Life Cycle Assessment of Industrial Hemp and Hemp-Based Products in Canada

by

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Abstract

Industrial hemp is a versatile crop producing nutrient-rich hempseed and a large quantity of biomass. Bast fibre and hurd are excellent materials derived from hemp straw, while bioactive ingredients are extracted from flower heads and leaves. The environmental impacts associated with hemp production were well-studied in the EU. However, Life Cycle Assessment (LCA) studies of hemp produced in Canada were limited despite being one of the largest hemp-producing countries. This thesis aims to evaluate the hemp production system and hemp-based products manufactured in Canada using the LCA approach. With an increasing global focus on sustainability, this research fills an important gap in understanding the environmental impact of hemp production in Canada, and provides necessary data for the development of environmental product declarations (EPDs) of current and future hemp-based products. The production of hempseed and straw was investigated first, followed by assessing the manufacturing of bast fibre, hurd and nonwoven mats.

The cradle-to-farm gate assessment of hempseed and straw comprised foreground data collected from growers, the Canadian Hemp Trade Alliance (CHTA), National Hemp Variety Field Trial (NHVFT) 2022 results, and provincial hemp production guides. The cradle-to-factory gate analysis of hemp-based products collected information from the manufacturer. Data for the background processes were taken from LCA databases. One kg of hempseed and straw were used as functional units in the first study, while one tonne of hemp-based products was the functional unit in the second study.

The results from the first study showed that dual-purpose production of hempseed had the lowest environmental impacts when allocating by mass, followed by grain-only production scenario and dual-purpose hempseed with economic allocation. Hempseed production from growers had lower footprints than that from NHVFT 2022 results and production guides. The Greenhouse Gas (GHG) emissions associated with hemp production in Canada were comparable to hemp produced in the EU. However, some LCA studies showed lower footprints than the present study due to higher yield, lower nutrient inputs and integration of organic fertilizer. The major contributors to GHG emissions were field emissions, fertilizer production, and field operations.

For the second study, bast fibre and hurd from co-harvested straw had the lowest production footprint when allocated by its market value, followed by fibre-only production of feedstock and co-harvested straw allocating by mass. A similar result was applied to the production of hemp-based nonwoven mats. The GHG emissions of hemp-based products were similar to those produced in the EU. Significant contributors to carbon footprints were hemp straw production and electricity consumed during manufacturing. Sensitivity analysis suggested that the use of higher quality and low carbon feedstock, low carbon intensity electrical energy, and dust significantly reduced overall GHG emissions.

The finding from this study provides benchmark information regarding hemp materials, which could be used in further investigations of hemp-based products. Long-term tracking of hemp production in Canada and site-specific environmental conditions will improve the accuracy of LCA and provide more representative results.

Preface

The research presented in this thesis is an original work of Qifan Wu under the supervision of Dr. John Wolodko. There are five chapters in this thesis: Chapter 1 contains an introduction and the objective of the project; Chapter 2 presents the literature review related to LCA studies and key considerations; Chapter 3 is a self-contained manuscript estimating the environmental impacts associated with industrial hemp produced in Canada using life cycle assessment approaches; Chapter 4 is a supplementary study to Chapter 3, and evaluates the environmental footprints associated with the decortication of hemp straw and production of nonwoven mats from hemp bast fibre via life cycle assessment; Chapter 5 presents the most relevant results and future opportunities of the study. Both chapters 3 and 4 will be submitted to relevant journals for publication.

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Chapter 1 : Introduction and objectives

Industrial hemp (Cannabis *sativa*), commonly called hemp, is a heritage crop human have cultivated for thousands of years. Hemp is a multipurpose crop which can supply hempseed for both food and non-food applications and durable fibres from the hemp straw which has been traditionally used to produce textiles, rope and sail [1]. Hemp is botanically related to cannabis or marijuana (Cannabis *sativa*, Cannabis *indica*) [2], and both plants contain tetrahydrocannabinol (THC) which is a psychoactive drug at higher concentrations [3]. As a result, hemp underwent similar regulation and management as cannabis by governments around the globe. In the early 1900s, most countries prohibited the production of hemp and cannabis. However, restrictions on industrial hemp production were lifted in the 1990s for those varieties (cultivars) that produced a THC concentrations of 0.3% or less. Canada has allowed industrial hemp production since 1998, and the sector is currently regulated by Health Canada [4].

Industrial hemp is currently produced in dozens of countries at various scales for both food (hempseed) and fibre applications as shown in Figure 1. Based on 2021 data, the major hemp-producing countries over last decade include North Korea, Canada, France, China and Russia. Canada had the highest hectarage of hemp production in 2019, with more than 37,000 ha harvested which dropped to 22,500 ha in 2021 and 28,800 ha in 2022 [5-6]. The European Union (EU) had almost 35,000 ha of cultivated area in 2019 and 32,000 ha in 2021 [7]. Of this amount, France accounts for 70% of all EU production. The Food and Agriculture Organization (FAO) of the United Nations suggests that more than 11,000 ha of hempseed and 74,000 ha of raw or retted hemp were produced in 2021 around the world. However, the FAOSTAT data set [8] is somewhat incomplete as it does not report hemp production from Canada and some other countries. From this dataset, France was the largest raw or retted hemp producer from 2019 to

2021, followed by China. Meanwhile, a *special issue on industrial hemp* from the United Nations (UN) [9] collected production statistics from various sources and suggested that Canada was the largest producer of hemp fibre and hempseed in overall cultivated area and total production in 2019.

The preceding fibre and hempseed production statistics highlighted different priorities between the hemp industry in Canada and other countries. In Canada, even though a significant proportion of acreage was registered for fibre and flower production, 85% of hemp acreage was intended to produce hempseed, while the remaining 10-15% was dedicated to producing straw [5, 10]. Horticultural hemp production to extract bioactive ingredients is relatively new compared to traditional broadacre production and occupies a niche market [10]. Other countries such as France and China prioritize producing hemp straw to utilize bast fibre and hurd from the decortication or scutching process [1].

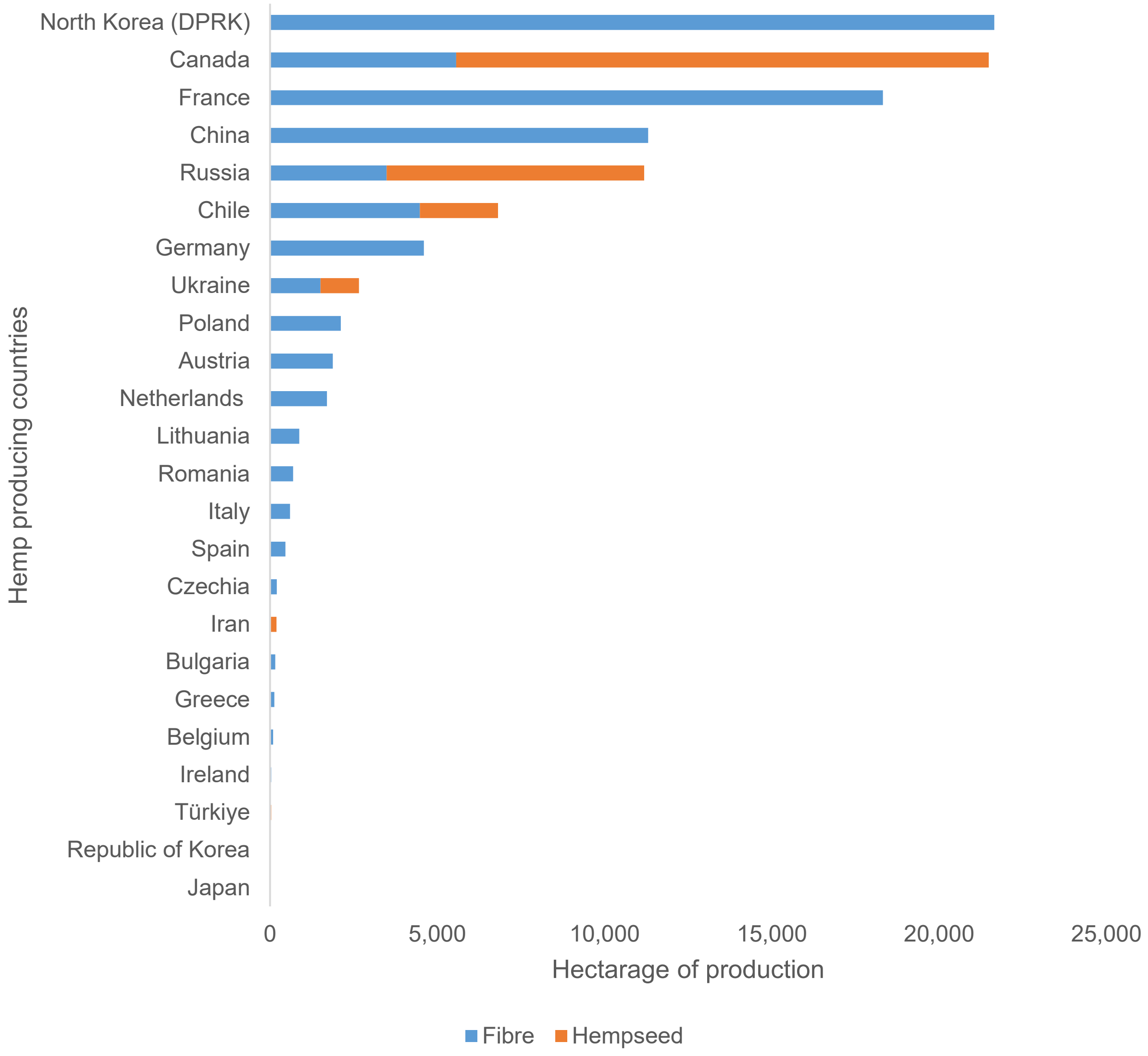

Figure 1.1 Estimated and reported hemp production hectarage by countries in 2021 [5, 8]

Industrial hemp is a very versatile, multi-purpose crop since straw, hempseed and other extractives can be produced and used in a variety of products. Studies estimate that more than 25,000 products can be made with hemp-based materials while utilizing the entire plant [1, 9]. Hempseed has high protein and oil content [11], making it nutritious and good at producing oil for various purposes such as food, feed, cosmetics and biofuel. Conversely, hemp straw can be used to produce two important derivatives: strong “bast” fibres which are located on the outside of the plant stem, and “hurd” (or shive) which is a woody (porous) material located at the interior or core of the plant stem [2]. These straw components are separated using a process called decortication or scutching. As part of this process, dust is also generated as a waste product which can be pelletized for use as a biofuel. A variety of novel products such as natural fibre products can be made with bast fibre and hurd including insulation products, biocomposites, and hempcrete (a combination of hemp hurd and a cement) [1, 9].

