potential pharmaceutical value as drugs or supplements, however more studies need to be done in this area. [37,38]

In *Bertoli 2010* [36], a consideration of using inflorescence from hemp cultivars crops grown for fiber is made. It's concluded that the harvesting of the essential oils (EO) in the inflorescence can be done in parallel with the harvesting of the fiber from the stalk. Despite, the EO obtained is different of other medical hemp purposed cultivars, but still has important properties and can be used as alternative flavors and fragrance additives.

Leaves & Stems

Nowadays, leaves (in fig 1) and stems in hemp plants are mostly seen as a crop residue, used as fertilizer or as biomass for generating energy (burning). The hemp industry, today, is mainly addressed to the production of seeds for flours and fixed oils extraction, as well as for the production of hemp fibers and hurds obtained from stalk. However, studies like [35,39,40] are trying to further explore these by-products.

In *Zhu 2021 and Ascrizzi 2020* [39,40] leaves further application where explored. In the first study as a nutritional complement/flavor addition, while for the second as an anti-fatigue drink, made with hemp leaves water extract (HLWE). Mice were subjected to swimming activities to simulate a fatigue generation situation. Based on the results, the potential of HLWE as an anti-fatigue food or drug is tremendous, not just reducing the formation of lactic acid, but also increase the activity of antioxidants defense enzymes.

In *Müssing 2020* [35], the focus are fibers (from process losses and stems) to use as a reinforcing agent for PLA polymers. At the same time, considerations on the harvesting time and cultivar variety are also done. In the study it was concluded that these types of fibers are suited for the manufacturing of PLA reinforced polymers. Also, it was concluded that harvesting times and cultivars influenced the results, being the harvesting time more impactful.

2.1.3- Hemp plantations

As already said, hemp crops can have different goals and outcomes, nevertheless is always an annual plant, growing from the seed every year. Depending on the desired final product, different ways of planting and maintaining the crop can be done. In general, industrial hemp crops are outdoors and depending on the purpose (fiber, seeds, flower) they have different characteristics.

One major characteristic of the cannabis plant is the fact that is dioecious: meaning that are different plants, male and female. Each with distinctive growth characteristics. The males are more suited for the production of hemp fibers, especially if there are only males. Fiber crops are dense, this will discourage the plant from flowering, forcing into grow taller (reaching up to 5m tall), with less branching, maximizing the number of fibers from the stalk. [14] As a fiber crop, a density of 30-65kg of seeds per hectare is suitable, depending on the cultivar. [41,42] (fig. 7)

In contrast, the females are more suitable to produce flowers since the female plant, in isolated situations (without males), do not produce seeds, and, if it doesn't get pollinated, it will maximize the growth of the flower and its cannabinoids contents. In hemp grown for medical purposes and essential oil, the main goal are the female unpollinated flower so, just like marijuana plantations, need more care, some are indoors and, to not affect the quality of the buds/flowers, while improving yield by letting the canopy grow, the plantation cannot be very dense.[17] (fig. 7)

So, depending on the purpose of the crop, different mixes of percentages of males and females will have different outcomes and objectives. Nowadays, with all the selecting breading and genetic manipulation, it already exists monoecious plants, that have both male and female parts. These plants are ideal for seed production.[43] A density of around 20kg/ha is recommended, but again, depending on the cultivar. [41,42]

Figure 7 Hemp crops orientated for seeds and/or inflorescence. (left) Hemp crop orientated for fibers. (right)

Regarding the quality and conditions of the soil, the literature has some contradictive information. However, most agrees that a pH around 6 is the best. [9,44,45] Grows in a large array of soils, but the preferred soils for hemp cultivation are loamy soils. [9,14] Nevertheless, hemp is sensitive to flooding and compaction. [44] The plants root system, due to its size and depth, additionally has a positive effect for farmers, as it aerates, improves the soil structure (prevent soil erosion and nutrient leaching) and even help removing poisonous substances and heavy metals (phytoremediation) from the soil and storing them within the plant. [46,47] Finally, it can be used as a rotational crop, increasing the yield of the succeeding crop in rotation cycle up to 10–15%. [48]

Regarding soil preparation, is like other spring crops, such barley, wheat, and oats. In the previous fall or winter the soil need to be plough. After resting during the winter, a fine seedbed is lay during the spring, just before sowing. Regarding fertilization, it depends on the cropping systems and rotational scheme in use but is similar to that of spring wheat. Additionally, hemp tolerate organic fertilizers like pig slurry. [42,49] Finally, during the growing season, exists continual shedding of the leaves, adding moist organic matter to the soil. These properties make hemp a good alternative to use in crop rotation programs to improve the yield of the main crop [14,19,45]

Regarding water, it is a medium to low demanding plant, only needing about 500 to 700 mm of precipitation/year [45] To have a comparison, here we show several different crops with different water needs. (Table 1) Crops like sugarcane or cotton, important industrial crops have bigger needs. Comparing to crops use as food source like tomato, potato, citrus, sunflower or banana has similar to lower needs. Despite the long roots, reaching up to 1.5meters underground, the average precipitation in all Portugal, is above 700mm/year (roughly 880mm/year)[50] depending on the location, the plant can take all of its required water uptake from the rain/ground water.

Regarding climate, cannabis has showed that can grow all over the globe, particularly in humid atmospheres. However, industrial hemp (*cannabis sativa L*) is adequate to moderate to cold climates, outside of the tropical zones. [45]. Hemp is a short-day plant, meaning that needs a minimum amount of darkness to start flowering. In most strains of industrial hemp, 13-14 hours of darkness are enough to start flowering, corresponding with the end of the summer/beginning of autumn in the northern hemisphere. [9].

The complete growth cycle of a hemp plant from germination to seed maturity takes between 4 to 6 months on average (fig. 8). Under optimal weather conditions the plants can grow up to 10 cm per day [45]. This is the reason why hemp is one of the only crops where almost no herbicides and pesticides need to be utilized after sowing, since the hemp outgrow the weeds and suppresses levels of fungi and nematodes in the soil. [14,25] As a comparison, cotton plantation, despite only using around 2-3% of global arable land, uses around 25% of worlds insecticides and 11% of pesticides. [24,51] Other benefit of the quick growth is the capacity of "carbon locking" in the plant, making it an excellent candidate for carbon sequestration.[14]

Crop	Crop water need (mm/total growing period)
Alfalfa	800-1600
Banana	1200-2200
Barley/Oats/Wheat	450-650
Bean	300-500
Cabbage	350-500
Citrus	900-1200
Cotton	700-1300
Maize	500-800
Melon	400-600
Onion	350-550
Peanut	500-700
Pea	350-500
Pepper	600-900
Potato	500-700
Rice (paddy)	450-700
Sorghum/Millet	450-650
Soybean	450-700
Sugarbeet	550-750
Sugarcane	1500-2500
Sunflower	600-1000
Tomato	400-800

Table 1 Different annual crops water requirements [102]

Depending on the objective of the crop (fiber, seeds, flowers, mix), different harvesting periods can be the optimal time. When fiber is the goal, harvesting is done at the flowering stage, and seeds are not collected, for example, [14] but on average, essential oils and fiber hemp varieties require 70–120 days from seeding to harvest, and grain hemp requires 120–180 days.[42] In Figure 8, the intervals of the growth cycle of hemp can be observed.

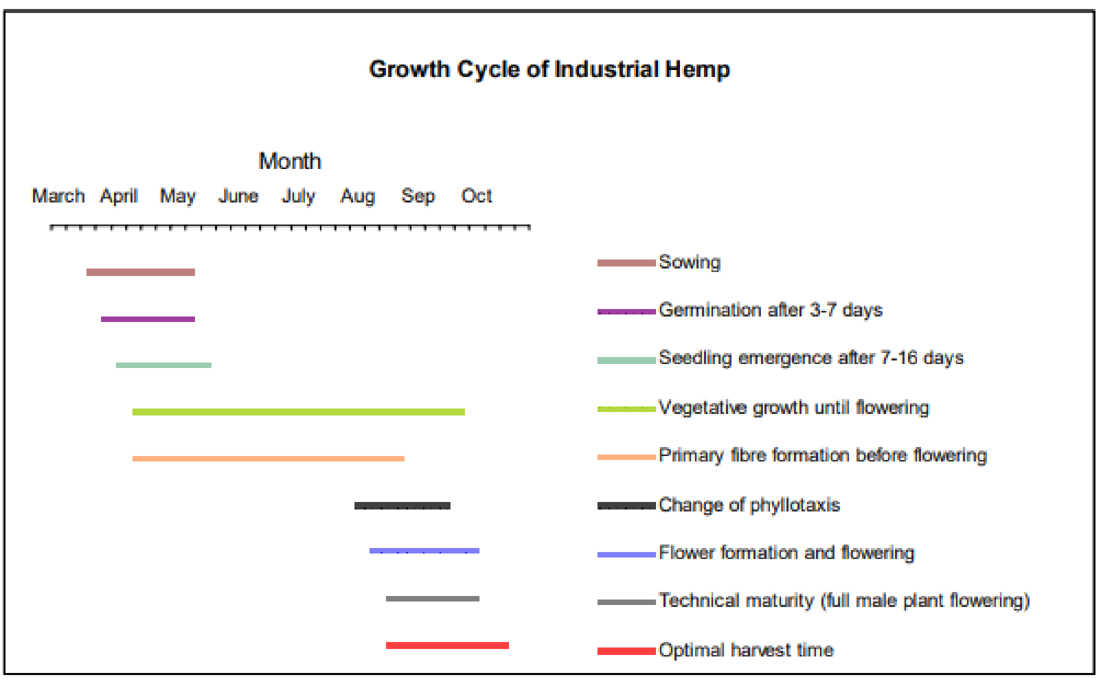

Figure 8 Growth cycles of hemp plant. [45]

2.1.4- Hemp industry in Portugal

In Portugal, the Hemp industry is very undeveloped. Nevertheless, it was one of the major resources of the country for centuries, especially for the maritime and textile industries. It was grown mainly in the fields of Ribatejo (Mondego and Tejo valleys) but in the current reality, hemp is scarce in Portugal. [13] For example, it is estimated that only 14.2 hectares have been planted between 2015-2018. [52]

During the 20th century, hemp was ostracized from the western world due to the association with marijuana and Portugal was no exception. [12,13] In the late 90's Portugal gave an important step in decriminalizing drug users, a small first step in the re-embrace of the cannabis plant. [52] Bills and laws have been passed ever since and in 1994 a parliamentary decree legalized industrial hemp once again in Portugal.[53] In the following years it was even incentivized, however during the next 2 decades was almost forgotten. Mainly due to the complications to have legal licenses. The laws were unclear and there were several government agencies responsible for the authorization to grow hemp. Many times, nobody would assume the decision, originating a bureaucratic nightmare just to obtain the permission to grow. [54] Only in August 2020 a Bill was produced stating that, independent of the application, any plantation of hemp is subject to authorization. For industrial applications Direção-Geral da Alimentação e Veterinária (DGAV) is the regulatory body, while for medical purposes is needed the authorization from INFARMED, the medical governmental entity from Portugal. Also, informing the local law enforcements and some personal information is also required. Even after this bill is still a hard and a time-consuming process to obtain permission because of the association with marijuana.[53,55] However during the 21st century more and more reports, like the recent 2020 "European Green Deal" from EU, where it has a whole page showing how environmental beneficial hemp could be (carbon storage, breaking the cycle of diseases, soil erosion prevention, biodiversity, low or no use of pesticides) are contributing to the shifting of old mentalities.[56]

Nevertheless, the shift is still confusing, for example, in 2021 happened a situation where a British citizen living in Portugal was arrested for planting hemp. It was its 4th year planting hemp, nevertheless the authorities argued that was marijuana, and adding the shifts in the laws and permits of the year before, they ended up by presenting the hemp plantation as "marijuana" and the plantation was destroyed. In fact, in the same year, only 22 of the 69 requests to plant hemp were approved. [57] Also, in 2022 an update of the 2020 bill was made and a minimum of 0.5ha is now required to have a permit to grow hemp, affecting the usage of the crop by small landowners. [58]

2.2 Concept of Biorefinery

"Biorefinery" is a concept based on the definition of a regular oil refinery, but applied to the refining of biomass, instead of oil, into multiple products. These products can be in various forms, such as chemicals, energy, fuels, fibers, oils and others. [4]

As stated in *Paone E, 2020* [59] "lignocellulosic biomass, ranging from softwood to agriculture and forestry wastes, represents the most abundant resource for modern biorefinery", biomass can be the future of biorefinery, in fact, the term "second-generation biorefinery" (use non-food biomass as feedstock) is an emerging one, mainly including the usage of lignocellulosic biomass to produce cellulose and lignin [60]. Industrial hemp (*Cannabis Sativa L.*) can be a valuable option, since all the main hemp components can find application within different biorefinery approaches, adding value to the conventional hemp crops (fibers, flower or seeds). [47]

2.2.1 Hemp Biorefineries

A Hemp biorefinery is something that already has been theorized but is yet to happened. Several studies have been done, where critical evidence shows how hemp regular crops (seeds and fibers) can be done, while maximizing profits and sustainability with the valorization of residues. (hemp hurds, stems, leaves, flowers and roots). Nevertheless, no case study, or evidence, of a working hemp biorefinery was found.

In *Moscariello 2021* [47], the focus of the study is a hemp biorefinery and biofuels (biodiesel, bioethanol and biomethane), and the different ways they can be obtain from different parts of the hemp plant. In Table 2 is possible to see the different fuels that can be achieved from the different parts thought different processes. At the same time, a technical/economic analysis is also conduct on the revenues on 2 different theoretical biorefinery approaches. In Fig. 9 is showed one of the scenarios (left) and its possible revenues (right).

Raw-materials / Transformation processes	Fibers	Seeds	Residues (Hurd, leaves, inflorescence)
Transesterification		Biodiesel	
Enzymatic hydrolysis +anaerobic fermentation	Bioethanol	Bioethanol	Bioethanol
Anaerobic digestion			Biomethane

Table 2 Biofuels that can be obtained from different parts of the hemp plant, through different transformation processes Based on Moscariello 2021 [47]

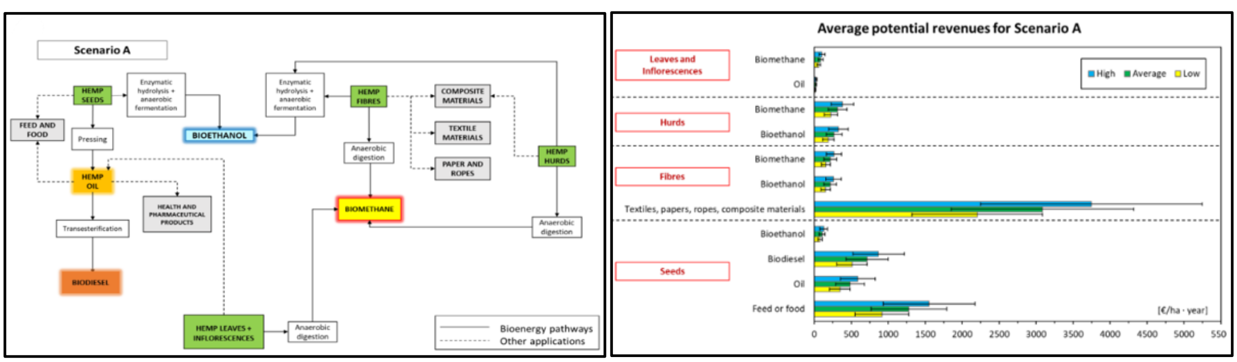

Figure 9 Flow diagram of a hemp biorefinery (left) and estimated revenues (right) [47]

In *Setti 2020* [33], the focus are seeds residues, in particularly hemp bran (HPB), compacted bars originated during the processes of converting seeds into flower and oil (the desirable final products). Usually, HPB is discarded or used as animal feed, but in this study 3 different processes were study to evaluate the viability extraction of polyphenols and proteins from HPB.