These products mentioned above have received considerable attention from various industries due to the renewable nature of the biomass feedstock and the potential to mitigate climate change by absorbing CO_2 from the atmosphere during the growth phase, temporarily storing carbon during its use phase [12]. For example, studies have emphasized that hemp-based composites have a lower carbon footprint than traditional materials such as glass fibre and concrete [13-14]. Global warming and climate change has become one of the most critical environmental problems in the last few decades. The United Nations Sustainability Development Goals address climate change with their short-term objectives, while the Paris Agreements have set up long-term roadmaps for society to combat global warming. For the hemp industry, understanding the environmental footprint and benefits of producing hemp-based products is critical to develop new sustainable products. As part of this, the qualitative and quantitative assessment of production data is seen as necessary step for the hemp industry to expand and make a contribution to the green economy.

Researchers have implemented the Life Cycle Assessment (LCA) method as a way to evaluate the environmental impact of both hemp production and hemp product manufacturing. However, most of these studies have been conducted in the European Union (EU) focusing on fibre products such as hempcrete, reinforced plastic and bioenergy [12-13, 15]. As a result, data gaps in the literature exist regarding the environmental footprint of hemp production in Canada as a whole, and also specifically for hempseed used for food applications. Canada is one of the world's largest producers of hempseed and straw, expanding from British Columbia on the west coast to Atlantic provinces in the east. However, most hemp production occurs in the prairies, and production practices differ regionally due to various climate conditions and field practices. Hempseed can be produced organically or with irrigation alongside conventional dryland production. Therefore, evaluating the production of Canadian hemp could provide the industry with helpful information comparing different production practises and locations.

This thesis aims to estimate the life cycle environmental impacts of hemp production in Canada for various production systems and for select hemp-based products. The following specific objectives were addressed:

1. To evaluate the environmental footprint associated with hempseed and hemp straw production in different production systems and regions across Canada using the LCA approach, and to investigate the influence of production parameters on the overall greenhouse gas (GHG) emissions (Chapter 3).
2. To estimate the environmental impacts of producing hemp-based products in Canada, including bast fibre, hurd, and nonwoven mats. The sensitivity analysis evaluates alternative inputs and their improvements on the overall GHG emissions (Chapter 4).

Chapter 2 : Literature review

2.1 Evaluating environmental impacts of hemp production using life cycle assessment

Life cycle assessment (LCA) is a standardized methodology to estimate the environmental impacts associated with products or services over their lifetime or a defined period. The guidelines for LCA are standardized by the International Standards Organization under standards ISO 14040 and ISO 14044 [16-17]. LCA usually consists of four (4) phases: 1) goal and scope definition, 2) life cycle inventory (LCI), 3) life cycle impact assessment (LCIA), and 4) interpretation. The definition creates the basic structure of the LCA, including system boundary, functional unit and other assumptions. LCI quantifies the inputs and outputs associated with the studied system, such as materials, energy and emissions. LCIA uses dedicated methods and factors to convert emissions from LCI that contribute to the same environmental impact category and report results in uniform units. Each phase works interactively with others to deliver the outcome [16-17]. Using the life cycle approach, researchers have been able to estimate industrial hemp's production footprint and potential environmental benefits.

2.1.1 Previous LCA studies on industrial hemp production

Literature screening was conducted using the Web of Science core collection with the search term "(TS=(life cycle*) OR TS=("life cycle assessment") OR TS=("life cycle analysis") OR TS=(LCA)) AND TS=(hemp)." The review was from Jan 1, 1999, to May 31, 2023.

A total of 51 LCA studies were identified, covering the primary production of hemp to the end-of-life (EOL) treatment of hemp-based products. The overall number of LCA studies (or publications) is shown in Fig 2.1. Some studies assessed more than one case at a time in their analysis, often estimating the footprint of different products. Therefore, a total of 56 LCA cases were identified, including 5 LCA cases discussing the production of primary hemp products, including hemp straw and hempseed. Additionally, 2 LCA studies evaluated the production of bast fibre and hurd, which are feedstocks for secondary processing. European researchers conducted most LCA studies with source information from EU countries. The number of LCA studies using production data sourced from each country is presented in Fig 2.2, which is dominated by European countries.

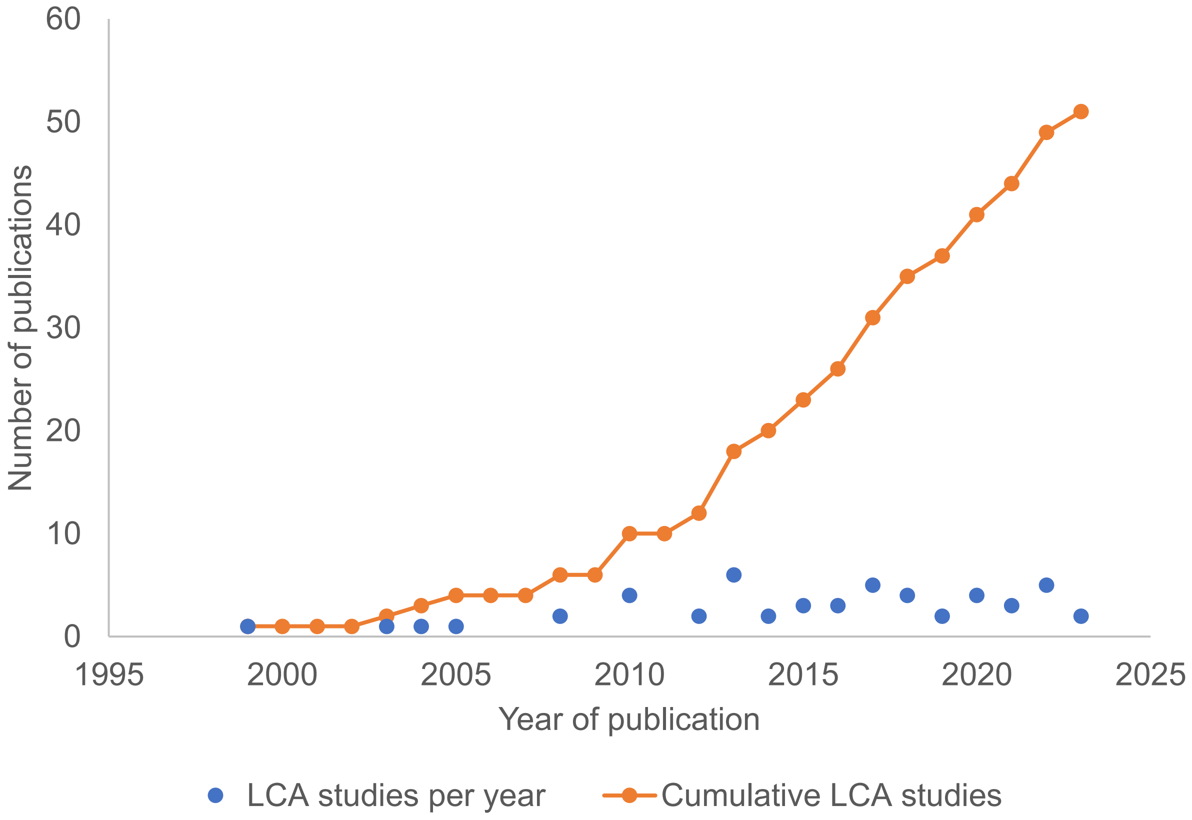

Figure 2.1 Number of LCA studies investigating the production of hemp and hemp-based products (n=51)

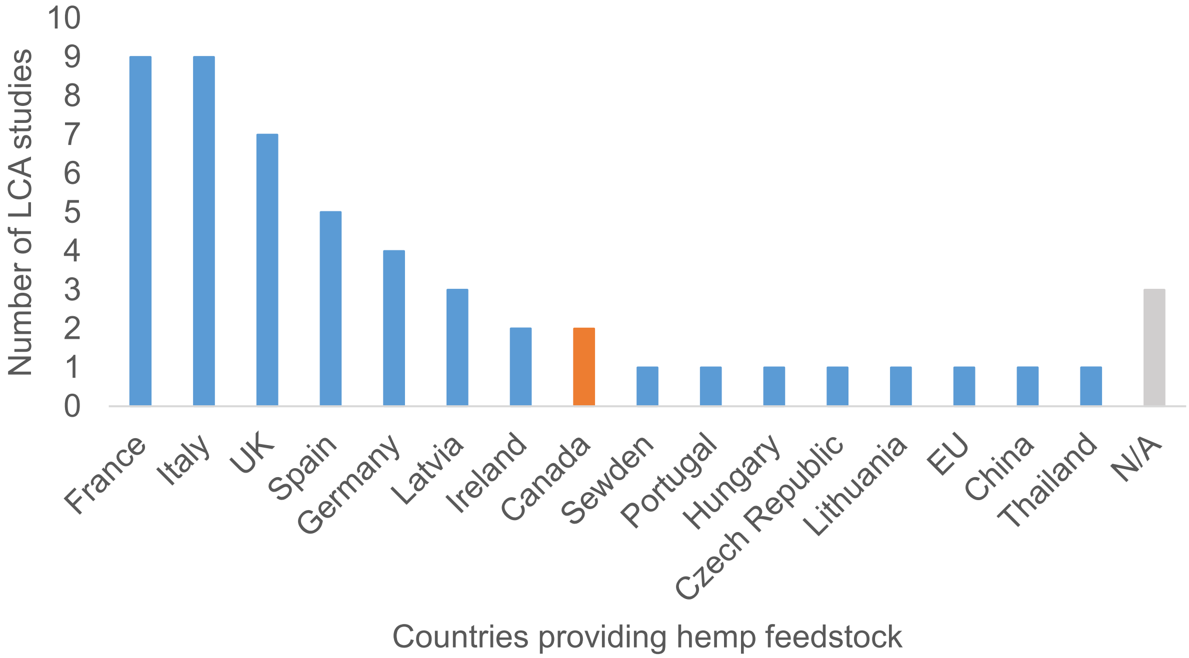

Figure 2.2 Number of LCA studies investigating hemp produced in each country

2.1.2 Previous LCA studies on hemp-based products

Hemp-derived materials are used in a variety of applications for both consumer and industrial use. The screened literature was subsequently categorized by its application and functional unit as shown in Table 2.1. The literature review identified 47 separate LCA cases that estimate the production footprint of hemp-based products. In addition, only one LCA study modelled the end-of-life options for hemp-based products [18].