1 – chemical extraction followed by enzymatic digestion,
2 – liquid fermentation by strains of *Lactobacillus spp*
3 – solid-state fermentation by *Pleurotus ostreatus*

The study concludes that seed residues (HPB), even after the industrial processes that are submitted, still have bioactive compounds that can be transformed to value-added products for food, cosmetic and pharmaceutical industries. However, it assumes processes can still be improved and does not make an economical/technological feasibility study.

There's also the MultiHemp project [49], developed within Europe (across Germany, Italy, France and Netherlands) between 2013-2017 with the support of the European Union. In one of the final reports of the study, not just all the different steps before the factory (sowing, plowing, harvesting, transportation) hemp as to go through, but also 2 biorefinery scenarios were developed and assessed. One of a small transformation plant (1500kg/h) and a big transformation plant (4000kg/h).

The idealized scenario was of a "total fiber line" where only hemp stalks would be harvest and several products could be obtain (fig 10). (the tables showing the specifications and results of the case study are in Annex A). The study showed positive results, with positive economical return with the technologies of today

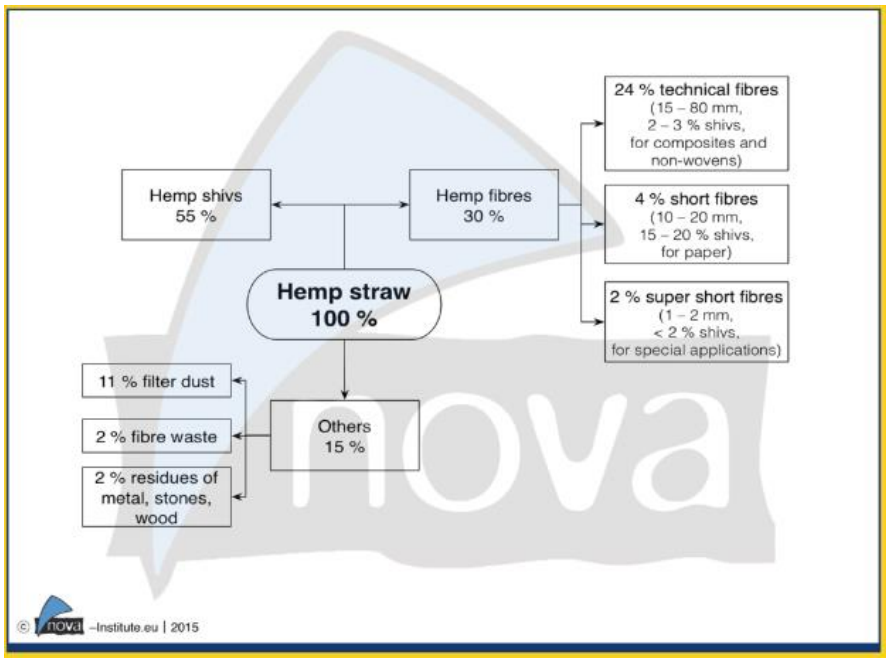

Figure 10 Total fiber line flow diagram [49]

Other example is the Hemp-30 project [61], developed by the York University, in the UK. It's not a biorefinery project, but instead a national project for the industry. Nevertheless, shows the willingness of developed countries in betting in this material.

It received financial support from the state and the plan is to make hemp a major crop in the UK in the next 10 years, increasing 100-fold the national production from 800 hectares to 80,000 hectares. The ambition is to use hemp across a range of industries, while offering environmental benefits such as a fast-growing 'break' crop that improves soil health and is efficient at capturing carbon, while creating new resources for a numerous of industries.

2.3 Portuguese Pulp and Paper industry

The pulp industry and paper industry go hand to hand, many times being bundle together. The pulp is the only raw material to make paper, while for making the pulp different raw materials can be used, even old paper (recycling of paper products).

Paper products are not just fine paper like printing/office paper or newspaper, but also cardboards, flyers, napkins, receipts, toilet paper, industrial papers, etc… meaning that, despite all the digitalization occurring around the world, contributing to less paper products, do not outstrip the rise in demand. [62]

In 2020, the global market size of the paper and pulp industry was almost 350bn USD, with around 400 million metric tons of paper products produced [63]. Employed a little over 1million people worldwide [64] and is an energy-consuming giant. In 2017, this industry was one of the largest consumers of energy, accounting for 6% of global industrial energy consumption [65]. At the same time, is one of the contributors for worlds pollution, classified as the 6th most polluting industry in 2019, contributing with gaseous, liquid and solid wastes discharges to the environment [66]. In 2010, Paper products constituted the largest single fraction of municipal solid waste. [67].

In Portugal, according to the yearly CELPA, the pulp and paper industries represented in 2019, 1.3% of the national GDP and employed 4400 people directly.[68] In the same year, with a production of 2.8 million tons of virgin pulp (1.2Mton converted into paper nationally, 1.6Mton to sell in the market) Portugal was the 3rd largest European producer of virgin pulp, with 7.2% of the market share. The largest clients were Spain, France and Germany, representing almost 45% of the exports. Form the pulp, 2millions tons of paper products were obtain. Of those, 71.3% were office paper, 19.7% were packaging paper and cardboard and only 9% where tissue. [68]

Regarding paper and cardboard production Portugal is the 11th European producer, with 2.5% of the market share. However, if we only look at uncoated woodfree (UWF) paper Portugal is the 2nd largest European producer, with 17.9% of the market share. [68]

To fuel these industries the main raw material used is *eucalyptus globulus*, a plant species native from Oceania, but due to the unique characteristics and geographic localization of Portugal, it gets along very well here. Is characterized for high yields, relatively short harvest periods and low maintenance required [69]. The national production is almost entirely for the pulp and paper industry, with a small amount (around 2% in 2016) for wood production. (fig. 11) [70]

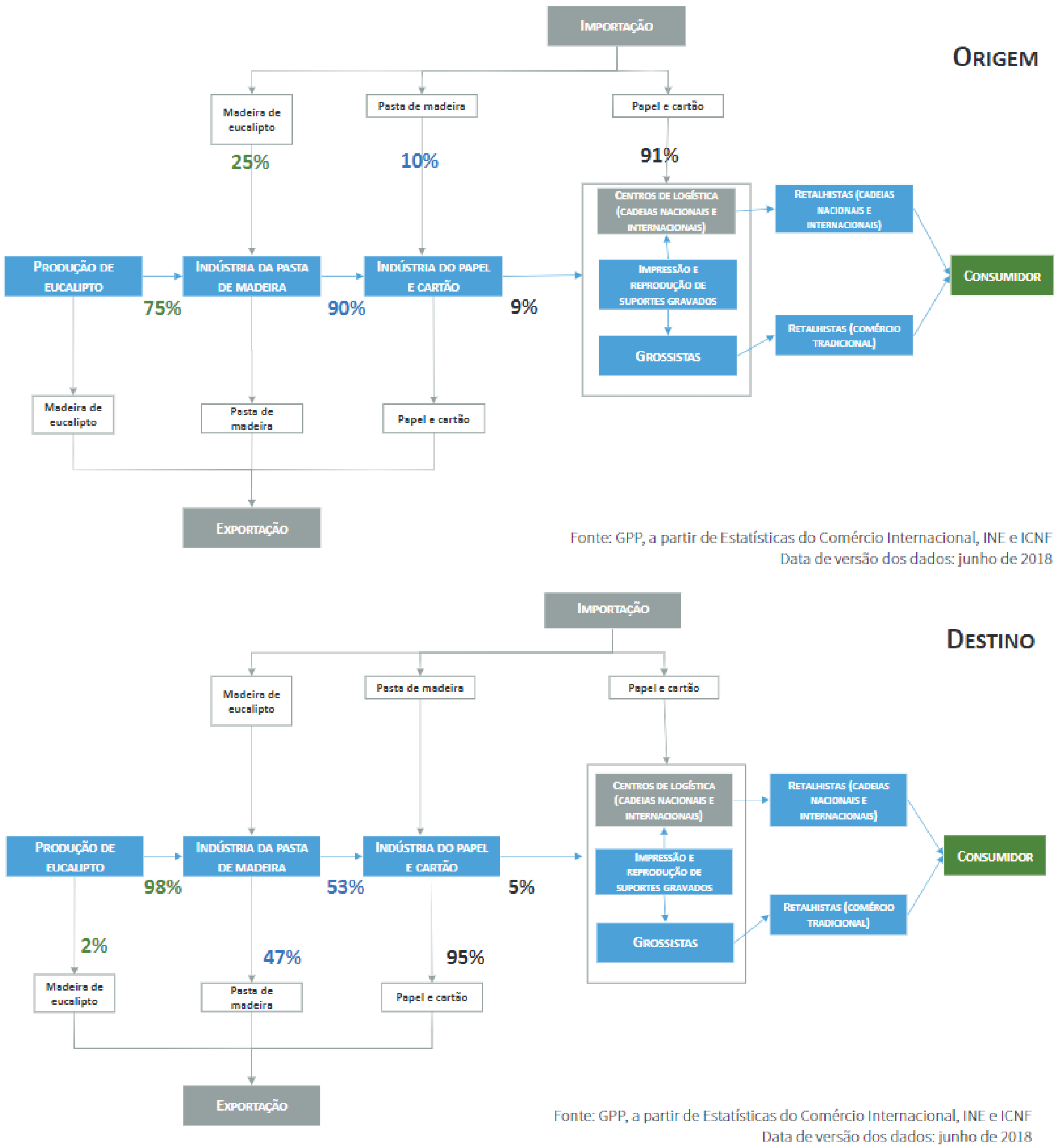

Figure 11 Flow diagram of the origin (top) and destiny (bottom) of raw material in the Portuguese pulp and paper industry in 2016 [70]

In figure 11 (referring to 2016) it's possible to see the schematic of the origin/destiny of the eucalyptus wood and intermediate products. It's also obvious that the majority of the products produced nationally are exported, meaning that for each 100 trees planted in Portugal, only about 2.5 are then converted to products used in Portugal. Leading to the necessity of importing paper/cardboard goods, mainly from Spain, Germany and Italy [70] , to satisfy the national demand.

As said, this is an industry with a high environmental impact, nevertheless Portugal is already doing its part in trying to reduce the industries ecological footprint. Comparing with 2018, reduction on water consumption (14%), particles emissions (38%) and noxious gases (14%) were drastic. At the same time, 69% of the fuel used in 2019 were biomass, 83% from black liquor and the rest mainly from wood residues (bark, twigs, stumps, leaves).[68] However, considerations on using wood residues as an energy source have to be made since, the higher the amount of residues that are gather, the higher the environmental impact (soil fertility) to the site. [71]

Worldwide, the demand for paper products is increasing, however there are ***key performance indicators*** (KPI) that can influence the future development of the sector.

Pollution/water consumption: As society is pressured to manage water consumption [72] and lower environmental pollution (air and water), all sector most contribute. Regarding air pollution, the main gases emitted in the paper and pulp industry are carbon dioxide and oxides of sulfur. [66] The major contaminants present in the wastewaters are sediments, effluent solids, chlorinated organic compounds, organic halides, chemical oxygen demand and biological oxygen demand contaminants. [73] Nowadays, research in the field of microbial technology is showing great results, not only in the treatment of wastes, but also in energy and water recovery. This could make recycling wastewater, not only environmentally feasible, but also economically profitable, [74] while reducing air emissions due to less outsource energy needs.

Raw materials: The main raw material for paper and cardboard production is wood. [15] Due to deforestation and biogenic carbon levels concerns, woody raw material starts to be more restricted, and alternatives must be found in order to maintain the sustainability of the industry. Other plants like straw, hemp, hay, cotton and other cellulose-bearing materials [75] can be, and some are, used to produce paper, however, in the beginning of the century less than 10% of paper products was made with non-wood raw materials.[15]. Recycling is already an established practice, contributing to the reduction of energy (28-70% less) and water requirement (up to 50% less), since the more resource intensive part is transforming wood into pulp, something not required with recycled paper. Emissions to the environment are also reduced, depending on the processes, reductions up to 95% of air emissions can be achieved. Regarding wastewater, most of the times, there is no need for bleaching the recycled paper, less hazardous chemical contaminants are present. Finally, landfill space is also spared., along side with new raw material. [76]

Digitalization: Global digitalization will play a major role in the paper industry, however how big is not yet fully understand. On one hand, can be negative, since dematerialization of several services (billing, office paper, legal documents, etc…) will contributed for less paper consumption [77]. On the other hand, digital technologies (machine connectivity, intelligent automation, and advanced analytics) will contribute for increased yields and savings, increasing the gains. Not only economical gains, but also environmental, since the digitalization will contribute for: improved forestry and water management, and milling activities [78].

Packaging: Packages come in all sizes and shapes. Nowadays, most of packages are made with plastics, many being single used ones (food, plastic bags, water bottles, plastic wrapping paper, etc). At the same time, packaging is the dominant generator of plastic waste, responsible for almost half of the global total waste in 2015 (141 MT of 302 MT) [79]. Social pressure is contributing to change this, with consumers agreeing that a cultural change is needed [80]. Also, with the increased of e-commerce contributing to the increase in packages circulation, cardboard containers, and bio-plastics made from cellulose, are seen as a real alternative, due to their improved environmental characteristics. [78]

Energy prices: The pulp and paper industries are very energy intensive [65]. Therefore, the energy prices will have a major influence in these industries. With the development of renewables, recovery systems of the processes and recycling, this can be mitigated. However, unpredictable situations like the Russian-Ukraine war contribute for the instability of the world energy market and in the next few years it can be hard to predict the consequences in the energy prices, not just for these industries, but across all sectors.

2.3.1 Paper production: eucalyptus and hemp as raw materials

Both crops can be used for production of paper, however the papers obtained will have different final characteristics, as seen in figure 12, where the comparison of some physical properties can be observed. This data comes from *Baptista 2020* [81], where not normal hemp paper (using only bast fibers) was studied, but the option of using whole stems to make 100% hemp paper and 50/50% (hemp and eucalyptus) was assessed. Here they tried to potentialized the wastes generated. Conclusions like stronger paper, more durable and less noxious emissions associated with production of fibers were achieved.

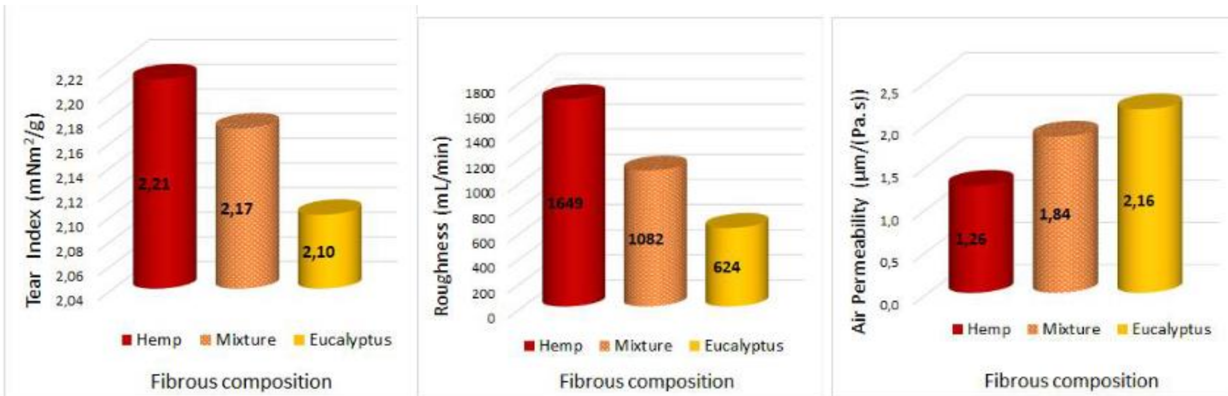

Figure 12 Physical properties (Tear index, roughness, air permeability) of: 100% hemp paper, 50/50 hemp and eucalyptus paper and 100% eucalyptus paper). [81]

This different physical property comes from the differences in the chemical composition of raw material used to produce pulp (table 3).

	Cellulose	Total Lignin	Extractives
Eucalyptus globulus wood	40.6-51.3	21.9-28.48	1.3-6.0
Hemp fibers	55.66	8.89	1.55
Hemp whole steam	53.25	21.8	2

Table 3 Comparison between chemical compositions of hemp fibers and eucalyptus wood. Based on [81,103]

To make pulp, the higher the cellulose content, and the lower percentages of extractives and lignin, the better. So, using hemp as a raw material allows improvement in some of the intermediate processes while reducing the use of noxious chemical reactants and energy. At the same time, creates a stronger paper that can be recycled up to 7/8 times. Normal paper can only be recycled 3 times on average. [15,81]

2.3.2- Eucalyptus globulus in Portugal

E. globulus, was first planted in Portugal in the 19th century for timber production used in railway sleepers. Only in the 20's of the 20th century it was first used for pulp manufacturing. Nowadays, *eucalyptus globulus* plantations represented around 777.8 thousand hectares of the national territory (roughly 25% of the forest stands in Portugal) [82]. Figure 13 shows how the stands are divided by species in the country. However, in 2020, only 145.8 thousand hectares (18.7%) were managed by companies of the forest industry, complying with FSC and PEFC regulations and sustainability concerns [68,70].

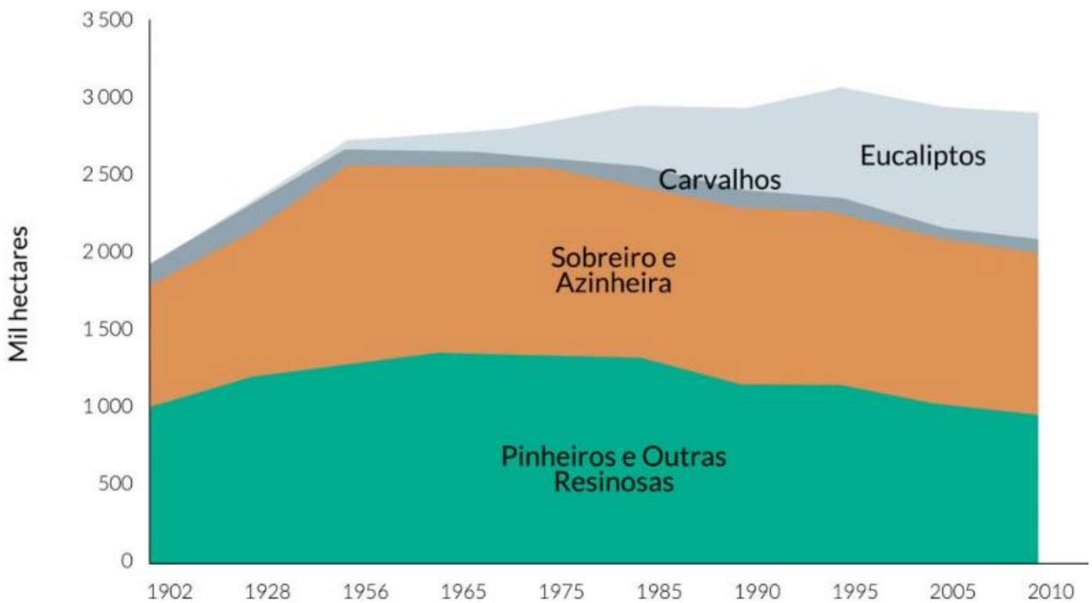

Figure 13 Portuguese forest stands distribution [104]

The remaining 81.3% is owned by small landowners, that invested in eucalyptus plantations with the hopes of rapid return on the investment with minimum to no care of the site. However, most of these private small landowners don't have the time or the money to ensure the safe and proper management of the eucalyptus stands [70], despite not being a crop with intense management, and on top, most planted eucalyptus stands without prior analysis of the land for the sustainability of the species. This lack of preparation and notions lead to low productivity, resulting in the abandonment of such plantations, because they are not profitable [46]. These abended sites are not only a risk for biodiversity, but also represent a fire hazard due to the debris inherit to the species that accumulate on the forest floor. [46] Main influence in fire management and contingency, is not the tree species itself, but the management of the forest stand. Fires prefer thickets and forest stands to agricultural fields and annual plants. Also contributing for fires, is the replacement of 1 500 000 ha of crop land to forest stands, in the last century. This leads to the increased of frequency and magnitude of fires and mega fires. [70]

2.4 Eucalyptus globulus characterization

Eucalyptus is the second most common tree type used in plantations around the world due to its high adaptability, fast growth, and high economic value.[83] More than 700 species are currently recognized, and all are native to Oceania, where they occur in almost all parts of the continent and inhabit several distinctive climatic zones and vegetation types (only in the driest places they cannot survive). [46] Nowadays they are in over 90 countries, mostly in temperate climates, covering a global area of around 20 million ha.[83] They are mainly used for paper pulp, firewood and timber, but also for medical and cosmetic applications. [84]

Eucalyptus globulus is one of the dominating eucalyptus species due to its valuable characteristics and plantations cover over 1.5 million ha in the Iberian Peninsula alone, having replaced native mixed forests over large areas. [83] Specially in Portugal, since more than 50% of those 1.5million ha are there, despite being several times smaller than Spain. Most are used for paper pulp production.

Physically, it is characterized as medium evergreen broadleaf tree (up to 70 m). The common name is Tasmanian blue gum, and it comes from the fact that its juvenile leaves are covered with a blue grey wax bloom. When they grow, the leaves changes becoming a leaf with a lanceolate shape and shifting to a vertical hanging. Also, they have circular glands containing aromatic oils (fig. 15). Regarding the bark, it shed every year in long ribbons [84] (fig. 14), leading to the creations of debris in the forest floor.

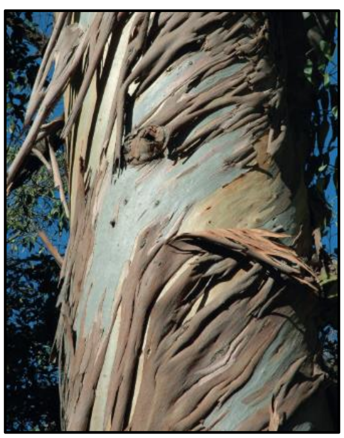

Figure 15 Eucalyptus globulus shedding bark [84]

Figure 14 Eucalyptus globulus leaf and circular glands [84]

2.4.1-Eucalyptus plantations

As any tree, *eucalyptus globulus* takes several years to grow. Generally, for industrial pulpwood plantations, a rotation system between 8-14years old is used. Also, due to the characteristics of the tree itself, three cutting cycles can be done. So, only after the third cycle, the stumps are removed before soil preparation for further applications. [85]

Despite being a species with high adaptation capability, *E. Globulus* does well in temperate climates with enough precipitation (around 800-900mm.year in Portugal). Other annual factors as fog frequency (air humidity) and regularity of droughts can change the annual water needs. [86] It doesn't get along with cold and frosts, being one of the main growths constrains, alongside nutrients and water availability. In air temperatures below -5°C foliar tissue dies. [84]

Despite *eucalyptus globulus* requires less water and nutrient in comparison with other short rotation woody species such as willow, a problem common to all short rotation wood crops is the intense use of ground resources. Other important consideration is that *eucalyptus globulus* take water from the ground all year round, and not just in growing seasons (warmer months) as other trees. [70] At the same time, the use of heavy machinery on harvesting and maintenance processes and nitrogen-based emissions derived from fertilizers also contribute, not only for the global warming, but also for acidification and eutrophication of soils and air.

Grows well on a wide range of soils, but requires good drainage, low salinity, and a minimum soil depth of 60cm. Studies have proved that mechanical soil preparation and additions of fertilizers increased growth rates and yields.[87] Regarding soil erosion, is worse than other wood crops, since it has shorter growth and harvesting cycles. [88]

Productivity is highly influence by the management of the stands. The theoretical average are 15-20m^3.ha.year.[70] In the beginning of the century, a study was conducted in Portugal to try to achieve maximum productivities. Up to 45m^3/ha.year were achieved in the study, [46] however Portuguese national productivity in 2013 was around 5.9 m^3/ha.year.[70] This is due to the lack of maintenance of most of the stands (see 2.3.2- Eucalyptus globulus in Portugal).

Regarding biodiversity, is almost unanimous the negative impact on the natural species [70,96]. Mainly on the plantations that are taken care. As it's possible to see in the fig. 16, the stand floor is maintained free of cover and debris, becoming a dry and harsh environment for animals. From plants to land animals and even insects and water invertebrates. On the other hand, all around the world, there is evidence of adaptation of some indigenous animals, mainly birds, that start using the seeds as food. [70] Also, this "naked floors" facilitates soil erosion [88].

On the right side of figure 16, an abandoned plantation is present. The differences in the vegetation on the forest floor are clear. The abundance of vegetation, and even others tree species are visible. This can be beneficial for animals, however, poses a major fire risk, due to the high concentration of vegetation, and dry debris (bark and twigs) from the eucalyptus itself.

Figure 16 Eucalyptus globulus forest stands: with proper maintenance (left) and abandoned (right)

3- Plantation Life cycle analysis: case studies

Life-cycle analysis (LCA) is a concept tool to support decision-making for sustainable development. Nevertheless, the concept is in constant improvement and, depending on who you ask, different definitions can be used. According to the U.S. Environmental Protection Agency, LCA is a tool to evaluate the potential environmental impacts of a product, material, process, or activity. In this method, assessing all direct and indirect environmental impacts across the full life cycle of a product system, is of crucial important to have accurate results. From the initial phases of materials acquisition and manufacturing, to use and final disposition, all phases must be considered. ISO 14040 (fig. 17) defines 4 different stages: (1) scoping; (2) compiling quantitative data on direct and indirect materials/energy inputs and waste emissions; (3) impact assessment; and (4) interpretation/improvement assessment. [89–91]

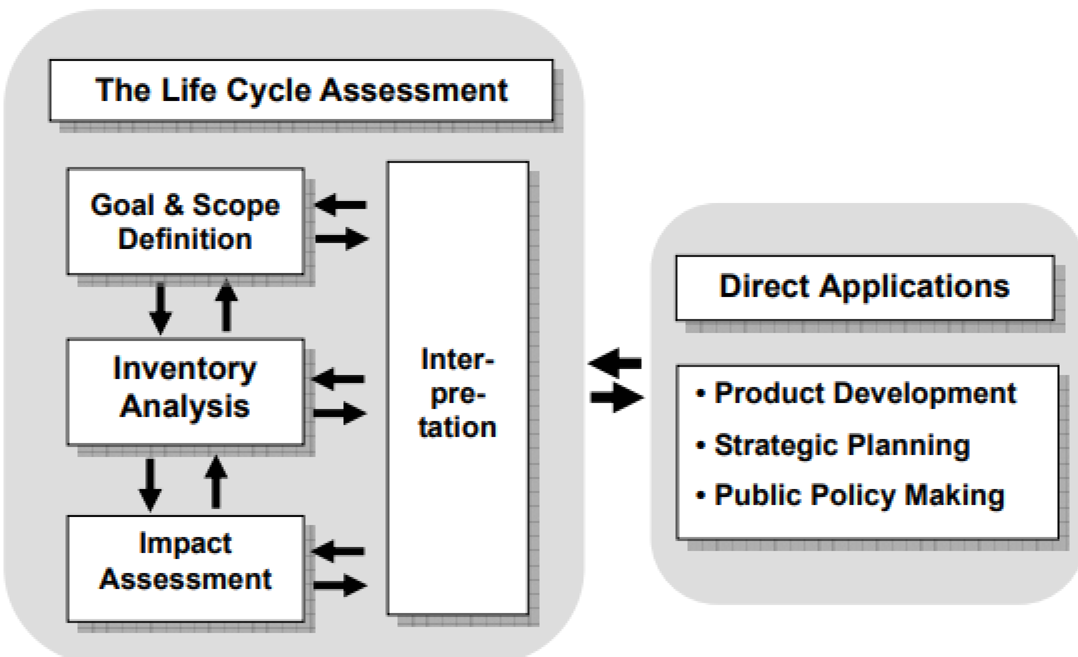

Figure 1.1 Phases of an LCA (ISO 14040, 1997)

Figure 17 Phases of a Life Cycle Assessment (LCA) [91]

3.1 System Boundaries

In order to have a correct comparison of the different impact each crop has, it's of most important to define the correct system boundaries.

In this thesis it was decided to development a life cycle assessment for the crop development, in order to asses the impacts of that initial stage (creation of raw material).

The comparation of *eucalyptus globulus* vs *cannabis sativa L* as a crop is evaluated across two different dimensions: environmental and economical. In figure 18 is possible to see the different steps that were evaluated.

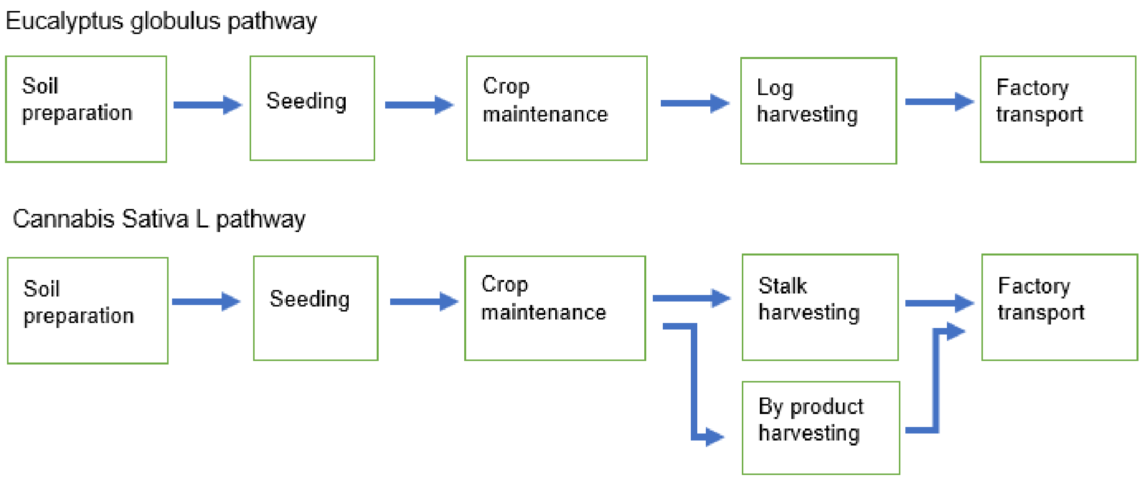

Figure 18 Flow diagram of the different steps assessed in the case studies (soil preparation, seeding, maintenance, harvest and transport to factory)

3.1.1 Functional unit

In order to have a correct comparison between these 2 very different crops (hemp annual crop, eucalyptus tree crop), a proper functional unit had to be decided. The decision led us to present the results in terms of *euro/hectare/year* in terms of costs. Despite eucalyptus harvest and operations are not done every year, the results are presented in this way to be easier to compare with annual (hemp) crops.