Table 2.1 Categorization of LCA cases from the literature based on the production of hemp and hemp-based products (n=56)

Material category	Application	# of LCA Cases	Reference
Cultivation		8	[12, 19-25]
Straw	Hempcrete	16	[13, 26-40]
	Insulation mat	5	[21, 30, 41-43]
	Reinforced plastic	12	[14, 38, 44-53]
	Pulp & paper	2	[54-55]
	Textile	1	[56]
	Bioenergy	7	[15, 25, 57-61]
Hempseed	Bioenergy	1	[62]
	Food	2	[38, 63]
	Feed	1	[64]
End of life		1	[18]

2.2 Defining LCA study with assumptions

As suggested by ISO 14040 [16], the first step to establishing an LCA model is defining the goal and scope of the study. The objective is identified at this stage, alongside the life cycle phases covered by the assessment. The functional unit defines the targeted products or services and is a quantitative reference for the following LCI and LCIA phases. Lastly, system boundaries are drawn to separate material and energy flows from other related streams in the present study [17].

2.2.1 Goal, scope, functional unit, and system boundaries of LCA studies

The functional units of the 56 LCA cases were categorized by the level of processing, except for one study discussing end of life (EOL) and the other 3 cases representing services. Most studies investigated the production of secondary products, followed by primary materials, as shown in Fig 2.3. Hemp straw, hempseed, hemp chaff, and hemp flower head/buds are primary products harvested directly from industrial hemp production. Secondary products require additional processing steps in dedicated facilities, and include examples such as bast fibre, hurd, and dust from the decortication of straw; hempseed oil, hempseed meal from oil extraction; dehulled hempseed from dehulling; Cannabidiol (CBD) from the extraction of hemp chaff and flowers, etc. There are also products which require even more refinement and may contain materials outside of the hemp production system (e.g. lime cement in hempcrete, and binders in insulation). The functional unit and the level of processing of the LCA studies investigated are presented in Appendix A.

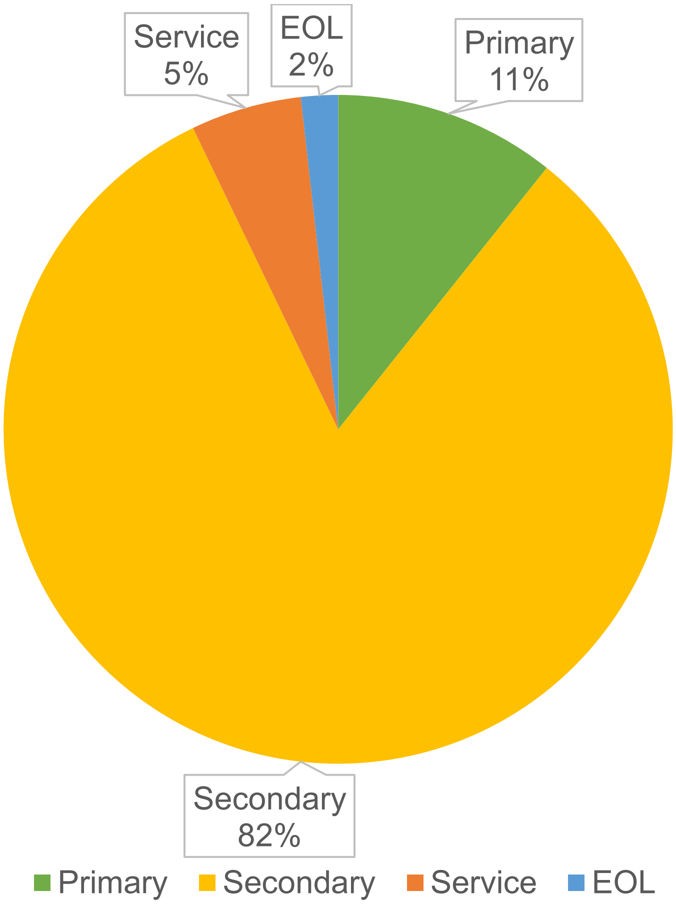

Figure 2.3 Production focus of hemp and hemp-based products evaluated in reviewed LCA cases (n=56)

Typical LCA studies cover all life cycle stages, from raw material extraction to the final disposal, called cradle-to-grave analysis. However, assessing the full system boundary including the use phase and end-of-life (EOL) phase of some novel or long-lasting products can be challenging. As a result, cradle-to-gate analysis is another common practice while conducting LCA. Cradle-to-gate analysis is most adopted amongst studies, covering more than half of all cases as indicated in Fig 2.4. The scope of LCA cases regarding hemp products is presented in Appendix A.

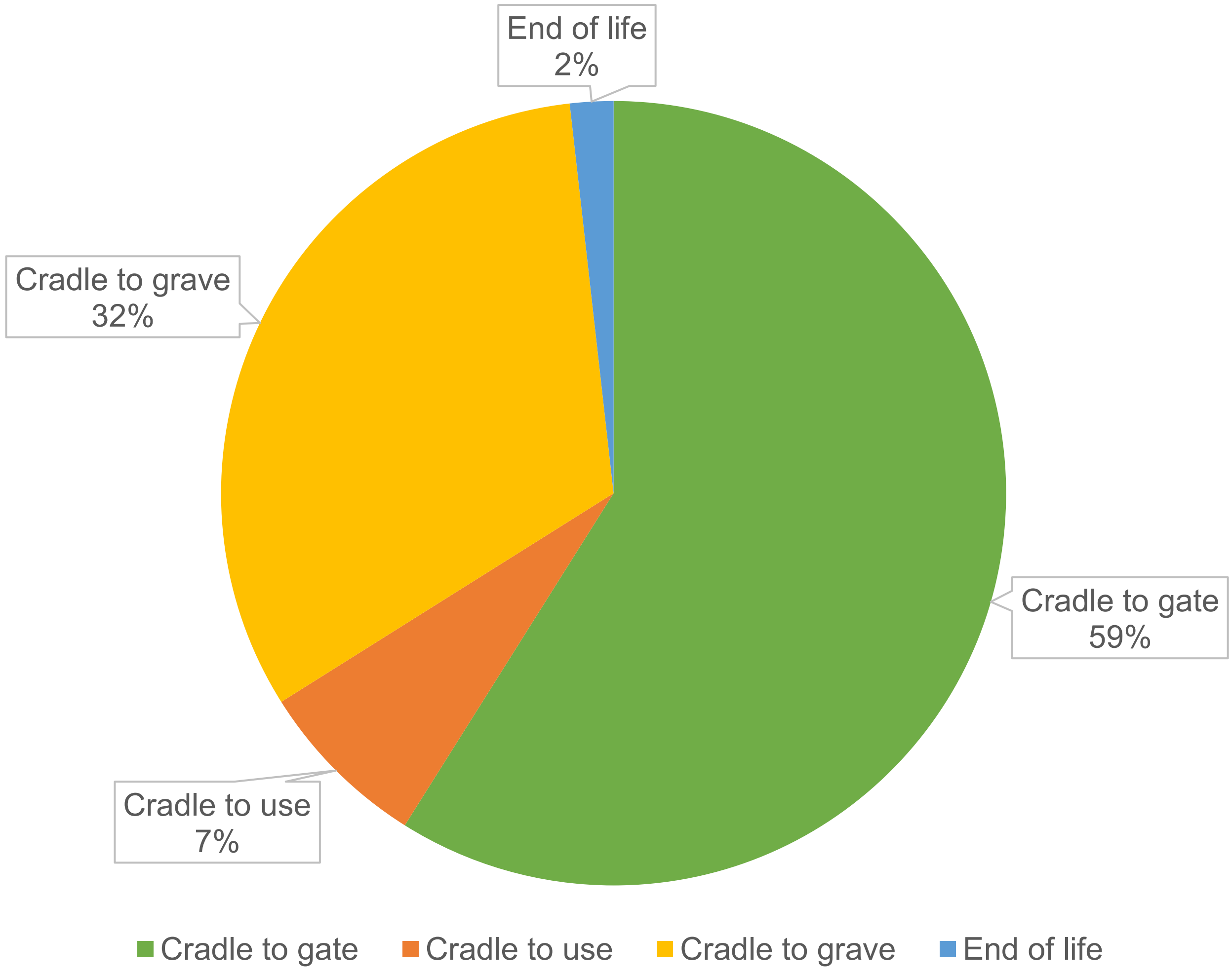

Figure 2.4 Scope of LCA cases estimate the production of hemp and hemp-based products (n=56)

2.2.2 Life cycle inventory of LCA studies

Life cycle inventory is the most critical phase in LCA studies which entails the collection of information and data about the specific steps and processes in producing hemp and hemp-based products. From the reviewed literature, researchers have utilized a variety of data collection methods as shown in Fig 2.5. It should be noted that the source of LCI information was not disclosed in 4 studies. Most LCA studies used several data sources starting with information obtained from questionnaires and interviews with producers. Researchers who didn't have access to hemp farmers used alternative (secondary) data sources including previous results from literature discussing hemp cultivation, published LCA studies, and LCA databases. However, hemp as a niche crop doesn't have a comprehensive LCA dataset. The information sources implemented by LCA studies are presented in Appendix A.