In terms of yield, for hemp *dry ton/hectare/year* was used, while for eucalyptus *m^3/hectare/year*. With the density of eucalyptus wood, we can convert to *ton/hectare/year*, allowing us to proper compare the 2 crops. The same logic applied to the cost functional unit was used.

3.1.2 Methodology

To proper evaluate both crops it was decided to break the crop development in several stages: Soil preparation, seeding, crop maintenance, log/stalk harvesting and transport.

The inputs taken into account were hours of labor, diesel, fertilizers, equipment and seeds. The outputs were tons of dried material and emissions to the environment, as it can be seen in figure 19.

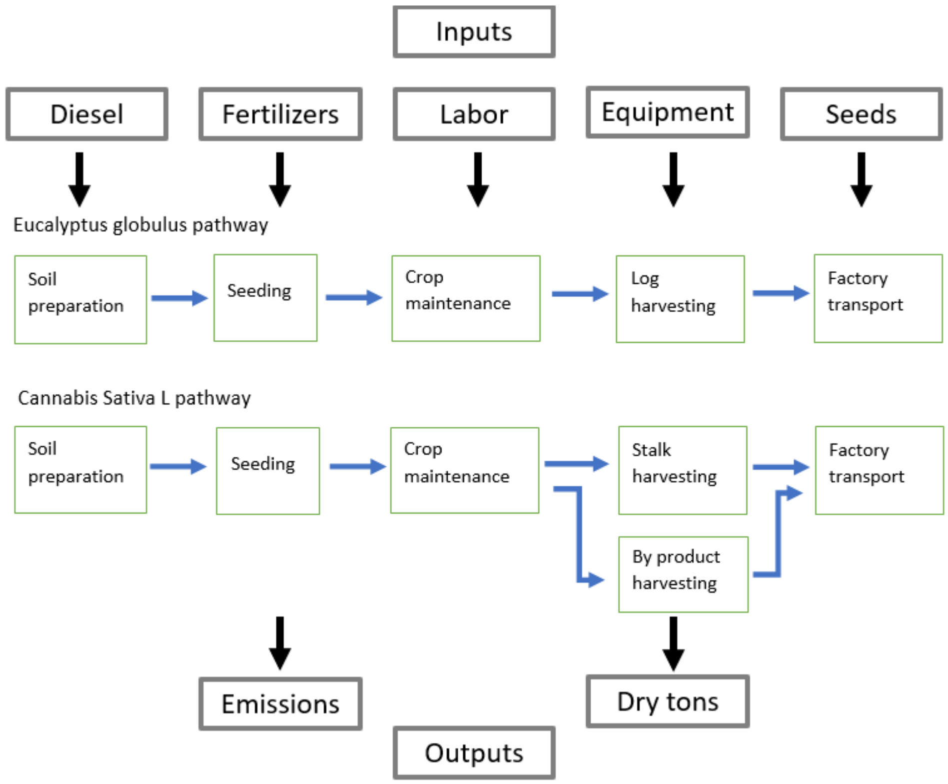

Figure 19 Inputs and outputs taken in consideration in the LCA

In the hemp case study, the two scenarios chosen were: 1- harvest of the stalk; 2- harvest of the stalk and seeds. Other possibilities like the harvesting of leaves or inflorescence can also occur, but due to the lack of reliable and quantitative data, the harvest of those resources is not analyzed.

The information acquired is from the literature, with no practical results to show since no partner wanted to join in this research, however, in the Multihemp case study, costs of labor, fertilizers and diesel are adapted to the Portuguese reality, to try to give a more realist result. Regarding eucalyptus globulus, information on Portuguese crops and markets was possible to obtain directly.

In the hemp case studies, the inputs: cost of equipment and hours of labor (descreminated in the annex B, C and D): transport information (table 4), fertilizers requirements (table 5), are directly taken from the MultiHemp project, [49]. Due to considerable differences between the cost of labor/diesel and fertilizers in Portugal vs the Multihemp project, those value were taken from other references, originating table 6 The cost/h of labor was taken from [92] and fertilizers/pesticide cost was taken from [82,93]. The cost of diesel, due to the current war economy, is assumed as a high value of 2euros/liter.

For the eucalyptus case study, information was gathered totally from the literature. The economic assessment is from *Gabinete de planeamento, 2018* [70], and the environmental data are taken from *Dias, 2012* [94]..

	Unit	Value
Travel distance	km	30
Average speed	Km/h	50
Average time to load/unload	h	0.5
Truck consumption	L/km	6
Truck capacity	ton	9

Table 4 Transport information for the hemp case study

Pesticide and Fertilizers	Amount (kg/hectare)
Gylsophate	3
K_2O	130
Urea (N)	60
P_2O_5	40

Table 5 Pesticides and fertilizers requirements per hectare for hemp plantations

	Unit	Value
Labor cost	€/h	5
Fertilizers		
P_2O_5	€/Kg	1.52
Urea (N)	€/Kg	1.29
K_2O	€/Kg	0.82
Gylsophate	€/Kg	19.08
Diesel	€/l	2

Table 6 Inventory of the extra data used and applied to the hemp case study

In table 7, the selling cost of raw material is shown. The information regarding hemp came from the MultiHemp project [49], while the price of the eucalyptus wood is from *Gabinete de planeamento, 2018.* [70]

Raw material	Unit	Selling price
Eucalyptus wood	€/ton	47
Hemp stalk	€/ton	130
Hemp seeds	€/ton	800

Table 7 Selling price of the materials harvest

In table 8, the conversion factors used are shown. CO_2 emissions per liter of diesel consumed was taken from [95], while the density of eucalyptus wood is from *Gabinete de planeamento, 2018.* [70]

	Conversion factor	Value
CO_2 emissions from diesel consumption	Kg/l	2.68
Density of eucalyptus wood	Kg/m^3	850

Table 8 Conversion factors used

3.2 Case Studies

3.2.1 Eucalyptus globulus crop impact: Alcochete case study

Here an analysis of the eucalyptus crop is done, with the goal of understanding what are the environmental and economic impacts of such crop.

First, there is the need of soil preparation with plowing and fertilizer application, to make a good bed for the young plants that are sowed. When the site already has trees (forest or previous crops), the action of stump removal is also necessary, in order to have space for the new trees.

During the growing phase, around the 6th year, there is the need of clearing the forest floor. This, to prevent fire by cleaning debris, but also to control infestations and competitor plants. From there, a close canopy is formed, making hard for the new growth of plants since the floor is totally in the shade. Regarding the rests of leaves and bark that fall, a balance must be obtain between self-feeding, generating the missing nutrients to complete the eucalyptus cycle, and the accumulation of debris that represent fire hazard.

On the 12th year happens the first cut, but there is no removal of the stumps, since this tree has the ability of sprouting from the stump after being cut. Non the less, this is the most expensive part, since it evolves heavy machinery to cut down the trees, turning them into movable logs and respective transportation. After the cycle is repeated, with the exclusion of the soil preparation and sowing, non the less new doses of fertilizers are added.

Economic assessment

Using a real case from Portugal, in particular of a forest producer in Alcochete county, we obtain real values of the cost/returns of a eucalyptus plantation in Portugal.

In table 9, the obtained yield, as the necessary yield to achieve breakeven are presented. On table 10 is possible to see the cost of the individual steps and the total cost of eucalyptus plantation by hectare and year, in a 12year period (one rotation). Finally, in table 11, the final economic balance is presented.

In this study, is not considered one major operation in eucalyptus plantation, the stump removal, since only happens after 2 or 3 rotations of 12years. So, unfortunately, this stage is not taken into account, despite its heavy impact.

Necessary yield to achieve breakeven (m^3/acre)	Achieved yield (m^3/hectare)
4.35	10

Table 9 Achieved yield and breakeven yield

Farm activity	Costs (€/hectare/year)
Mechanical soil preparation	10
Fertilizers cost	19
Plowing +fertilizer application	10
Seeds and sowing	19
Cutting down + preparing for transport + transport	140
others	6
Total	204

Table 10 Operating Costs

	Profit (€/hectare/year)
Total costs by acre	-204
Total revenue by acre	470
Profit by acre	266

Table 11 Final economic balance for harvesting eucalyptus wood

Environmental assessment

For the environmental assessment, a different study was used, where they assess several scenarios of eucalyptus plantations. [94]

In scenario 1- “Eucalyptus big corporation stand”, a high intensity management of the stands is studied, where the best management practices recommended for the industry are applied in all forest operation (from infrastructure necessary like roads and soil preparation to sowing and harvesting) Logging is done with heavy machinery (harvesters and forwarders) for felling and extraction, a common practice when large areas are harvested, especially in intense forest management by forest product industries.

Scenarios 2 – “Eucalyptus small owner stand” shows a low intensity management, where only the operation of site preparation is performed. Afterwards logging is done with light machinery (chainsaws for cutting down the trees and modified traditional farm tractors for extraction)

In table 12 is possible to see the emissions made by each crop of eucalyptus per hectare.

Emissions	Scenario 1 (kg/hectare)	Scenario 2 (kg/hectare)
CO_2 (Kg)	111.5	68.7
CH_4 (Kg)	0.00	0.01
N_2O (Kg)	0.11	0.00
SO_2 (Kg)	0.07	0.04
CO (Kg)	0.51	1.85
NH_3 (Kg)	0.87	0.02
NO_x (Kg)	1.02	0.56
NO^{3-} (Kg) (water leaching)	9.49	0.19
P (Kg) (water leaching)	0.03	0.01

Table 12 Emissions made per 1ton/hectare/year harvested of eucalyptus wood

3.2.2 Cannabis Sativa L crop impact: Multihemp case study adapted

Using a major European project called as source Multihemp, here the environmental and economic assessment of the hemp crop is done. At the same time, in order to approximate the results to the Portuguese reality, some values (presented in the methodology) are from other sources Two scenarios are analyzed:

Scenario 1 – The harvest of the stalk of the plant, where the main goal are the fibers and hurds.
Scenario 2 – The harvest of the stalk and the seeds, where the main goal are the fibers, hurds and seeds.

In hemp crops, as in all annual crops, soil preparation is needed. The use of glyphosate is common to kill any weeds that may prior exist. Before sowing, a tractor is used to plow the field. As said before, hemp does not need any pesticides/herbicides during its growth, but to further enhance the yield, fertilizers are used before sowing. Finally, the sowing occur. This all with the help of common farm tractors. [49]

Economic assessment

In table 13, the discriminated cost can be seen, as well the total cost of cultivating hemp (without harvesting). These processes are the same, regardless of the final harvest material (eg: just stalk or stalk and seeds). In the appendix B it’s possible to see the detailed costs of the different stages, and the different assumptions made.

Farm activity	Costs (€/hectare)
Herbicides application	67.26
plowing	116.1
Seeds and sowing	226.06
Fertilizers application	248.91
Transportation costs	18.2
Total	676.53

Table 13 Cost of preparing the fields

Scenario 1- Harvesting of the stalk

In this scenario only the harvest of the stalk is considered. The first operation is the cutting down of the plants. This cuts the hemp stems into lengths of 60-80 cm and puts the stems in disordered swaths. After, they are left to dry, leading to a form of natural retting (field retting). After 2-3weeks they are collected and submitted to baling, turning the disordered swaths into compact bales. In Appendix C it's possible to see the detailed costs of the different stages, and the different assumptions made. [91] Presented in table 14 is the discriminated costs of harvesting just the stalks.

According to the Multihemp project [49] the average productivity is 8.7 tons of dried straw in the end of this processes and the sealing price of the straw was 130€/tons. With this numbers we got table 15, with the final economical balance.

Harvesting stage	Costs (€/hectare)
Cutting	234.58
Turning	30.38
Swathing	18.26
Baling	72.3
Total	355.42

Table 14 Discriminated costs of harvesting just the stalks

	Profit (€/hectare)
Cost of soil preparation, sowing and transportation	-676.53
Cost of harvesting	-355.42
Total cost	-1031.95
Return	1131
Profit	99.05

Table 15 Final economic balance for harvesting just the stalks

Another way of looking to the results is in terms of harvest material (ton) per amount of money. In that case, each ton of straw costs 118.61€

Scenario 2 - Harvesting of the stalk and seeds

In this scenario the stages are the same as in the previous scenario (just stalk), however, during the cutting process, the harvest of the seeds is also done, with a specialized equipment. For further information check the appendix D. In table 16 is presented the discriminated costs.

According to Multihemp project [49] the average productivity in this dual-purpose crop is 1ton of seeds and 6. 5-8.7 tons of dried straw per hectare. In this thesis it was decided to use 7ton, in order to prevent overestimates. With the respective selling prices of 800€/ton for seeds and 130€/ton of straw. From here the tables 17 and 18 were obtained, where the return of selling the seeds and straws, and the final economic balance are respectively presented.

	Costs (€/hectare)
Cutting/ harvesting seeds	264.37
Turning	30.38
Swathing	18.26
Baling	72.3
Total	385.31

Table 16 Discriminated costs of harvesting stalks and seeds

	Return (€/hectare)
Return from seeds	800
Return from straw	910
Total return	1710

Table 17 Discriminated returns from the 2 resources

	Profit (€/hectare)
Cost of soil preparation, sowing and transportation	-676.53
Cost of harvesting	-385.31
Total cost	-1061.84
Return	1710
Profit	648.16

Table 18 Final economic balance for harvesting stalks and seeds

In this scenario, each ton of material costs 132.73€. However, is important to notice that of the 8 tons harvested, 1 ton is seeds while the other 7 are straw.

Environmental assessment

For the environmental assessment the same study was used. Emissions of every stage (except harvest and including final transport) were taken into account resulting in table 19. The results are expressed in kg/hectare. CO_2 emission accounts not only for the decomposition of urea but also from the use of motorized diesel vehicles during farm activities /except harvest) and transport.

In table 20, the specific emissions of CO_2.that occur during the harvest is shown. In Scenario 1 38.92l of diesel per hectare was use during harvest, and in Scenario 2 41.28l.

In the table 21 is possible to see the total emissions per hectare of both scenarios.