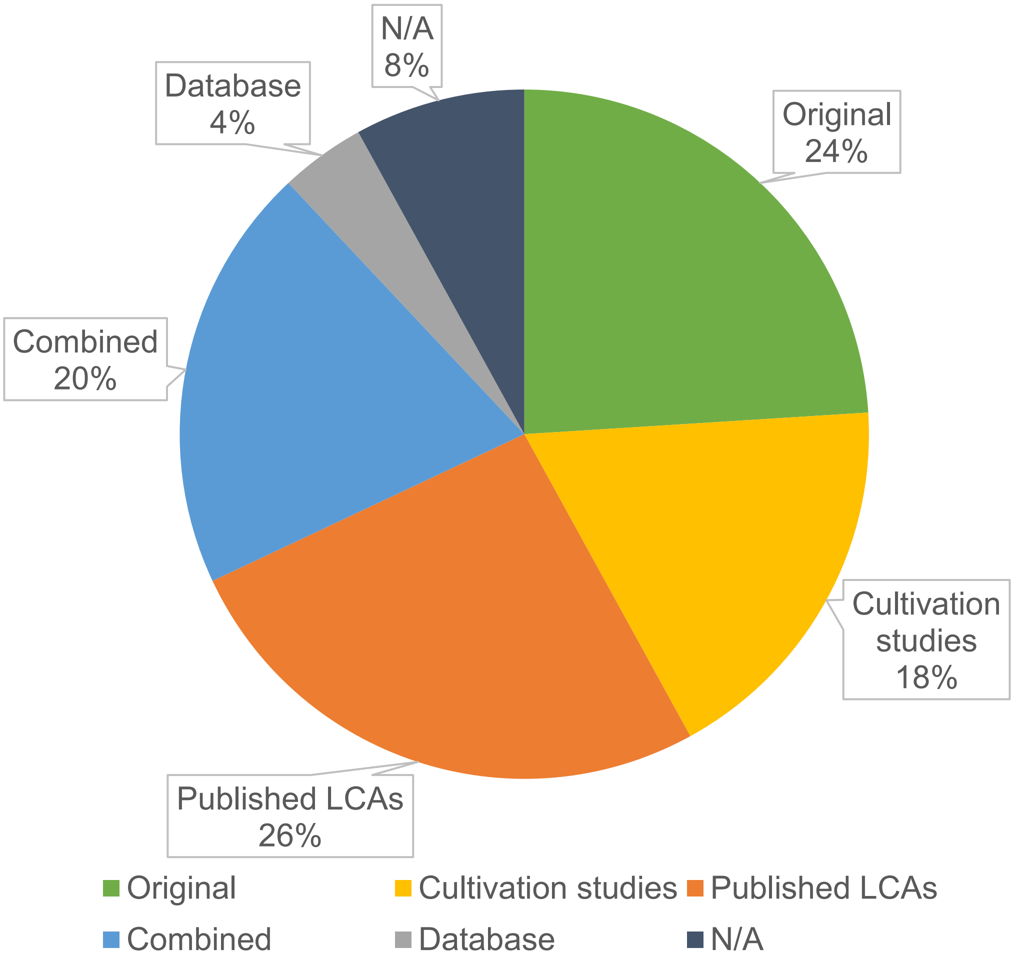

Figure 2.5 LCI source of LCA studies estimates the production of hemp and hemp-based products (n=50, Study investigates EOL doesn't include foreground production of hemp; "original" indicates that the study authors obtained some data through interviews directly with farmers/producers)

2.2.2.1 Emissions associated with the application of fertilizer

The production of annual crops requires a large amount of fertilizer, which has a significant environmental footprint. In LCA studies regarding crops, it is common to implement the production of fertilizers from databases. However, the soil emissions after applying fertilizers require additional attention and calculation.

Field emissions of greenhouse gases (GHGs) primarily consist of nitrous oxide originating from applying N fertilizer. It also includes carbon dioxide emitted from the application of urea and emissions associated with field burning of residue [65]. IPCC [66] has suggested three tiers of methods to calculate field emissions. The basic equation (tier 1) assumes that 1% of the N fertilizer applied is emitted back into the atmosphere as nitrous oxide. Tier 2 methods are dedicated to individual countries or regions, where researchers have developed country-specific models based on field measurements over decades. The third tier of methods are more accurate than the previous two since it considers localized information regarding soil, climate, specific N sources, application methods, etc [66]. However, more accurate methods demand more site-specific and detailed information. As a result, most researchers have implemented tier 1 or 2 methods while calculating field emissions. Studies adopting LCI data from a specific research site are more likely to estimate the production footprint accurately than studies covering larger areas with aggregated parameters.

Among the 51 LCA studies identified, 50 included the production of hemp material in the system boundaries (all except the EOL study). Most studies have reported an aggregated environmental footprint associated with the supply of hemp, while 9 studies have reported separately in the form of fertilizer production, field emissions, fieldwork and other processes. Meanwhile, 23 studies have provided precise methods for estimating field emissions such as N_2O

and CO_2 emissions to air, ammonia, nitrate and phosphate to water, and heavy metal and herbicide emissions. Details of the calculation are presented in Appendix A. Earlier LCA studies usually combined equations from dedicated research to calculation field emissions to the environment [19]. Later studies took advantage of published methods adopted by common LCA databases, such as ecoinvent and World Food LCA Database (WFLCA), where standardized equations are recommended [12, 22, 37].

2.2.2.2 Emissions associated with land use and land use change

Land use and land use change could contribute a significant amount of CO_2 due to the loss of C from the soil, especially for cropland converted from other forms such as forest land and grassland [65-66]. The majority of cropland has been cultivated for decades, and the agricultural practices influence the carbon flow in the production system. For cropland to remain cropland, four land management changes (LMCs) are suggested by the National Inventory Report (NIR) 2022 [65], including changes in the mixture of crop type; change in tillage practices; change in crop productivity/crop residue C input; and manure application. If no changes are made to the management practices, C stocks are assumed at equilibrium.

2.2.2.3 Emissions associated with field operations

The operation of tractors and other farming equipment emits GHGs in various forms. Production of field crops requires at least seeding and harvesting; additional operations such as soil preparation and fertilization increase the overall carbon footprint. There are several methods to estimate the GHG emissions associated with field operations, similar to calculating field emissions.

The most common method in LCA is to use background information from databases, which is easy to perform with lower data requirements. However, it has a limited variety of operations and variability of parameters. Lovarelli and Bacenetti [67] highlighted the importance of site-specific data by comparing LCI from the ecoinvent database with field measurement and other models. Tassiellia et al. [68] have conducted similar research with various operations and parameters. These studies have concluded that inventory results from databases such as ecoinvent only represent the average situation.

Researchers have also established country-specific methods to provide more accurate results, such as the Farm Fieldwork and Fossil Fuel Energy and Emissions model (F4E2) discussed by Dyer and Desjardins in Canada [69], and the ENVironmental Inventory of Agricultural Machinery operations (ENVIAM) proposed by Lovarelli et al., in the EU [70]. These models have been verified by farm energy use surveys or field measurements from research sites. However, it also requires information that farmers are less likely to provide. For example, these models commonly require working time and fuel consumption. It is challenging for farmers to estimate the exact time and fuel spent on an individual operation for a specific crop, especially for farms that produce several crops simultaneously.

2.2.4 Life cycle impact assessment results of LCA studies

Researchers have implemented several impact assessment methods to quantify the production footprints associated with the targeted products or services. These methods include conversion factors for substances emitted to the environment and aggregate results under each impact category. Literature dedicated to a single impact category was implemented by earlier LCA studies due to the lack of a standardized LCIA method. Later studies have utilized completed sets of methods such as ReCiPe, CML and others. However, environmental impacts are categorized differently and reported in various units, making it difficult to compare the LCIA results of similar products. Unlike other impact categories, IPCC was commonly used to evaluate carbon footprint due to the urgency to tackle climate change. Chapters 3 and 4 compare hemp products' global warming potential or carbon footprint with other studies and materials.

2.3 Mitigating climate change with industrial hemp

Over a single growing season, industrial hemp can produce a significant amount of biomass, and has one of the highest growth rates amongst crops grown in Canada. Considering a 50% carbon content, hemp can sequester a similar amount of carbon as a 25-year-old high-yielding pine plantation with the same land occupation in one year [14]. The European Commission also highlighted the carbon storage potential of hemp (alongside other environmental benefits), suggesting one hectare of hemp absorbs approximately 9-15 tonnes of CO_2 during its growth period [7]. More importantly, various hemp-based products can potentially achieve long-term carbon storage including applications such as bio-composites, insulation and hempcrete in building construction.

2.3.1 Root biomass and carbon sequestration

As mentioned in Chapter 2.2.2.1, crop residue could contribute carbon to the soil and subsequently increase Soil Organic Carbon (SOC). The fibre-only production scenario and dual production of hempseed and straw collect most of the aboveground biomass. Below-ground biomass is the main contributor of carbon in these scenarios. Hemp has an extensive root system, which can reach a depth of 130 cm and account for more than 2 t/ha [71-72]. Amaducci et al. [71] also found that hemp has a similar root length density (RLD) as maize and sugar beet, higher than other major crops such as barley, oat, and winter wheat. Combining hemp's deep roots and wide adoption of conservational tillage can provide great steady-state carbon sequestration potential in soils.

2.3.2 Carbon stored in hemp-based products

Biogenic carbon stored in hemp-based products is a hot topic among LCA studies. Several studies indicated that hemp straw could sequester 1.63-1.84 kg of CO2 per kg [37, 53], while 1 kg of hurd had a -1.29 kg CO2 equivalent footprint from biogenic carbon [12]. When hemp material was used in long-lasting products such as hempcrete and insulation, it could last between 12-100 years [30, 38]. During the use phase of hemp-based products, biogenic carbon is stored in a steady state and temporarily removed from the atmosphere. Even though these hemp-based products will be disposed of at the end of their lifespan and may slowly release carbon back into the atmosphere, the temporary storage effect still mitigates climate change and provide opportunities for a reduction in global warming.

2.4 Hemp-based products and its environmental footprints

Hemp materials derived from hempseed, straw, leave, and inflorescence have been utilized in various areas. Hempseed contains high protein and lipid content, making it an excellent food source. Hemp straw is processed into construction materials, composites, paper, textiles, and sorbent. The medical industry utilizes hemp extracts such as CBD, which is hardly found in other crops. The entire plant could be used to produce energy in the form of heat, electricity and biofuel [1, 9].

2.4.1 Hempseed as a source of food and oil

Utilizing hempseed as a food ingredient is popular in Canada and is beginning to expand in the EU. Hempseed production was compared in LCA studies with other major grains (such as maize and wheat), as well as oilseeds (including sunflower seed and rapeseed) [19, 63]. Van der werf [19] found that field production of hemp requires low inputs such as fertilizers, pesticides, and diesel, similar to sunflower and flax. However, Bernas et al., [63] suggested that hemp cultivated for oil production has higher environmental footprints relative to rapeseed oil and sunflower oil based on equal volume. Hempseed contains high oil content which makes hempseed oil comparable with vegetable oil extracted from common oilseed crops. Hempseed oil can also be used to produce biodiesel, and its production footprint was compared with fossil-fuel based diesel in LCA studies. Casas and Pons [62] found that hemp-diesel has lower environmental impacts such as global warming potential (GWP) and Ozone layer destruction potential than fossil-based diesel, but with higher eutrophication potential.

Some hemp production guides recommend that farmers provide similar amounts of nutrients to hemp as for high-yielding wheat [2, 73]. However, the average yield of hempseed is lower than major oilseeds, such as canola (rapeseed) and oilseed-type soybeans. The typical yield of hempseed is 700-1000 kg/ha, as suggested by production guides [74-76]. The Canadian Grain Commission showed that the 5-year average yield of canola in Canada was 2160 kg/ha in 2022, and the average yield of oilseed-type soybean was approximately 3,000 kg/ha in 2021 and 2022 [77-78]. Flaxseed had a lower average yield at about 1,500 kg/ha, while mustard had the lowest yield compared with other oilseeds at 740 kg/ha in 2022 [79-80].

2.4.2 Hemp straw derived materials for various application

The use of hemp straw has expanded beyond traditional fibre material in the past decades, and both bast fibre and hurd from hemp are starting to be used as construction materials. As an example, hempcrete is a non-load-bearing construction material with excellent insulation properties that is composed of hemp hurd and a lime-based cement binder [1]. LCA studies have compared hempcrete with conventional concrete (i.e. Portland cement) and bricks, or walls insulated with rock wool, glass fibre and polymers. Ip and Miller [13] found that the hemp-lime wall investigated has a negative net carbon footprint over a lifespan of a 100 years. Biogenic and lime binder contributed -82.71 kg/CO_2 eq via absorption and sequestration of carbon dioxide, while production, transportation and installation emitted 46.63 kg/CO_2 eq. Pretot et al., [27] indicated that hemp concrete contributes significantly less to climate change comparing to brick wall and concrete blocks with mineral wool. Sinka et al., [31-32] confirmed results from the previous studies such as the negative carbon dioxide emissions and the much lower carbon footprint of hempcrete than traditional materials.

Insulation mats made with hemp bast fibre also have a lower carbon footprint than traditional materials [21, 42]. Zampori et al., [21] found that hemp mats used as insulation were more sustainable than mineral-based counterparts, with negative greenhouse gas protocol (GGP) emissions and 28.8% lower cumulative energy requirement than rock wool. Pennacchio et al., [42] added hemp fibre to wool insulation, and found the new panel had lower energy demand comparing with other alternatives made with extruded polystyrene (XPS) and glass fibre. They concluded that hemp fibre reduces the environmental impacts of panels while maintaining good insulating properties.

Biocomposites are another market that utilizes hemp bast fibre, and is a material composed of bio-fibre with a polymer or cement matrix. Applications for biocomposites include automotive, consumer goods, packaging and building construction, and is often considered a sustainable replacement for synthetic fibre composites such as glass-fibre. Even though hemp bast fibre isn't as strong as glass-fibre, the carbon and energy footprint are much lower [14]. Compared with other natural fibres such as flax and jute, the production of hemp bast fibre has similar environmental impacts [49]. However, hemp paper had a higher production footprint relative to traditional materials, such as eucalyptus, used in the pulp and paper industry [55].

The traditional textile market is currently dominated by cotton and synthetic fibre, while flax and hemp supply specialty fibre at a smaller scale. The U.S. Department of Agriculture (USDA) [81] reported a 5-year average cotton yield of 972 kg/ha from 2018/19 to 2022/23. Hemp has the potential to produce up to 14-16 tonne/ha straw, and it contains 20-30% bast fibre [2, 74]. Therefore, hemp could be more efficient at producing fibre than that of cotton. Van der Werf and Turuen [56] showed that hemp had similar productivity in producing fibre as flax, and the environmental footprint of yarn made with hemp fibre was similar to flax fibre.

Other than using hemp material as a feedstock for manufacturing, both hemp biomass and hempseed oil could potentially used in bioenergy applications. Casas and Pons [62] evaluated the environmental impacts of hemp-diesel which was found to have negative carbon dioxide emissions during its cultivation and production phases. The various byproducts such as dried cake and straw could allocate some of the carbon footprint besides hemp-diesel production. Gonzalez et al., [57] found that ethanol from hemp and other lignocellulosic feedstock reduces greenhouse gas emissions, but have negative impacts on other categories including acidification, eutrophication, and photochemical smog.

Chapter 3 : Life cycle assessment of industrial hemp produced in Canada

3.1 Introduction

Industrial hemp is varieties of *Cannabis* L. genus with a 0.3% or lower tetrahydrocannabinol (THC) content [1]. The plant has a woody and hollow core material called hurd (or shive) while the outer part of the stalk is composed of long, strong bast fibres. The plant also produces a complex mixture of secondary metabolites, mostly concentrated in trichomes (flower heads or buds) [9]. Hemp also produces its seed later in the season and is a food source rich in protein and oil [11].

Hemp is produced worldwide using low inputs and maintenance [3]. Biomass and hempseed yields have limited reactions to phosphorus and potassium fertilization [82]. Increasing nitrogen supply significantly increases industrial hemp yield, but the effects only apply to low and medium doses [24, 83]. Due to its fast-growing character, hemp can also be cultivated without herbicides and insecticides [3, 74]. Experiments have also confirmed that hemp can be used in bioremediation of sites polluted by heavy metals or radioactive materials [84].

The European Union is one of the largest hemp producers in the world and allows legal cultivation of industrial hemp for textile, food, construction, paper and other uses [7]. Hemp has been cultivated in the EU and China over the past few decades primarily for fibre. Conversely, Canada has been producing hempseed for food and oil, which represents the majority of acreage, while fibre and fractions (such as flowers or leaf) account for a smaller proportion [85]. Health Canada approved 87 industrial hemp cultivars by May 2023 and issued thousands of licences in

Canada [86]. Between 20,000 to 30,000 hectares of hemp were cultivated annually in Canada from 2018 to 2021 [5].

Despite being a heritage crop, the hemp industry faces many challenges. In the 1930s, industrial hemp was banned alongside cannabis or marijuana as illicit plants in most parts of the world [3], however, countries such as Canada started to loosen restrictions on industrial hemp cultivation in the late 1990s [4]. The traditional fibre market has been dominated by cotton and synthetic materials since the 20th century, forcing the hemp industry to diversify the utilization of hemp material. Research suggests that hemp-derived materials such as bast fibre, hurd, hempseed oil and extracts can produce thousands of potential products [1, 3]. As a result, Canada and other major hemp-producing countries such as China and France are experiencing rapid expansion in hemp production and usage [87].

Global warming and climate change is an ongoing challenge in the world today and is the driver for the development of more sustainable materials and energy options. The International Panel on Climate Change (IPCC) reported that the average temperature in higher latitude regions such as Canada have experienced greater increase than the global average [88]. As temperature increases, drought and flooding could occur more frequently or with longer duration. Therefore, Canadian hemp production may encounter a greater risk induced by climate change. However, the hemp industry could play an important role in the green bioeconomy and help mitigate global warming. Dried hemp biomass contains approximately 40%-50% biogenic carbon, which has the potential to remove carbon dioxide from the atmosphere [14]. The EU estimates that one ha of hemp absorbs 9 to 15 tonnes of CO_2 during its 5-month growth period [10]. The production footprint of novel hemp-based materials such as hempcrete and insulation have lower embodied carbon than traditional materials made with cement, rock wool and glass fibre [13, 21].

There is increasing interest by both farmers and manufacturers in producing and utilizing hemp due to green-house gas (GHG) reduction through carbon sequestration in soil and long-lived fibre products [19]. Industrial hemp has great potential to be a low-carbon material for both food and manufacturing sectors, and it could be classified as a sustainable crop from its beneficial characteristics. This is a result of crop rotation practices, biodiversity management, improved soil health and revenue diversification (multi-use applications of seed, straw, and chaff). However, the environmental benefit of producing hemp has not been well studied by scientific community compared to other major crops, such as canola/rapeseed, soybean and cotton.