	Emissions (Kg/hectare)
CO_2 (kg)	139.55
NH_3 (kg)	3.39
NO_X (kg)	1.56
N_2O (kg)	1.59
NO^{3-} (kg) (water leaching)	79.71
PO_4 (kg) (water leaching)	0.8

Table 19 Emissions made in field preparation and final transport of hemp per hectare

	Emissions (Kg/hectare)
Scenario 1 harvesting CO_2 emission (kg)	104.31
Scenario 2 harvesting CO_2 emission (kg)	110.63

Table 20 CO2 emissions per hectare during harvested

Emissions	Scenario 1 (Kg/hectare)	Scenario 2 (Kg/hectare)
CO_2 (kg)	243.86	250.18
NH_3 (kg)	3.39	3.39
NO_X (kg)	1.56	1.56
N_2O (kg)	1.59	1.59
NO^{3-} (kg) (water leaching)	79.71	79.71
PO_4 (kg) (water leaching)	0.8	0.8

Table 21 Hemp total emissions per hectare

4 Discussion of the Results

In this chapter a critical comparison between the results obtain in the previous chapter is made. At the same, considerations about the lack of data and/or hardness to evaluate certain aspects are also considered.

4.1 Economical assessment

As it can be seen in the figure 20, in terms of costs, hemp plantations always are more expensive, however, depending on the scenario, the profit can be bigger than eucalyptus plantations. Being the reason of the extra profit, the possibility of harvesting and selling two separate raw materials. An important note, in the eucalyptus scenario present in figure 20, the transportation cost is included in the harvest, and not bundled with soil preparation and sowing, as in the hemp case.

Regarding eucalyptus, this shows the appealing economical side of eucalyptus plantations, that with minimal investment of money and time (when compared to annual crops), can bring profits. However, it is important to point out that these profits came in the long term (at least 12years for the first rotation). Also, this was a plantation that benefit of proper site management, not only during the growing phase, but also during the site preparation. Even in this case, we are talking of a few yearly operations, not a "full time job". Unfortunately, data about a site with minimal to no care was not possible to find out, but the value of minimal yield to achieve breakeven in the case study was also showed (4.35m^3/hectare/year). A value that we cannot say for sure if it would be achieved without site management, in fact, I believe that it won't.

Regarding hemp, variation of profit comes basically from the possibility to use hemp plantations as a multi-goal crop. The capability of harvesting more than 1 material (straw and seeds), with virtually no increase in the production costs (2.96% increase), leads to a big increase in the profit margin (650%). Leading to the questioning of using hemp as a single purpose crop. On the other hand, this crop requires bigger investments, not only in terms of money, but in time, since is an annual crop. This leads to major obligations and complications but allows to start retrieving the investment sooner.

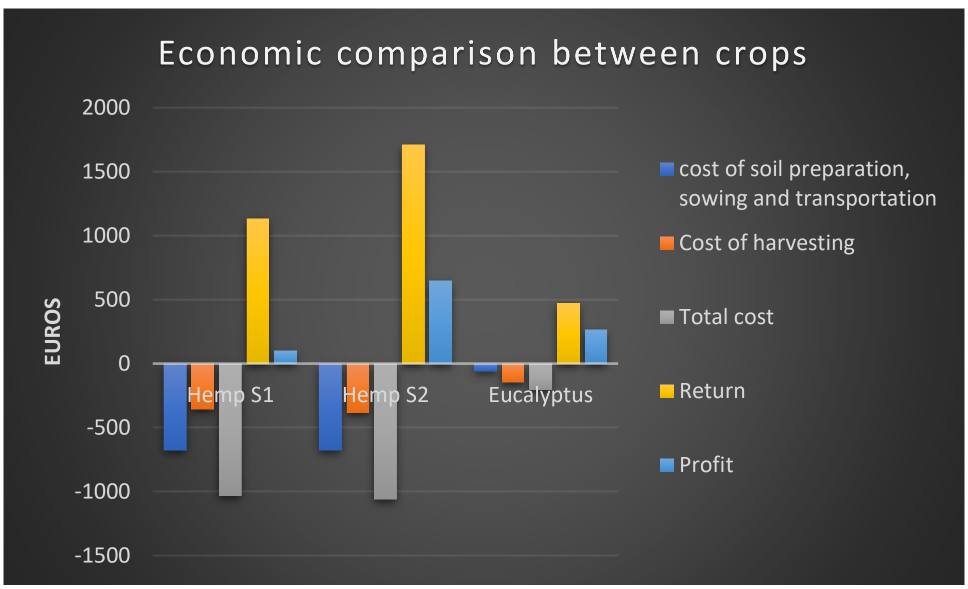

Figure 20 Economic comparison between crops.
Note: in the eucalyptus scenario the transportation cost is included in the harvest, and not bundled with soil preparation and sowing, as in the hemp case

Other important economic consequence is the creation/fortification of permanent jobs in the agricultural industry. Despite all the technological advancement and machinery that already exists, annual crops requires care all year round, while tree stands, only need care in particular times for the realization of certain activities. Even if we talk about using hemp as a break crop, this will generate more work for the already existing farms and farmers. Therefore, it would contribute for the creation of jobs, helping to fight the rural abandonment that is occurring in Portugal. [70]

One important remark is about the average yield of abandon sites. Going back to the review chapter, where it was showed that only 18.7% of the stands were managed by companies of the industry with proper care, with yields =>10-20m^3/hectare/year. At the same time, the average yield in Portugal in 2013 was 5.9m^3/hectare/year. There was no number of abandoned sites available in the literature, however, with the gathered data, we imagine here 2 scenarios regarding those abandoned sites, just to have an idea of the amount:

1- If we assume that half of the remaining 81.3% private stands (40.65%) was properly manage (with a yield of 10m3/hectare/year), for the national average to be 5.9m^3/hectare/year in 2013, means that the remaining 40.65% (311,2 thousand hectares) would have to have an average of way less than 4.35m^3/hectare/year, approximately 0 in fact.
2- If we assume that only 20% of the remaining 81.3% (16.26%=) complies with proper management practices (with a yield of 10m3/hectare/year), then the average yield of the sites with minimal to no care (126.5 thousand hectares) would be around 3.725m^3/hectare/year, also a very low number, most likely not enough to achieve breakeven.

   Anyways, what can be conclude is that most of these abandoned/minimal care eucalyptus plantations, probably doesn't achieve breakeven and are in a very big number.

To conclude, in an economical point of view, hemp as a dual crop is in fact more profitable than eucalyptus (244% more) and can contribute to extra added value (creation/fortification of jobs, increase value of the land itself through phytoremediation) in the agricultural sector, and even fight rural exodus. At the same time, brings return faster than *eucalyptus globulus* plantations. However, this comes at a cost, not just a bigger investment, but also time (increased labor).

4.2 Environmental Assessment

Between the parameters evaluated in these case studies, it's easy to see, that hemp, when compared directly to eucalyptus, has a bigger impact on the environment, when regarding noxious emissions. Regardless of the intensity scenario choose of eucalyptus plantations. Despite the hemp case study didn't considered emissions of CH4, SO2, P and CO. (figure 21). Depending on the chosen gas emitted, up to 10 times more. (ex: N_2O and NO^{3-})

Other important note is that this study does not consider the carbon sequestered within the plants. According to UK-30[61], hemp is the best crop (annual or woodland) to sequester carbon, so would be of most important to take this into account for a future investigation. Each hectare of hemp absorbs around 18t of CO2, according to *Bediva, 2014* [29].

At the same time, if hemp would be in fact used as a break crop, that would be another positive impact that is not considered here. Not just the added carbon sequestered, but also the "revitalization" of the land, however, not sure how this could be evaluated in an environmental quantitative way, despite in *Renalli 2004* [48], it is referred that increases up to 10-15% in future crops yields.

Finally, is important to remember that in the eucalyptus scenario, the stump removal is not considered, one of the major impact activities.

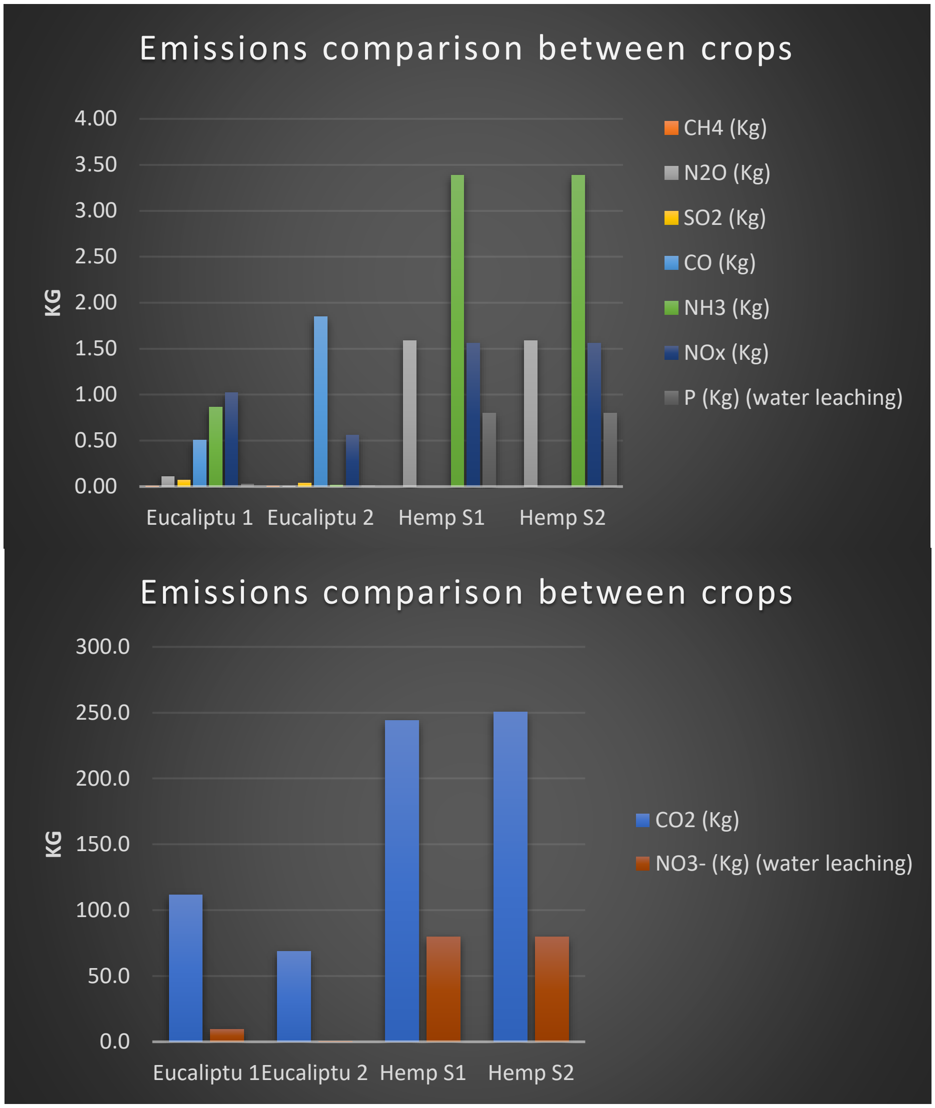

Figure 21 Emissions comparison between crops

Also, it's hard to evaluate other dimensions such biodiversity loss, soil erosion and fire hazards. Important dimensions when we talk about the Portuguese reality, where the monoculture of *eucalyptus globulus* is a problem, mainly due to the abandonment of eucalyptus plantations caused by rural exodus [70], alongside with wildfires.

Also, one of the initial premises of the UK 30 project is that hemp can produce up to 4times more paper per hectare than wood crops, another very important aspect when comparing the environmental impacts of substituting one crop for the other. Because, in fact, the comparison would not be 1 hectare vs 1 hectare, but 1 hectare vs X hectare. Where X would depend on the goal of the hemp crops.

To have a better notion of each style of crop (annual crop and tree crops), here is presented two extra comparisons:

- On top (fig. 22) a brief comparison of several fiber crops (kenaf, jute and flax), versus several scenarios in the Multihemp project, including the harvest of hemp seeds and stalk.
- On the bottom (fig 23), a comparison of three different scenarios, with different exploiting intensities, between eucalypt and maritime pine, 2 of the main tree species present in Portugal.

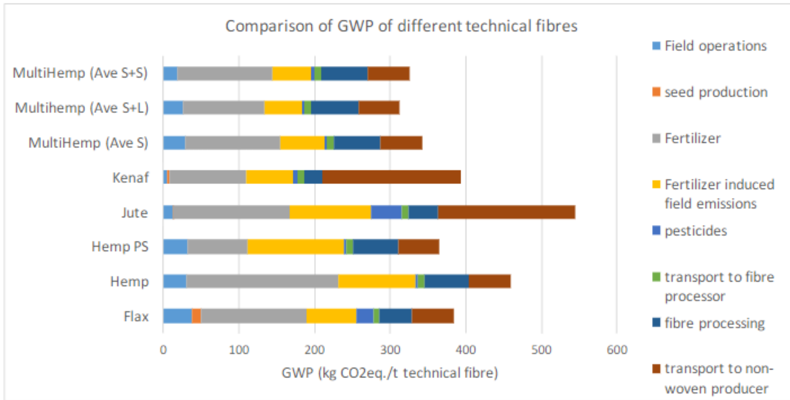

Figure 22 Comparison of GWP of different annual fiber crops. [49]

	Eucalypt scenarios			Maritime pine scenarios		
	1E	2E	3E	1MP	2MP	3MP
Inputs:						
Diesel (g)	3490	2753	1896	3211	2729	1133
Petrol (g)	37.7	311	273	0	176	176
Lubricants (g)	176	150	106	161	144	63.4
Triple superphosphate (g)	0	0	0	667	667	0
Superphosphate (g)	528	528	528	0	0	0
Ternary fertilizer 1 (g) [a]	94.4	94.4	94.4	0	0	0
Ternary fertilizer 2 (g) [b]	2083	2083	0	0	0	0
N-based fertilizer (g)	1250	1250	0	0	0	0
Outputs:						
Wood (m^3 ub)	1	1	1	1	1	1
Air emissions:						
CO_2 (g)	11,149	9694	6866	10,148	9188	4144
CH_4 (g)	0.198	0.775	0.664	0.106	0.478	0.425
N_2O (g)	11.7	11.6	0.488	0.443	0.380	0.159
SO_2 (g)	6.98	5.51	3.80	6.42	5.46	2.27
CO (g)	50.8	215	185	25.2	131	118
NH_3 (g)	86.7	86.7	1.73	0.0257	0.0224	0.00959
NO_x (g)	102	81.0	55.9	93.4	79.9	33.5
Water emissions:						
NO^3 (g)	949	949	18.7	0	0	0
P (g)	3.03	3.03	1.28	2.94	2.94	0

[a] 15% N, 12% P_2O_5, 9% K_2O.
[b] 15% N, 8% P_2O_5, 8% K_2O.

Figure 23 Comparison between eucalyptus globulus and maritime pine plantations, across 3 different intensities scenarios [94]

In figure 22 is easy to see that the scenario analysis in this thesis (the 1st, "Multihemp (Ave S+S) is the second with lowest environmental impact. It is common that field trials lead to better yields and lower emission that commercial farming [49], however even the commercial hemp (Hemp PS and Hemp) are in line with the other fiber crops. The "PS" means "pig slurry" an organic waste that can be used as fertilizer. Many crops do not tolerate these types of organic waste, however hemp does. The use depends on the availability and cost of such waste. Leading to conclude that hemp is a fiber crop with "normal to low" environmental impact.

On the bottom figure, there is no doubt that, for all scenarios, eucalyptus plantation is always more impactful for the environment than maritime pine plantations.

Also, further will be assessed the possibility of a biorefinery based on the hemp plant, so it's important to remind the difference between a crop with just 1 purpose (paper and energy trough recovery processes and waste management) and a crop that can have several purposes besides paper, and still have the similar energy recovery and waste management's systems.