The complexity of the crop production system can be evaluated through the life cycle assessment (LCA) method. Several LCA studies have been carried out regarding the production of primary hemp materials such as hempseed and straw: Gonzales-Garcia et al., [20] investigated the production footprint of hemp fibre for pulp and paper industry in Spain; Van der Werf et al., [19] is one of the earliest study evaluated hemp straw production in France; Luca Zampori et al., [21] modelled the manufacturing of hemp-based insulation, including the production of hemp straw feedstock; and Enio Campiglia et al., [24] one of the few studies focusing on hempseed production, and conducted their research in Italy. While most of the studies in the literature have focused on hemp production practices in Europe, there have only been a very limited number of LCA studies from a Canadian perspective. Furthermore, these Canadian studies have focused only on hemp straw and fibre production, not the production of hempseed which is the primary output from the Canadian producers. Pervaiz and Sain [14] investigated the carbon storage potential of composite containing hemp material. Substituting glass fibre by hemp fibre reduced 3 t CO_2 eq per ton of composite product, while offering 21% weight reduction and maintaining comparable mechanical performance. George and Bressler [50] evaluated the environmental footprint of chemically treated hemp fibre and its composites. The production of treated hemp fibre has lower environmental, human and ecosystem impacts comparing to glass fibre. This limited understating of the environmental impact of hemp production in Canada is a significant gap in the literature and is particularly important due to the increasing scale and growth of the Canadian hemp industry.

In this study, a life cycle assessment was carried out to estimate the environmental footprint of hemp production in Canada, including primary outputs such as hempseed, hemp straw (containing bast fibre and hurd), and hemp chaff. The aim is to investigate various production practices in all provinces including moisture management (dryland and irrigated), production technique (conventional and organic), harvested fractions (single-purpose and multi-purpose). Canadian hempseed and straw should have comparable footprints as hemp products produced in the EU and other oilseeds in Canada, the results were compared with published LCA studies. The difference between diverse climate conditions and production scenarios in Canada were addressed. Environmental hotspots regarding the major contributors to GHG emissions and other impact categories were highlighted. The multi-purpose production of hemp products should have lower footprint compared with single-purpose production; the results were analysed with different allocation methods.

3.2 Materials and Methods

A life cycle assessment of hemp production in Canada was conducted according to ISO 14044 [17]. The study comprised four phases: Goal and scope definition; Life Cycle Inventory (LCI); Life Cycle Impact Assessment (LCIA); and interpretation. The LCA software OpenLCA 1.10.3 by GreenDelta was used in calculating environmental impacts.

3.2.1 Goal and Scope Definition

This study aimed to evaluate the environmental sustainability of industrial hemp grown in Canada through a cradle-to-farm-gate LCA. The project has implemented three approaches: Approach A comprises a “bottom-up” analysis which assesses the environmental impacts of hemp production at the farm-level using information collected from individual farmers during the 2021 and 2022 production seasons. Approach B was also structured as a “bottom-up” analysis but was implemented using long-term data from the National Hemp Variety Field Trial (NHVFT) 2022 [89-90]. For this analysis, the production of hemp varieties at each research site was modelled independently using the average yield from 2018 to 2022. Approach C was a “top-down” analysis using published hemp cultivation guides available from the governments of Alberta (AB), Saskatchewan (SK), Manitoba (MB), and Ontario (ON) [2, 73-75, 91-98]. This data set is highly aggregated without production years. The objective of looking at these three approaches was to compare the estimates of environmental impacts using various methods (i.e. farm level versus aggregated).

A number of production scenarios were investigated, and were categorized by geological region in Canada including the prairie provinces: Alberta (AB), Saskatchewan (SK) and Manitoba (MB) where a majority of hemp is produced, and other provinces including British Columbia (BC), Ontario (ON), Quebec(QC), New Brunswick (NB), Nova Scotia (NS), Prince Edward Island (PEI), Newfoundland and Labrador (NL) and Yukon (YT). All provinces and territories listed had licensed industrial hemp producers based on information from Health Canada [83]. The production scenarios were further categorized by moisture management (dryland or irrigated production), and production technique (conventional versus organic). Finally, results were also summarized by the number of primary output materials produced from operations including one (denoted “single purpose”), two (“dual purpose”) or three (“tri-purpose”) of the main components derived from hemp: hempseed, hemp straw, and/or hemp chaff/flower). Horticultural production of hemp (which is not common in Canada) was not included in this study.

Based on these analysis approaches and categorization schemes, the present study provides a variety of estimates for the environmental impact of Canadian produced hemp and their output products. These results are both compared between each other, and with studies conducted in the EU and other countries (focusing only on global warming potential impacts).

3.2.2 Functional Unit and System Boundary

The Canadian hemp industry utilizes all plant fractions, including hempseed, hemp straw, and hemp chaff (flowering buds and leaves). The functional unit was defined as 1 kg of products, namely 1 kg of hempseed (uncleaned, with 9% moisture); 1 kg of hemp straw (baled, with 15% moisture); and 1 kg of dried hemp chaff (with desirable moisture content by the producer).

The system boundary of this study was defined as “cradle to farm-gate” including all upstream material inputs (such as fertilizers, herbicides, and fuel), and emissions from field operations including soil preparation, seeding, crop management, harvesting and post-harvesting processing. The flowchart of hemp production is presented in Fig 3.1. The study also included the drying and pre-cleaning of hempseed and chaff which usually occurs before products leave the farm. However, seed cleaning operations were considered to be beyond the system boundary as these usually occur in external processing facilities (after leaving the farm). Therefore, the hempseed referred to above was uncleaned with a hull attached and may contain 10% to 20% cleanouts consisting of mostly bird-grade seed.

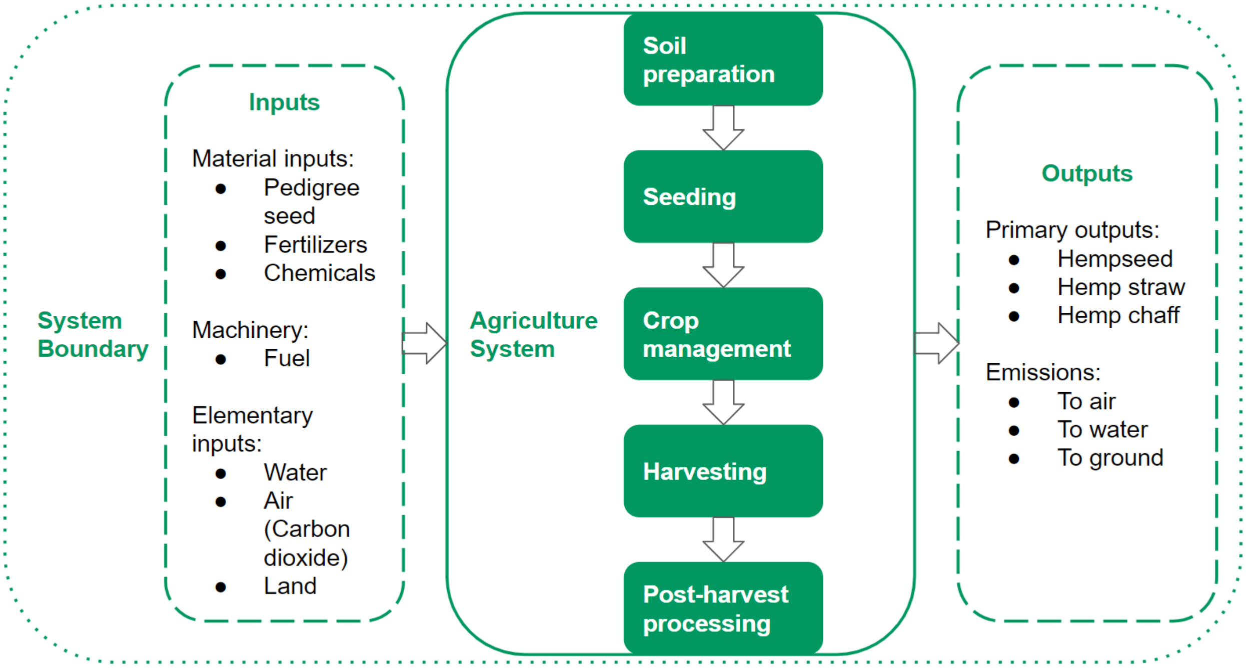

Figure 3.1 Hemp production processes and the system boundary

3.2.3 Life Cycle Inventory

3.2.3.1 Primary data collection

Primary data for Approach A was collected via interviews with 15 independent hemp farmers from 5 provinces in Canada (AB, SK, MB, ON, QC), two companies and one research institute who produce hemp via contracted farmers at various scales and purposes. Information collected includes all inputs and outputs directly related to hemp production in the 2021 and 2022 growing seasons. Farming inputs includes the location, acreage and soil conditions of hemp fields; industrial hemp cultivars, seeding rate and supplier; dosage, composition and suppliers of fertilizers and other chemicals; fieldwork activities, frequencies, and equipment specifications associated with operations; post-harvesting activities including drying and storage. Output information collected include the yield of hempseed, straw, and chaff, alongside its downstream utilization. The questionnaire used for data collection is presented in Appendix B. The Canadian Hemp Trade Alliance (CHTA) and Manitoba Harvest helped recruit hempseed farmers, providing terminologies and other hemp production information alongside other subject matter experts. Information regarding fibre-only production was collected from Canadian Rockies Hemp Corporation (CRHC) and Innotech Alberta at Vegreville, AB.