So, in environmental terms, is hard to correctly compare the 2 crops, not just because of the available data, but due to the inheritance differences between the species and respective crops. A proper study, that would not just take into account the neglected situations here referred, but also with real case data from Portugal would be necessary to firmly conclude which crop has a bigger impact.

4.3 Remarks

Other important thing to point out is that would be necessary installations for the transformation of hemp raw material into products. Otherwise, export would be the solution. However, this would lead to an increment in environmental emissions due to transport, and loss of value added for the country due to the loss of a new industry. Especially important if we notice that in Europe the industry of transforming hemp is still very undeveloped, so being one of the first to invest in it could generate major benefits, despite the normal setbacks that are expected in establishing new processes and industries.

These new facilities could be drawn from scratch, to perfectly match the needs of a hemp biorefinery, or it could be adapted form an old facility that already treats fibers. This would probably decrease some costs, since hemp fibers separation and treatments are similar to others fibers already in use.

5 Hemp biorefinery in Portugal

Ideally, a second case study, with the goal of making a life cycle assessment of the second stage, the "product stage", where the impact of the products developed with hemp could be compared to other products with "mainstream" raw materials would also be done. However, due to the lack of data, that was not possible.

Nevertheless, applying the information gathered during the technological review, and the conclusions taken from the case studies, is here presented an "ideal" hemp project (plantation + biorefinery) applied to Portugal. Where the factory and plantations would be all part of a major endeavor, maximizing the sustainability of the project and minimizing intermediate steps. Due to the lack of data, definite conclusions cannot be reached, but a plan for a future case study and life cycle assessment was drawn.

In fig. 24 a sketch flow chart is present of such ideal project, partly based on the "total fiber line" of the Multihemp project. However, further transformation of the resources obtained (into composites, medicines, cosmetics, paper, hempcrete, isolation material, etc...) or different transformation paths for the initial raw materials (seeds and straw) should also be evaluated in a future work and should be chosen accordingly to the final goal of such work.

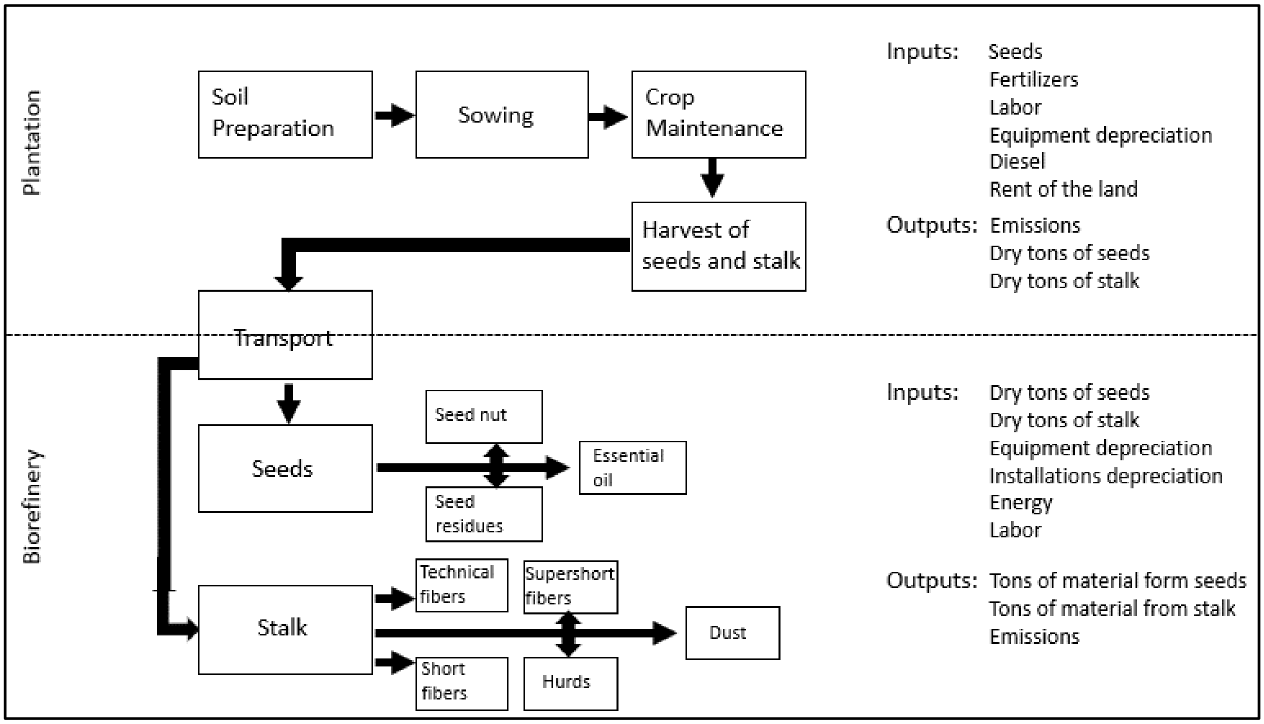

Figure 24 Flow chart of an integrated hemp project (plantation + biorefinery)

Regardless of that future study, here is presented some considerations/assumptions about this ideal integrated project.

Initial assumption

Based on the work developed so far, it can be firmly assumed that the use of a dual-purpose crop is better that a single-purpose crop: it maximizes profits, minimizes emissions/per ton of material, and maximizations of possibilities for posterior resource conversion.

- Use a dual-purpose crop

Hectares needed

First, the amount of raw material processes annually in the factory, was decided.

Let's use the "total fiber line Multihemp project" big transformation plant as an example. The factory requires 12 544 ton/year of straw (annex A). In a dual-purpose crop, yields of 7tons of dried straw can be achieved, so it would be necessary around 1800 hectares of hemp crops to fulfill such factory needs.

Then, crops would have to be instituted across the country. For that, exits 3 possible ways:

- Use hemp as a rotational crop in already established crop lands. Here it would be necessary to talk with farmers and evaluate where could be better and in which time frame.
- Use hemp as a substitute for part of the *eucalyptus globulus* stands that have minimal to no care. This would give value to the land in hand and diminish environmental impacts such as fire hazardous or biodiversity (monocultures) but not the ones associated with fertilizers.
- Create new crop land, by deforestation or appropriation of other already in use lands.

Combining the 2 first option would be good, since no new space for crop land would be necessary. Specially for only 1800 hectares. Even if all these hectares were to substitute current eucalyptus plantations, we would be only replacing 0.23% of the total 777 800 hectares. According to previous calculations, way more than 0.23% of eucalyptus plantations are abandoned, so replacing that amount would most likely have no impact in the owners, or even in the industry, representing almost none of the national production of eucalyptus wood for pulp and paper making. Specially considered that part of the raw materials obtain from those new hemp crops (small fibers) could be for making paper also.

Annual production

Since we are using a dual-purpose crop, it would also be generated another raw material, seeds. Based on the case study, the yield of seeds is 1ton/hectare, meaning that would be generated around 1800 tons of hemp seeds.

Regarding straw, the same values from the hemp total fiber line project was chosen.

These assumptions result on table 22.

Comes From	Type of Raw Material	Tons
straw	technical fibers	3010.56
	short fibers	501.75
	super short fibers	250.88
	shives	6899.2
	dust	1379.84
seeds	seeds	1800

Table 22 Total production of the idealized biorefinery

Economic considerations

Here there is an important detail to take into notice. None of the projects previous evaluated are from an integrated project of producing and transforming hemp. They are all made in separate. By joining the two parts, costs and emissions can be minimized. For example, in the Multihemp project, the cost of the straw to be transformed in the factory is 130euros/ton. For the seeds, 800euros/ton is the price farmers sell them to be transformed later. If it was made of an integrated project, the biorefinery here imagined would not have to pay 1710euros to have 7ton of straw and 1 ton of seeds, but instead 1043euros (the cost of producing those amounts). A considerable reduction of almost 40% in the cost of raw materials.

Also, transportation costs would probably change. The whole project would be designed to be as “tight” as possible to minimize unnecessary travels. 1800 hectares are equal to 18km2. Most likely the farmland would not be continuous, and space for factory facilities and roads is still needed, but assuming that this integrated facility would be comprehend in a space less than 300km2 (20kmx15km) is a realistic thought. This would mean that the mean transport to/from factory would always be less then 30km, the distance used in the case study. So, production costs (where transportation costs are included) would also decrease.

Regarding equipment, cost would probably diminish, because less duplicate equipment would be required. Since all plantations would be a part of one project, equipment of harvest, and transportation, could all be the same (if it's enough to guarantee the proper function of the facilities). While in the case study, it was from a perspective of individual farmers, that each of them would need their own equipment (tractors, harvesters, transports, etc..)

At the same time, the biorefinery present in the "total fiber line multihemp project" only treats straw. And even so it's profitable (roughly 870 000 €/year), despite acquiring their raw material for 130€/ton. However, in the dual-purpose crop, straw production only accounts to 7ton/hectare, so, in fact, the cost of the straw per hectare is greater than 130€ (151,7€). But the extra 1ton of seeds is as if it got acquired for 0 euros. Or we can make the argument on the other way around. If the 1 ton of seeds counts if is acquired for 800euros/ton, the normal commercial cost, then each ton of straw is as if it cost only 37.40 €/ton.

Anyways, the generation of seeds opens the door for a "new universe" in terms of revenue. In the worst-case scenario, the seeds could always be sold directly for posterior transformation, at the price of 800euros/ton. With 1800hectares being farmed, we are talking of approximately extra 900 000euros, with marginal increase in production costs (as seen in the case study). Only storage costs were not assessed, but the extra income generated would probably surpass those costs.

If the transformation of seeds were also conducted as in *Moscariello 2021* [47] or *Setti, 2020* [33], not just from the seeds itself, but also from seed residues, value added products could be made. Additional profit could be generated however, with the data collected, we cannot know for sure. Extra costs would have to be considered like investment for the new facilities, energy consumption and labor to keep the new line running.

Environmental considerations

In terms of environmental impact there would also be positive consequences of an integrated production/transformation hemp facility. In terms of emissions associated with transport, since travels distances could decrease, using the assumptions above, leading to less consumption of diesel and less depreciation of the equipment's.

Regarding farm equipment, less duplicate equipment means, less resources were spent to make the equipment that would be used, leading to a smaller environmental footprint associated with the project.

For the creation of the 1800hectares of hemp, as stated before, eucalyptus stands would need to be replaced. At the same time, in coordination with local farmers, the use of hemp as a break crop in already existing farmlands, could add positive impact in the environment. To make sure, a proper study would have to be made, where a proper assessment comparing the beneficial effects (CO_2 up take and less CO2 emissions, diminishing monoculture, less fire hazards, freeing of land) vs the negative effects (more fertilizers use → leading to the associated emissions). Uses of GWP_{100} and other environmental indicators could be a good option.

6 Final conclusions and considerations

In this final chapter, a more personal opinion is made about the information gathered during the making of this thesis.

First, let's talk in terms of plantations:

It was compared 2 very different crops: *cannabis sativa L*, an annual crop vs *eucalyptus globulus*, a tree crop. A very difficult comparison to make, not just because the inherit differences of the species, but also due to the lack of data available.

In the case of *cannabis sativa L*, national actualized information is very hard to gathered. Mainly because of the lack of plantations and industrial hemp related projects in the country nowadays. Nevertheless, with information gathered from other sources, an approximation to the Portuguese reality was tried. Regarding *eucalyptus globulus* it was easier to get more national reliable data, despite the lack of interest of the major companies of the industry in participate in this thesis. Nevertheless, was possible to find studies, and even information from national companies was available.

Regarding quantitative environmental impacts, as shown, is hard to conclude on the preferred crop, with hemp being worst in terms of noxious emissions (N_2O NH_3 NO_x $NO_{3,}$ $CO_{2)}$, derived from fertilizers utilization, but conclusions on the global warming potential, total CO2 emission and other parameters, where not achieved. Even so, in my opinion, hemp crops should be instituted in Portugal. Not just because history, as science, already showed that it gets along well in Portuguese climate and soils, but also because is a way to fight back against the invasive species *eucalyptus globulus*, that already took a lot of space in the country. While fighting another 2 big Portuguese problems: the rural abandonment and wildfires. These problems are related, since is the abandonment of the rural areas and plantations that facilitates wildfires and megafires.

Finally, it was not assessed in this thesis the impact of harvesting leaves/stems or the flowers, due to lack of data and technologies available. Nevertheless, I believe that if this path is pursuit, and proof regarding the added value of harvesting these parts of the plant is obtained, hemp will have an improved environmental impact since the emissions made will be spread out for more tons of raw material to be converted.

On top, if we use the economical assessment made here as final argument, there is no doubt that hemp, as a dual-crop plantation, is a better option than eucalyptus (eucalyptus profit 266€.ha.year; hemp as a dual-crop profit 648€.ha.year.). However, it takes more initial investment and labor.

In my opinion, hemp crops applied to the Portuguese reality can be beneficial in situations like:

- Replacement of continuous abandoned eucalyptus sites for hemp crops. This would result in minor fire hazards (the hemp crops would act as a "green fire barrier"), incentive to fight the rural exodus and a reduction of extensive eucalyptus monoculture fields, all while generating revenues.

Talking about the transformation facility, as said, no practical conclusion could be achieved, but several considerations were made.

Using the biorefinery scenario assessed before, the small fibers produced can be for the production of paper (or even all the stems [81]) a strong Portuguese industry, that has a major European presence because of the amount of *eucalyptus globulus* plantations. The replacement of some stands, as saw, can have some positive environmental impacts, without the loss of raw material for the paper industry. At the same time, the transformation of hemp fibers into paper has a minor environmental impact than transforming eucalyptus paper. Finally, if this new paper was made for national markets, this would contribute for less import of paper goods, also a better option for the environment.

The remaining technical fibers could be for high end automotive reinforced composites, an industry that already exists in Portugal with companies manufacturing body parts panels for high end brands.

The hurds could be used to develop a new branch on the national cement companies, the organic hemp concrete (hempcrete). Other technical applications as highly absorbent material, or biodiesel, can also be manufactured from the hurds, or can be used as something as simple as animal bedding,

The seeds also have an enormous potential but can be harder to insert in the national economy. An easy option could be selling the seeds as food supplements. More complex ideas, involving transformation facilities, could be cosmetic pharmaceutical, biofuels or industrial applications Regardless of the final application chosen, it will always be a natural, and renewable resource, making it sustainable. Also, is an expensive resource, making it sustainable not just in environmental terms, but also in economic terms.

In my opinion, Portugal can be a major player in the European hemp industry in the future. Not just in terms of seizing the opportunities this revitalized industry will have, but also to improve the already established industries, all while improving the countries environmental impacts and economics!