Approach B regarding the NHVFT 2022 implemented same types of foreground information, and it was obtained from contacts and project reports [89-90]. The field trial experiments include 18 locations with 62 seeded sites. The present study selected four industrial hemp cultivars at 12 locations for analysis based on their popularity and data availability. Grain-type varieties include X59, Katani, and CFX-2; each cultivar was produced with more than 1000 ha per year from 2018 to 2021 [5]. CRS-1 was used as a control and a dual-type cultivar; hempseed and straw were harvested. As the NHVFT 2022 reports [90] suggested, not all sites had trial experiments in all five years. The number of years at each location is presented in Table 3.1; each site entry included a minimum of 2 years of data. The average yield over five years was used for LCA modelling. The target nutrient level of 120 lb/ac of N and 40 lb/ac of P_2O_5 was implemented for all sites with mineral fertilizer. Potassium and other chemicals were applied according to the local production guide for wheat [90]. The specific seeding rate for each hemp cultivar was obtained from the CHTA e-guide [94]. Input variables are presented in Table 3.2. The median value was taken and used for calculation when input was reported as a range. All sites in the present study implemented no-till or minimum tillage practices and combined harvesting on dryland, except at the Lethbridge site, where irrigation and swathing are commonly performed [91].

Table 3.1 Selected industrial hemp cultivars, locations and number of years cultivated from the CHTA, NHVFT 2022

	Hemp Cultivars				
Locations	X59	Katani	CFX-2	CRS-1 (hempseed)	CRS-1 (dual)
Breton AB	3	3	3	4	4
Entwistle AB	3	3	3	3	4
Falher AB	3	3	3	5	4
Lethbridge AB	4	4	4	5	5
Vegreville AB	4	4	4	5	5
Indian Head SK	4	3	3	4	3
Arborg MB	3	2	2	4	4
Carberry MB	2	1	1	2	3
Melita MB	3	2	2	3	4
Roblin MB	4	4	4	5	5
St Hugues QUE	4	4	4	5	5
Cocagne NB	3	4	4	4	3

(Katani and CFX-2 cultivar produced in Carberry, MB, was excluded from the study)

Table 3.2 Production parameters at selected locations from the CHTA, NHVFT 2022 (n=12) [2, 73, 75, 89-98]

Province	Location	Region	Moisture management	N lb/ac	P (as P2O5) lb/ac	K (as K2O) lb/ac	Chemicals
AB	Breton	Prairie	Dryland	120	40		Glyphosate (Round Up), ethalfluralin (EDGE)
	Entwistle	Prairie	Dryland	120	40		Glyphosate (Round Up), ethalfluralin (EDGE)
	Falher	Prairie	Dryland	120	40		Glyphosate (Round Up), ethalfluralin (EDGE)
	Lethbridge	Prairie	Irrigated	120	40		Glyphosate (Round Up), ethalfluralin (EDGE)
	Vegreville	Prairie	Dryland	120	40		Glyphosate (Round Up), ethalfluralin (EDGE)
MB	Arborg	Prairie	Dryland	120	40	15-30	15 lb/ac S, Glyphosate (Round Up), ethalfluralin (EDGE)
	Carberry	Prairie	Dryland	120	40	15-30	15 lb/ac S, Glyphosate (Round Up), ethalfluralin (EDGE)
	Melita	Prairie	Dryland	120	40	15-30	15 lb/ac S, Glyphosate (Round Up), ethalfluralin (EDGE)
	Roblin	Prairie	Dryland	120	40	15-30	15 lb/ac S, Glyphosate (Round Up), ethalfluralin (EDGE)
SK	Indian Head	Prairie	Dryland	120	40		Glyphosate (Round Up), ethalfluralin (EDGE)
QC	St. Hugues	Other	Dryland	120	40	24	Glyphosate (Round Up), ethalfluralin (EDGE)
NB	Cocagne	Other	Dryland	120	40		Glyphosate (Round Up), ethalfluralin (EDGE)

In Approach C, hemp production guidelines were obtained online from provincial government sites for the provinces of AB, SK, MB and ON [2, 73-75, 91-92], and suggested input and prospective output were aggregated from these sources and used in the LCA. Information recommended for financial budgeting was used as the default value since it provides a precise yield number when calculating the net revenue. When budgeting wasn't available from the guideline, the maximum fertilizer input dosage and yield value were used for analysis. Specific information is presented in Table 3.3. The provincial hemp production guides don't specify specific cultivars, and as such, the present study used Finola in LCA modelling as it is the most common cultivar grown in Canada since 2018 [5].

The prospective hempseed yield suggested by production guides ranged from 220 kg/ha to 2200 kg/ha [2, 73-75, 91-92]. Some guides also provide a typical yield recommended for farmers to budget their production: Ontario guide [2] suggests 800 lb/ac (900 kg/ha); Manitoba guide [73, 75] recommends 673-898 kg/ha for experienced farmers; Saskatchewan guide [92] presents a typical yield from 740 to 1200 kg/ha; Alberta guides [74, 91] indicate a average yield of 760 lb/ac (850 kg/ha), while using 1073.9 lb/ac (1200 kg/ha) for the budgeting of dryland production, and 1678.74 lb/ac (1880 kg/ha) for irrigated production. When input or output materials were presented in a range, the upper end of the number was used in the estimation.

Prospective hemp straw yield presented by production guides ranging from 2.6 to 14 t/ha of dry retted stalks [2, 73-75, 91-92]. Ontario guide [2] suggests a 1.5 tonne/ac (3.7 t/ha) yield for co-harvested straw; Manitoba guides [73, 75] indicate similar yield of 0.75-1.5 tonne/ac (1.85-3.7 t/ha).

Table 3.3 Production parameters recommended by hemp cultivation guides [2, 73-75, 91-92]

Province	Location	Region	Moisture management	N	P (as P2O5)	K (as K2O)	Seeding rate	Chemicals	Prospective yield
AB	Vegreville	Prairie	Dryland	65 lb/ac	18 lb/ac	11 lb/ac	24-36 kg/ha	11 lb/ac S, Quizalofop P-Ethy and Ethalfluralin	1073.9 lb/ac
	Lethbridge	Prairie	Irrigated	84 lb/ac	17 lb/ac	9 lb/ac	24-36 kg/ha	8 lb/ac S, Quizalofop P-Ethy and Ethalfluralin	1678.74 lb/ac
MB	N/A	Prairie	Dryland	135 kg/ha	45 kg/ha	67 kg/ha	18-23 lb/ac	17 kg/ha S, glyphosate	898 kg/ha
SK	N/A	Prairie	Dryland	100 kg/ha	50 kg/ha	67 kg/ha	22-34 kg/ha	17 kg/ha S, glyphosate	1200 kg/ha
ON	N/A	Other	Dryland	99.7 kg/ha	36.4 kg/ha	50 kg/ha	20 lb/ac		800 lb/ac

3.2.3.2 Secondary data collection

Secondary data, such as the production of fertilizers, chemicals, farming equipment and fuel, were obtained from the Ecoinvent v3.7, Agribylase v3, and USDA LCA Commons database. All three approaches defined in chapter 3.2.1 follows the same practices while implementing this supportive information. Default Canadian-specific data was used in modelling for all scenarios, followed by North American data (RNA), Global dataset without EU (Row) and Global source (GLO).

Specific compounds regarding fertilizers and herbicides were applied if farmers provided more detailed information. Otherwise, a generic fertilizer source and recommended herbicide dosage were implemented. In this case, actual nutrient input was used in the LCA as reported by farmers in Approach A, and target nutrient input level was used for cases in Approaches B and C. As suggested by Ecoinvent, the compound of macronutrient fertilizer was obtained from IFASTAT [99], referring to the entire Canadian agricultural sector in 2020.

A unified fleet of farming equipment and corresponding field operations were obtained from the Ecoinvent database and implemented for approach B and C. Equipment with similar size and power category from the USDA LCA database was used when farmers provided additional information in Approach A.

3.2.3.3 Life cycle inventory assumptions and parameters

All hemp varieties approved by Health Canada [86] were potential targets of the study, and there were 87 industrial hemp cultivars available by May 2023. However, only 16 varieties were cultivated with more than 100 hectares in 2021 [5]. Therefore, only select hemp cultivars were evaluated in the present study. Varieties with marginal or no production record were excluded due to the lack of commercial-scale production from farmers. As mentioned in Table 3.1, four hemp cultivars were evaluated by Approach B: X59, Katani, CFX-2, and CRS-1. Finola was the most popular cultivar among Canadian producers [5] and was the only hemp cultivar modeled by Approach C. Number of hemp cultivars evaluated by Approach A is available in the result section 3.3.1.

Beside materials flowing in and out of the agricultural system, there are various parameters and corresponding assumptions to precisely describe the production practices. The following information applied to all three approaches mentioned in chapter 3.2.1.

Hemp products were harvested with variable moisture content depending on locations and specific situations. The current study assumes that excess moisture was removed from hempseed to achieve 9% moisture content for safe storage, unless specified by farmers. The assumption was based on the recommended conditions by the government of Manitoba [73], that hempseed should have less than 10 % moisture, and farmers usually store it with between 7 % to 9 % moisture content; The nitrogen content of hempseed was calculated from crude protein content suggested by Vonapartis et al., [101] and it was used for nutrient uptake calculation. Average N content was used for cultivars not included in the study; Farmers who reported cleaned weight will be applied with 20% cleanout to calculate uncleaned yield unless specified with actual dockage.

This study assumes hemp straw was baled with 15% moisture content. While other production guide may suggest lower level, such as the 14 % moisture recommended by Manitoba Agriculture [73]. The current research assumes that hemp straw contains 1 % N dry matter (DM). It is based on the measured N content of hemp straw from studies and databases, ranging from 0.4% to 1% [102]. Hemp straw has no value for farmers who only produces hempseed, and it was usually chopped and worked back into the soil or left on the field. Therefore, the overall amount of aboveground residue (straw) had to be estimated for each case according to hempseed yield and the character of cultivar. The Harvest Index (HI) [85] indicates the proportion of hempseed to the aboveground biomass, was implemented for this analysis and is detailed in Appendix B. The average value was applied to the hemp cultivar without its dedicated HI. The present study assumed that farmers who provided their straw yield had minimum aboveground residue left on the field. The weight of hemp straw was also estimated using HI for farmers who reportedly collected hemp straw but without known yield information. The belowground biomass was estimated based on a ratio between hemp straw and hemp root of 5.46:1 [103]. Belowground biomass is assumed to have the same 1% N content DM as hemp straw. The production of chaff was assumed to be marginal and highly specialized. Therefore, no assumptions were made regarding moisture content and nitrogen content.