Appendixes

A - Multihemp total fiber line biorefinery specifications

Investment and financing	Unit	Small plant	Large plant
1. Investments			
All movable assets (machinery, vehicles, other equipments)	€	2,580,000.00	4,800,000.00
Buildings			
Space for production facility in m^2	m^2	700.00	1,000.00
Storage space in m^2	m^2	1,000.00	2,000.00
Administration building in m^2	m^2	0.00	0.00
Construction costs in €/m^2	€/m^2	280.00	280.00
Total investment buildings	€	476,000.00	840,000.00
Floor space			
Floor space required in m^2	m^2	5,000.00	10,000.00
Price in €/m^2	€/m^2	25.00	25.00
Total investment floor space		125,000.00	250,000.00
Total investment	**€**	***3,181,000.00***	***5,890,000.00***
2. Useful life of movable assets and buildings			
Movable assets	Years	10.00	10.00
Buildings	Years	30.00	30.00
3. Depreciation of movable assets and buildings			
Movable assets	€/a	258,000.00	480,000.00
Buildings	€/a	15,866.67	28,000.00
4. Financing			
Total investment		***3,181,000.00***	***5,890,000.00***
Capital owned respectively venture capital	€	1,590,500.00	2,945,000.00
Investment subsidy (if applicable)	€	0.00	0.00
Regional investment grants	€	0.00	0.00
Loan	€	1,590,500.00	2,945,000.00
Imputed interest rate for the capital owned	%	4.00	4.00
Duration of Loan in years	Years	10.00	10.00
Effective interest rate in %	%	7.00	7.00
Payment rate per annum		12.00	12.00
Monthly interest and repayment costs	€/month	18,467.05	34,193.95
Annual interest and repayment costs	€/a	221,604.64	410,327.37

Process capacity and output	Unit	Small plant	Large plant
1. Capacity of the process	**kg/h**	1,500.00	4,000.00
2. Effective running time	**%**	90.00	80.00
3. Raw material costs incl. transport costs	**€/kg**	0.13	0.13
4. Nominal realizable yield			
Technical fibres	%	24.00	24.00
Short fibres	%	4.00	4.00
Super short fibres	%	2.00	2.00
Shives	%	55.00	55.00
Dust	%	11.00	11.00
5. Output			
Technical fibres	t/a	1,270.08	3,010.56
Short fibres	t/a	211.68	501.76
Super short fibres	t/a	105.84	250.88
Shives	t/a	2,910.60	6,899.20
Dust	t/a	582.12	1,379.84

Operating time and labour costs	Unit	Small plant	Large plant
1. Salaries incl. costs accessory to salaries			
Managing director	€/month	4,500.00	4,500.00
Managing engineer	€/month	3,750.00	3,750.00
Sales manager	€/month		
Office staff + internal logistics	€/month	2,000.00	2,000.00
Agronomist	€/month		
2. Wages (shift work)			
Skilled workers	€/h	24.00	24.00
Number of workers per shift	Workers per shift	1.00	5.00
Unskilled workers	€/h	13.00	13.00
Number of workers per shift	Workers per shift	1.00	1.00
3. Duration of shifts			
Skilled workers	h/shift	8.00	8.00
Unskilled workers	h/shift	8.00	8.00
4. Working weeks per year	Weeks/a	49.00	49.00
5. Number of shifts per week	shifts/week	10.00	10.00
6. Number of shifts per day	shifts/day	2.00	2.00
7. Capacity utilisation	h/a	3,920.00	3,920.00
8. Total labour costs			
Managing director	€/a	54,000.00	54,000.00
Managing engineer	€/a	45,000.00	45,000.00
Sales manager	€/a	0.00	0.00
Office staff + internal logistics	€/a	24,000.00	24,000.00
Agronomist	€/a	0.00	0.00
Skilled workers	€/a	94,080.00	470,400.00
Unskilled workers	€/a	50,960.00	50,960.00
Workers Union	€/a	5,924.22	5,924.22
Total labour costs	**€/a**	**268,040.00**	**644,360.00**

Energy costs	Unit	Small total fibre line	Large total fibre line
1. Electricity			
Constant power	kW	200.00	300.00
Electricity price	€/kWh	0.05	0.05
Electricity costs	€/a	35,280.00	47,040.00
2. Diesel			
Diesel demand	l/t fibre	1.60	1.60
Diesel price	€/l	1.00	1.00
Diesel costs	€/a	4,656.96	11,038.72
3. Total energy costs	**€/a**	**39,936.96**	**58,078.72**

Packaging costs	Unit	Small plant	Large plant
1. Packaging costs (Material)			
Fibres	€/kg	0.001	0.001
Super short fibres	€/kg	0.01	0.01
Shives	€/kg	0.02	0.02
Fibres	€/a	1,481.76	3,512.32
Super short fibres	€/a	1,058.40	2,508.80
Shives	€/a	64,033.20	151,782.40
Total packaging costs	**€/a**	**66,573.36**	**157,803.52**

Feedstock costs	Unit	Small plant	Large plant
1. Hemp straw costs incl. storage and transportation	**€/kg**	0.13	0.13
2. Straw demand	**t/a**	5,292.00	12,544.00
3. Total feedstock costs	**€/a**	**687,960.00**	**1,630,720.00**

Other costs	Unit	Small plant	Large plant
1. Replacement parts & maintenance	**€/a**	44,750.00	89,500.00
2. Insurance	**€/a**	6,112.00	12,224.00
3. Disposal costs	**€/a**	0.00	0.00
4. Other costs	**€/a**	49,140.19	98,280.38
Total other costs	**€/a**	**100,002.19**	**200,004.38**

Cost shares	Unit	Small total fibre line	Large total fibre line
Per year:			
Capital costs	€/a	221,604.64	410,327.37
Depreciation	€/a	273,866.67	508,000.00
Labour costs	€/a	268,040.00	644,360.00
Energy costs	€/a	39,936.96	58,078.72
Packaging costs	€/a	66,573.36	157,803.52
Feedstock costs	€/a	687,960.00	1,630,720.00
Other costs	€/a	100,002.19	200,004.38
Total costs	€/a	**1,657,983.82**	**3,609,293.99**
Per tonne straw:			
Capital costs	€/t straw	41.88	32.71
Depreciation	€/t straw	51.75	40.50
Labour costs	€/t straw	50.65	51.37
Energy costs	€/t straw	7.55	4.63
Packaging costs	€/t straw	12.58	12.58
Feedstock costs	€/t straw	130.00	130.00
Other costs	€/t straw	18.90	15.94
Total costs	€/t straw	**313.30**	**287.73**
Per ha:			
Capital costs	€/ha	335.00	620.30
Depreciation	€/ha	414.01	767.95
Labour costs	€/ha	405.20	974.09
Energy costs	€/ha	60.37	87.80
Packaging costs	€/ha	100.64	238.55
Feedstock costs	€/ha	1,040.00	2,465.19
Other costs	€/ha	151.17	302.35
Total costs	€/ha	**2,506.40**	**5,456.23**

Revenues, profits or losses	Unit	Small total fibre line	Large total fibre line
1. Market prices			
Technical fibres	€/kg	0.70	0.70
Short fibres	€/kg	0.30	0.30
Super short fibres	€/kg	0.40	0.40
Shives	€/kg	0.30	0.30
Dust	€/kg	0.04	0.04
2. Revenues			
Per year			
Technical fibres	€/a	889,056.00	2,107,392.00
Short fibres	€/a	63,504.00	150,528.00
Super short fibres	€/a	42,336.00	100,352.00
Shives	€/a	873,180.00	2,069,760.00
Dust	€/a	23,284.80	55,193.60
Total Revenues	€/a	**1,891,360.80**	**4,483,225.60**
3. Profits or loss			
Annual profit (target: 10% profit margin)	€/a	233,376.98	873,931.61
Profit margin (target: 10%)	%	12.34%	19.49%
Value added	€/a	996,888.29	2,436,618.98
Value added	€/tdm straw	188.38	194.25
Profit	€/tdm straw	44.10	69.67
Calculatory minimum price for technical fibres for covering costs	€/kg	0.52	0.41
Max. straw price for covering all other costs	€/kg	0.17	0.20

B - Hemp cultivation (excluding harvest) cost and environmental impacts calculation

COSTS

Machinery refers to machinery depreciation, oil use, equipment wear down

herbicides application cost (per hectare)

	Unit cost (€)	Quantity needed	Total cost (€)
Gylsophate (kg)	19.08	3	57.24
Labour (h)	5	0.22	1.1
machinery	-	-	9.22
Total cost (€)	-l	-	67.26

plowing cost (per hectare)

	Unit cost (€)	Quantity needed	Total cost (€)
Labor (h)	5	1.74	8.7
machinery	-	-	107.40
Total cost (€)	-l	-	116.1

sowing cost (per hectare)

	Unit cost (€)	Quantity needed	Total cost (€)
Seeds (kg)	3	48	144
Labour (h)	5	0.79	3.95
machinery	-	-	78.11
Total cost (€)	-l	-	226.06

Fertilizer application cost (per hectare)

	Unit cost (€)	Quantity needed	Total cost (€)
P_2O_5 (kg)	1.52	40	60.8
urea (N) (kg)	1.29	60	77.4
K_2O (kg)	0.82	130	106.6
Labor (h)	5	0.15	0.75
machinery	-	-	4.11
Total cost (€)	-	-	248.91

Tot 658.33 euros/hectare

transportation cost (per hectare)

	Unit cost (€)	Quantity needed	Total cost (€)
Labor loading/unloading (h)	5	1	5
Labor travelling (h)	5	1.2	6
Diesel consumption (l)	2	3.6	7.2
Total cost (€)	-I	-	18.2

Environmental emissions

total CO2 emission (except harvest) per hectare

	Diesel used (l)	CO_2 Emitted (kg)
Prepering soil	42.5	113.9
Final transportation	3.6	9.65
Urea decomposition	-	15.97
Total emissions	-	139.55

C - Hemp Harvest of stalk: costs and environmental impacts

Using a modified maize, the HempCutwhich cuts the hemp stems into lengths of 60-80 cm and puts the stems in swaths. Is characterized as the most common technology of harvesting only hemp stalks in Europe. Purchase costs of such a field chopper amount to about 300,000 € and, according to KTBL, the technical utilisation potential is 3,000 h and the economic utilisation potential 10 years. Since the HempCut is basically a standard field chopper, the assumption of an annual utilisation at the threshold, i.e. 300 h/a, was made.

Machinery refers to machine depreciation, oil use, equipment wear down

Costs

cutting cost per hectare

	Unit cost (€)	Quantity needed	Total cost (€)
Labor (h)	5	1.27	6.35
machinery	-	-	228.23
Total cost (€)	-	-	234.58

turning cost per hectare

	Unit cost (€)	Quantity needed	Total cost (€)
Labor (h)	5	0.64	3.2
machinery	-	-	27.18
Total cost (€)	-	-	30.38

Tot of swathing cost per hectare

	Unit cost (€)	Quantity needed	Total cost (€)
Labor (h)	5	0.32	1.6
machinery	-	-	16.66
Total cost (€)	-	-	18.26

baling cost per hectare

	Unit cost (€)	Quantity needed	Total cost (€)
Labor (h)	5	0.69	3.45
machinery	-	-	68.85
Total cost (€)	-	-	72.3

Tot of harvesting stalks per hectare – 355.52
tot of harvesting stalks per tdm - 40.86

Environmental emissions

CO2 emission per hectare of straw harvested

	Diesel used (l)	CO_2 Emitted (kg)
Harvest emissions	38.92	104.31

D – Hemp harvest stalk and seeds: costs and environmental impacts

This scenario considers a dual use harvesting of straw and seeds, using a combine harvester with a Kemper header. This system is considered as the standard technology for the harvest of seeds and straw in Europe, with long-time record of experience and improvements. Purchase costs for this machinery amount to about 300,000 € and the same assumptions of an annual utilisation of 300 h was made. The field operations following the cutting (swathing, turning, baling) are considered to be the same as in the standard scenario.

Costs

Machinery refers to machine depreciation, oil use, equipment wear down

Tot cutting/harvesting seeds cost per hectare

	Unit cost (€)	Quantity needed	Total cost (€)
Labor (h)	5	1.47	7.35
machinery	-	-	258.33
Total cost (€)	-	-	264.37

turning cost per hectare

	Unit cost (€)	Quantity needed	Total cost (€)
Labor (h)	5	0.64	3.2
machinery	-	-	27.18
Total cost (€)	-	-	30.38

Tot of swathing cost per hectare

	Unit cost (€)	Quantity needed	Total cost (€)
Labor (h)	5	0.32	1.6
machinery	-	-	16.66
Total cost (€)	-	-	18.26

~

Tot of baling cost per hectare

	Unit cost (€)	Quantity needed	Total cost (€)
Labor (h)	5	0.69	3.45
machinery	-	-	68.85
Total cost (€)	-	-	72.3

Total cost of harvesting 385.31 per hectare
total cost of harvesting: 55.04 (tdm)

Environmental impact

CO2 emissions per hectare of straw and seeds harvested

	Diesel used (l)	CO_2 Emitted (kg)
Harvest emissions	41.28	110.63

References

[1] Attah N v. Environmental Sustainability and Sustainable Growth: A Global Outlook. 2010.

[2] van den Bergh J. Evolutionary Analysis of the Relationship between Economic Growth, Environmental Quality and Resource Scarcity. 2003.

[3] energy information admistration E. Biomass definition n.d.

[4] Hedenus F, Sandén B, Pettersson K. Assessing biorefinaries. 2014.

[5] Anwar F, Latif S, Ashraf M. Analytical characterization of hemp (Cannabis sativa) seed oil from different agro-ecological zones of Pakistan. 2006. https://doi.org/10.1007/s11746-006-1207-x.

[6] USDA. Industrial Hemp in the United States:Status and Market Potential 2000.

[7] businesscann. Europe's Decision to Raise Permitted THC Levels in Hemp Crops Is 'A Victory For Science' 2021.

[8] Crini G, Lichtfouse E, Chanet G, Morin-Crini N. Applications of hemp in textiles, paper industry, insulation and building materials, horticulture, animal nutrition, food and beverages, nutraceuticals, cosmetics and hygiene, medicine, agrochemistry, energy production and environment: a review. Environ Chem Lett 2020;18:1451–76. https://doi.org/10.1007/s10311-020-01029-2.

[9] Vogal E. Hemp (Cannabis sativa L.) for Medicinal Purposes: Cultivation under German Growing Conditions. UNIVERSITÄT HOHENHEIM: 2017.

[10] Zou S, Kumar U. Cannabinoid receptors and the endocannabinoid system: Signaling and function in the central nervous system. Int J Mol Sci 2018;19. https://doi.org/10.3390/ijms19030833.

[11] Factsheet_endocannabinoids-1 n.d.

[12] Kramer LS. HEMP AS RAW MATERIAL FOR THE FASHION INDUSTRY-A study on determining major factors hampering hemp to be integrated in the textile apparel supply chain 2017. https://doi.org/10.13140/RG.2.2.21830.98889.

[13] Fernando Pessoa U. MARIANA OLIVEIRA SANTOS O Cânhamo como material de construção: Viabilidade e Oportunidade. 2013.

[14] Vasantha Rupasinghe HP, Davis A, Kumar SK, Murray B, Zheljazkov VD. Industrial Hemp (Cannabis sativa subsp. sativa) as an Emerging source for value-added functional food ingredients and nutraceuticals. Molecules 2020;25. https://doi.org/10.3390/molecules25184078.

[15] Edyta M, Piotr P, Marcin D, Marta K, Kamila B. Comparison of papermaking potential of wood and hemp cellulose pulps. vol. 91. 2015.

[16] Crocq MA. History of cannabis and the endocannabinoid system. Dialogues Clin Neurosci 2020;22:223–8. https://doi.org/10.31887/DCNS.2020.22.3/MCROCQ.

[17] Congressional Research Service. Defining Hemp: A Fact Sheet. 2019.

[18] Amaducci S, Zatta A, Raffanini M, Venturi G. Characterisation of hemp (Cannabis sativa L.) roots under different growing conditions. Plant Soil 2008;313:227–35. https://doi.org/10.1007/s11104-008-9695-0.

[19] Nováková P. Use of technical hemp in the construction industry. MATEC Web of Conferences, vol. 146, EDP Sciences; 2018. https://doi.org/10.1051/matecconf/201814603011.

[20] Ryz NR, Remillard DJ, Russo EB. Cannabis Roots: A Traditional Therapy with Future Potential for Treating Inflammation and Pain. Cannabis Cannabinoid Res 2017;2:210–6. https://doi.org/10.1089/can.2017.0028.

[21] Liu M, Thygesen A, Summerscales J, Meyer AS. Targeted pre-treatment of hemp bast fibres for optimal performance in biocomposite materials: A review. Ind Crops Prod 2017;108:660–83. https://doi.org/10.1016/j.indcrop.2017.07.027.

[22] Stevulova N, Cigasova J, Estokova A, Terpakova E, Geffert A, Kacik F, et al. Properties characterization of chemically modified hemp hurds. Materials 2014;7:8131–50. https://doi.org/10.3390/ma7128131.

[23] Fernandez-Tendero E, Day A, Legros S, Habrant A, Hawkins S, Chabbert B. Changes in hemp secondary fiber production related to technical fiber variability revealed by light microscopy and attenuated total reflectance Fourier transform infrared spectroscopy. PLoS One 2017;12. https://doi.org/10.1371/journal.pone.0179794.

[24] stexfibers. A BRIEF HISTORY OF HEMP n.d.

[25] Schumann E, Peil A, Weber WE. Preliminary results of a German field trial with different hemp (Cannabis sativa L.) accessions. vol. 46. 1999.

[26] Environmental Protection Agency (EPA) U. Reducing Air Pollution from: Fiberglass Fabrication Operations Could your family be affected? 2005.

[27] Meng F. Environmental and cost analysis of carbon fibre composites recycling Sustainability analysis of carbon fibre composite recycling View project Life cycle assessment of butanol and hydrogen production from municipal solid waste (MSW) via mixed waste autoclaving View project. 2018.

[28] Gandolfi S, Ottolina G, Riva S, Fantoni GP, Patel I. Analysis of hemp hurds. vol. 8. 2013.

[29] Bedlivá H, Isaacs N. Hempcrete – An environmentally friendly material? Adv Mat Res, vol. 1041, Trans Tech Publications Ltd; 2014, p. 83–6. https://doi.org/10.4028/www.scientific.net/AMR.1041.83.

[30] Borhade SS. Chemical Composition and Characterization of Hemp (Cannabis sativa) Seed oil and essential fatty acids by HPLC Method. vol. 5. 2013.

[31] Kumar N, Goel N. Phenolic acids: Natural versatile molecules with promising therapeutic applications. Biotechnology Reports 2019;24. https://doi.org/10.1016/j.btre.2019.e00370.

[32] Mnekin L, Ripoll L. Topical use of cannabis sativa l. Biochemicals. Cosmetics 2021;8. https://doi.org/10.3390/cosmetics8030085.

[33] Setti L, Seyedeh &, Samaei P, Maggiore I, Nissen L, Gianotti A, et al. Comparing the Effectiveness of Three Different Biorefinery Processes at Recovering Bioactive Products from Hemp (Cannabis sativa L.) Byproduct. 2020. https://doi.org/10.1007/s11947-020-02550-6/Published.

[34] Asokan MA, Prabu SS, Bollu A, Reddy MA, Ram A, Sukhadia DS. Emission and performance behavior of hemp seed oil biodiesel/diesel blends in di diesel engine. Mater Today Proc, vol. 46, Elsevier Ltd; 2021, p. 8127–32. https://doi.org/10.1016/j.matpr.2021.03.064.

[35] Müssig J, Haag K, Musio S, Bjelková M, Albrecht K, Uhrlaub B, et al. Biobased 'Mid-performance' composites using losses from the hackling process of long hemp – A feasibility study as part of the development of a biorefinery concept –. Ind Crops Prod 2020;145. https://doi.org/10.1016/j.indcrop.2019.111938.

[36] Bertoli A, Tozzi S, Pistelli L, Angelini LG. Fibre hemp inflorescences: From crop-residues to essential oil production. Ind Crops Prod 2010;32:329–37. https://doi.org/10.1016/j.indcrop.2010.05.012.

[37] Schluttenhofer C, Yuan L. Challenges towards Revitalizing Hemp: A Multifaceted Crop. Trends Plant Sci 2017;22:917–29. https://doi.org/10.1016/j.tplants.2017.08.004.

[38] Vogel E. Hemp (Cannabis sativa L.) for Medicinal Purposes: Cultivation under German Growing Conditions. 2017.

[39] Ascrizzi R, Iannone M, Cinque G, Marianelli A, Pistelli L, Flamini G. "Hemping" the drinks: Aromatizing alcoholic beverages with a blend of Cannabis sativa L. flowers. Food Chem 2020;325. https://doi.org/10.1016/j.foodchem.2020.126909.

[40] Zhu J, Yi J, Kang Q, Huang J, Cui Y, Zhang G, et al. Anti-fatigue activity of hemp leaves water extract and the related biochemical changes in mice. Food and Chemical Toxicology 2021;150. https://doi.org/10.1016/j.fct.2021.112054.

[41] Amaducci S, Scordia D, Liu FH, Zhang Q, Guo H, Testa G, et al. Key cultivation techniques for hemp in Europe and China. Ind Crops Prod 2015;68:2–16. https://doi.org/10.1016/j.indcrop.2014.06.041.

[42] Jeliazkov VD, Angima S. Soil, Seedbed Preparation and Seeding for Hemp Biological activities of medicinal plants View project Long-term impact of agricultural practices on plant and soil nutrients in drylands of Eastern Oregon. View project. n.d.

[43] Spano M, di Matteo G, Ingallina C, Botta B, Quaglio D, Ghirga F, et al. A multimethodological characterization of cannabis sativa l. Inflorescences from seven dioecious cultivars grown in Italy: The effect of different harvesting stages. Molecules 2021;26. https://doi.org/10.3390/molecules26102912.

[44] Rehman M, Fahad S, Du G, Cheng X, Yang Y, Tang K, et al. Evaluation of hemp (Cannabis sativa L.) as an industrial crop: a review 2021. https://doi.org/10.1007/s11356-021-16264-5/Published.

[45] Bengtsson E. Obtaining high quality textile fibre from industrial hemp through organic cultivation. 2009.

[46] Tomé M, Almeida MH, Barreiro S, Branco MR, Deus E, Pinto G, et al. Opportunities and challenges of Eucalyptus plantations in Europe: the Iberian Peninsula experience. Eur J For Res 2021;140:489–510. https://doi.org/10.1007/s10342-021-01358-z.

[47] Moscariello C, Matassa S, Esposito G, Papirio S. From residue to resource: The multifaceted environmental and bioeconomy potential of industrial hemp (Cannabis sativa L.). Resour Conserv Recycl 2021;175. https://doi.org/10.1016/j.resconrec.2021.105864.

[48] Ranalli P, Venturi G. Hemp as a raw material for industrial applications. Euphytica, vol. 140, 2004, p. 1–6. https://doi.org/10.1007/s10681-004-4749-8.

[49] Final report on integrated sustainability assessment. 2017.

[50] Portuguese Enviromental Association. Relatório do Estado do Ambiente Portugal. 2019.

[51] Coste-Maniere I, Croizet K, Sette E, Fanien A, GUezguez H, Lafforgue H. Circular Economy in Textiles and Apparel. 2019.

[52] Sensi Seeds. Cannabis in Portugal – Laws, Use, and History 2021.

[53] Silveira Botelho J. Novas regras para o cânhamo industrial ou combate ao CBD? 2022.

[54] Ramos L. Produtores de Cânhamo Industrial exigem respostas ao Governo 2019.

[55] Ramos L. Agricultores ponderam desistir de investimentos no cânhamo em Portugal 2022.

[56] European Comission. Hemp production in the EU 2020.

[57] Ramos L. A história de Barry ou como Portugal trata agricultores de cânhamo como traficantes 2022.

[58] Portuguese Republic. ECONOMIA E TRANSIÇÃO DIGITAL, FINANÇAS, ADMINISTRAÇÃO INTERNA, JUSTIÇA, SAÚDE E AGRICULTURA Portaria n.º 14/2022. 2022.

[59] Paone E, Tabanelli T, Mauriello F. The rise of lignin biorefinery. Curr Opin Green Sustain Chem 2020;24:1–6. https://doi.org/10.1016/j.cogsc.2019.11.004.

[60] Preetha Ganguly, Rwiddhi Sarkhel, Papita Das. The second- and third-generation biofuel technologies: comparative perspectives. Sustainable Fuel Technologies Handbook, 2021, p. 29–50.

[61] of York U. Hemp-30 Phase I Final Report Contents List. n.d.

[62] PG paper Company. The Global Paper Market-Current Review. 2018.

[63] Ian Tiseo. Global paper industry. 2022.

[64] IBISWorld. Global Paper & Pulp Mills Industry - Market Research Report. 2020.

[65] Lipiäinen S, Kuparinen K, Sermyagina E, Vakkilainen E. Pulp and paper industry in energy transition: Towards energy-efficient and low carbon operation in Finland and Sweden. Sustain Prod Consum 2022;29:421–31. https://doi.org/10.1016/j.spc.2021.10.029.

[66] Purkait MK, Mondal P, Chang C-T. Treatment of Paper and Pulp Industry Effluents. Treatment of Industrial Effluents, CRC Press; 2019, p. 157–82. https://doi.org/10.1201/9780429401763-7.

[67] Nicholas P. Cheremisinoff, Paul E. Rosenfeld. Sources of air emissions from pulp and paper mills. Handbook of Pollution Prevention and Cleaner Production, William Andrew Publishing; 2010, p. 179–259.

[68] CELPA. Boletim Estatístico 2019. 2019.

[69] Navigator Company. Conhecer o eucalipto. 2020.

[70] Gabinete de Planeamento P e AG(. CULTIVAR. 2018.

[71] Malico I, Gonçalves AC. Eucalyptus globulus coppices in portugal: Influence of site and percentage of residues collected for energy. Sustainability (Switzerland) 2021;13. https://doi.org/10.3390/su13115775.

[72] A. Jury W, J. Vaux Jr. H. The Emerging Global Water Crisis: Managing Scarcity and Conflict Between Water Users. Advances in Agronomy, 2007, p. 1–76.

[73] Kirton U company. PAPER MILLS UNDER PRESSURE TO REDUCE WATER FOOTPRINT n.d.

[74] Patel K, Patel N, Vaghamshi N, Shah K, Duggirala SM, Dudhagara P. Trends and strategies in the effluent treatment of pulp and paper industries: A review highlighting reactor options. Curr Res Microb Sci 2021;2. https://doi.org/10.1016/j.crmicr.2021.100077.

[75] Afiqah Adnan N, Sapuan SM. Pulp and paper production: A review Synthesis, Characterization and DC Electrical Properties of Polyamide and Polyester/Multi-Walled Carbon Nanotube Composites View project. 2021.

[76] Bajpai P. Introduction. Recycling and Deinking of Recovered Paper, 2014, p. 1–19.

[77] GeSI. SMART 2020: Enabling the low carbon economy in the information age. 2008.

[78] Gerdin C, Vainberg G, Singh K, Lapo Mori A, Lingqvist O. Tapping digital's full potential in pulp and paper process optimization 2021.

[79] Ritchie H, Roser M. Plastic Pollution. . OurWorldInDataOrg 2018.

[80] Oloyede OO, Lignou S. Sustainable paper-based packaging: A consumer's perspective. Foods 2021;10. https://doi.org/10.3390/foods10051035.

[81] Baptista C, Santos N, Rosa M. Portuguese Hemp Plant as Raw Material for Papermaking. Athens J Sci 2020;7:15–28. https://doi.org/10.30958/ajs.7-1-2.

[82] Estatísticas da Pesca. 2020.

[83] Ferreira V, Larrañaga A, Gulis V, Basaguren A, Elosegi A, Graça MAS, et al. The effects of eucalypt plantations on plant litter decomposition and macroinvertebrate communities in Iberian streams. For Ecol Manage 2015;335:129–38. https://doi.org/10.1016/j.foreco.2014.09.013.

[84] Eucalyptus_globulus n.d.

[85] Gominho J, Lopes C, Lourenço A, Simões R, Pereira H. Eucalyptus globulus Stumpwoodas a Raw Material for Pulping. vol. 9. 2014.

[86] Roger G. Skolmen, F. Thomas Ledig. Eucalyptus globulus Labill. n.d.

[87] Pereira JS, Tomé M, Madeira M, Almeida H. Eucalypt plantations in Portugal. n.d.

[88] Navigator Company. Eucalyprus globulus fact sheet - Navigator company. Navigator Company Web Site n.d. https://www.navigator-paper.com/en/faqs/eucalyptus.

[89] M.El Haggar S. Rural and Developing Country Solutions. Environmental Solutions, 2005, p. 313–400.

[90] Brusseau ML. Sustainable Development and Other Solutions to Pollution and Global Change. Environmental and Pollution Science (Third Edition). third, 2019, p. 585–603.

[91] Life Cycle Assessment Best Practices of ISO 14040 Series Ministry of Commerce, Industry and Energy Republic of Korea Asia-Pacific Economic Cooperation Committee on Trade and Investment. 2004.

[92] Salary expert. Hourly pay in portugal agriculture n.d.

[93] loja agropecuaria. Cost of glysophate n.d.

[94] Dias AC, Arroja L. Environmental impacts of eucalypt and maritime pine wood production in Portugal. J Clean Prod 2012;37:368–76. https://doi.org/10.1016/j.jclepro.2012.07.056.

[95] https://people.exeter.ac.uk/. Calculation of CO2 emissions n.d.

[96] Centre for Agriculture and Bioscience International. Eucalyptus globulus (Tasmanian blue gum) n.d. https://www.cabi.org/isc/datasheet/22680#torainfallRegime (accessed August 7, 2022).

[97] McPartland JM. Cannabis Systematics at the Levels of Family, Genus, and Species. Cannabis Cannabinoid Res 2018;3:203–12. https://doi.org/10.1089/can.2018.0039.

[98] Multihemp project. Hemp – A natural biorefinery n.d.

[99] Book ·. Images and Literature about production and medical use of Dronabinol-Δ9-Tetrahydrocannabinol 2014. https://doi.org/10.13140/2.1.2697.9202.

[100] Weaving Hemp into the Northern California Fibershed n.d.

[101] Burton RA, Andres M, Cole M, Cowley JM, Augustin MA. Industrial hemp seed: from the field to value-added food ingredients. J Cannabis Res 2022;4. https://doi.org/10.1186/s42238-022-00156-7.

[102] C. Brouwer, M. Heibloem. IRRIGATION WATER MANAGEMENT Training manual no. 3. 1986.

[103] Reina LM. Eucalyptus globulus chemical composition and its effect on Kraft pulping parameters. n.d.

[104] ICNF. Evolução da ocupação das principais espécies e formações florestais, 1902 – 2010 2010. https://www.agroportal.pt/floresta-portuguesa-ocupa-mais-de-um-terco-do-pais/ (accessed October 28, 2022).