Field emissions of greenhouse gases were calculated using modified equations from part 2 of the NIR 2022 report [65]. The method consists of a combination of tier 1 and tier 2 equations estimating direct and indirect N_2O emissions from agricultural soil, alongside CO_2 emissions from crop residue burning, liming and urea fertilization [66]. The proposed method was adjusted for farmers who applied less irrigation than the deficit between evapotranspiration and precipitation. Equations used to calculate field emissions in the present study were down-scaled from ecodistrict level to farm level, and are presented in Appendix B. Emission factors representing average conditions in AB, SK, MB, and ON derived from AAFC were utilized in calculating GHG emissions for the top-down Approach C. Non-GHG emissions to air regarding Non-methane volatile organic compound (NMVOC), Particulate Matter (PM), and field burning were calculated according to the EMEP/EEA air pollutant emission inventory guidebook 2019 [104].

The emission of ammonia to the air from the application of manure and mineral fertilizers, as well as missions of nitrogen and phosphorus to water, were calculated according to Nemecek and Schnetzer [105]. Herbicides and pesticides were 100% emitted in the soil compartment. Heavy metal emitted into water and soil was not considered in this study.

Environmental conditions used in calculations, such as precipitation, evapotranspiration, soil texture and clay content, were obtained from the national and provincial databases depending on farm locations. Detailed information and sources are provided in Appendix B. Average climate data from 1990 to 2020 was obtained from Holos v4 and originated from NASA [106-107].

3.2.4 Life Cycle Impact Assessment (LCIA)

This study used an attributional approach regarding environmental impacts. ReCiPe 2016 Midpoint (H) was selected as the LCIA method. It consists of 18 impact categories: Ozone formation, Human health (kg NO_x eq); Mineral resource scarcity (kg Cu eq); Human carcinogenic toxicity (kg 1,4-DCB); Terrestrial acidification (kg SO_2 eq); Terrestrial ecotoxicity (kg 1,4-DCB); Ozone formation, Terrestrial ecosystems (kg NO_x eq); Water consumption (m^3); Land use (m^2a crop eq); Marine ecotoxicity (kg 1,4-DCB); Marine eutrophication (kg N eq); Freshwater eutrophication (kg P eq); Stratospheric ozone depletion (kg CFC11 eq); Freshwater ecotoxicity (kg 1,4-DCB); Human non-carcinogenic toxicity (kg 1,4-DCB); Global warming (kg CO_2 eq); Ionizing radiation (kBq Co-60 eq); Fine particulate matter formation (kg PM2.5 eq); and Fossil resource scarcity (kg oil eq). Software OpenLCA v1.10.3 was used as a supportive tool for calculating LCIA results. Results from Approach A and B were analysed using the assessment method. Not all impact categories were calculated for Approach C due to the availability of aggregated emission factors and other environmental factors

Allocation was required since industrial hemp produces more than one product (hempseed, fiber and/or chaff/flowers) from some production systems [16]. Therefore, mass allocation and economic allocation were implemented for scenarios that generate more than one product. Market prices of major hemp products were obtained from hemp farmers and processors. The pedigree seed was produced with the same practice as commercial hempseed for food purposes, and the remaining pedigree seed will be sold as a food ingredient. Therefore, economic allocation didn't differentiate conventional hempseed from certified pedigree hempseed. However, organically produced hempseed has a higher market value, and the price of hemp products can be found in Appendix B. No allocation was implemented if the product system only had one output.

The weighted average carbon footprint from Approach A was calculated and presented separately considering uneven distribution of production volume. Average global warming potential from Approach B and C were presented with its major contributors.

3.2.5 Sensitivity Analysis

Sensitivity analysis was conducted to investigate the impact of data variance and study assumptions [108]. Changes in the following parameters were included: Yield variation in Approach C using information from hemp cultivation guides, where the highest value of the typical yield or the budget yield was used as baseline scenarios. The lower end of the typical yield bracket was modelled as a poor production scenario, and the percentage reduction from low yield situation was inverted and added to the default value and simulating a better yield scenario. The proportion of hemp straw harvested in Approach B was manipulated to simulate common harvesting practice with 50% aboveground residue, including straw wasted during hempseed harvesting and stubbles above the soil surface. The sensitivity analysis wasn't conducted on Approach A since each individual farmer implemented different practices, which introduced multiple variables. Therefore, changes in the overall production footprint cannot be attributed to a single independent variable, and the aggregated result will blur the influence of the variable.

3.2.6 Study Limitations

The life cycle modelling of a multi-purpose crop such as industrial hemp is challenging. The following limitations may influence the accuracy of this assessment:

1) Western Canada experienced excessive heat waves and drought in the 2021 growing season, and the yield of industrial hemp was negatively impacted. The following growing year (2022) was considered average and representative by many farmers. Therefore, the lack of long-term information and productive years might compromise the yield and overestimate the production footprints.

2) The GHG emissions were calculated according to the NIR 2022 [65] which was based on 30-years average climate data from 1990 to 2020. This method is more accurate at estimating long-term average conditions, however, it might not accurately estimate the emission for 2021 or future years experiencing higher than normal temperatures since global warming can significantly impact higher latitudes and extreme weather events may occur more often [109].

3) The fertilizer inputs modelled in the present study might not accurately represent the actual nutrient requirement and uptake of hemp. Most participants have grown industrial hemp

over the years and incorporated hemp in various crop rotation sequences. The nutrient level available for hemp before applying fertilizers were highly variable. Farmers who conducted soil nutrient tests after harvesting in the fall season or before seeding in the spring can adjust actual nutrient input accordingly. Therefore, the remaining nutrients in the soil from the previous crops determined the actual nutrient inputs for hemp produced in the following year. Other farmers who didn't conduct soil nutrient testing rely on their experience and estimated based on yield projections. The long-term observation could provide a better idea regarding nutrient input for hemp production in rotation with other crops.

4) As suggested in the life cycle inventory, the target nutrient level was used in calculating fertilizer usage in Approaches B and C, where the standardized production practices were implemented. Due to the lack of soil fertility results, it overestimated the nutrient requirement and the overall environmental footprints.

5) A generic fleet of equipment and field activities were applied to all LCA models in the present study without considering the impact of soil texture and topography. As suggested by Lovarelli et al. [110] and Tassielli et al. [68], local conditions and equipment parameters significantly impact the overall environmental footprint of the same field operation. Both research found that the environmental impacts of soil tillage was about 50% lower on sandy soil than the medium texture reference, while operation footprints on clay soils was significantly higher than the reference, from 40% to 156% [68, 110]. However, as stated from the LCA database, emissions associated with fieldworks are usually measured under medium conditions. Therefore, it was impossible to evaluate all farming operation accurately in the present study due to lack of available dataset. As such, it emphasizes variations in fertilization, regional climate and soil conditions, and the corresponding field emissions.

3.3 Results

3.3.1 Impact results from farm level dataset (Approach A)

3.3.1.1 Hemp production report based on farmer interviews

Most farmers interviewed were based in the prairie provinces (AB. SK, MB), with only two participants located in Eastern Canada (one farmer from Quebec and a pedigree seed producer from Ontario). Therefore, the present approach only analysed hemp produced in the prairie provinces using the LCA approach due to poor data availability from the other provinces. A total of 27 cases prioritizing hempseed production were established. Besides hempseed production, 65 cases were modelled at the farm level for the fibre-only production scenario. The present study covered more than 5,500 acres (2,230 ha) of hempseed production and about 4,500 acres (1,820 ha) of fibre-only production in 2021. In addition, it also covered more than 4,500 acres (1,820 ha) of hempseed production and 5,800 acres (2,350 ha) of fibre-only production in 2022. Overall, data collected via farmer interviews have covered more than 20,000 acres (8,200 ha) of hemp production in 2021 and 2022.

The number of cases from farmer interviews corresponding to hemp production scenarios is presented in Table 3.4. Farmers in the present study produced 16 hemp varieties in 2021 and 2022. The proportion of interviewed farmers who produced hempseed organically accounted for 9 out of the 27 cases, representing more than 4,600 acres (1,860 ha). Among hempseed production, 10 cases implemented irrigation to provide additional moisture for hemp accounting for 1,900 acres (770 ha). All fibre-only production cases applied mineral fertilizer without irrigation.

Table 3.4 Hemp production cases modelled in the prairie provinces (AB, SK, MB) (n=90)

Production scenarios	Conventional, dryland	Conventional, irrigated	Organic, dryland	Organic, irrigated
Hempseed	5	1	4	2
Hemp straw	63			
Dual-purpose (hempseed + straw)	6	4		3
Dual-purpose (hempseed + chaff)	1			
All three (hempseed, straw, chaff)	1			

The hempseed yield variation from 2021 and 2022 is presented in Fig 3.1. Uncleaned Hempseed yields from the prairie provinces range from 2200 lbs/ac (2470 kg/ha) for conventional irrigated production in prairies to 270 lbs/ac (300 kg/ha) for conventional dryland production. The overall weighted average yield of hempseed was 870 lbs/ac (980 kg/ha) in 2021 and 990 lb/ac (1100 kg/ha) in 2022. Finola was the most popular grain-hemp cultivar among interviewed farmers, and its popularity was also shown by the number of licensed acreages according to Health Canada [83]. Irrigated fields produced more hempseed per acre than dryland; it had a weighted average yield of 1,550 lb/ac (1740 kg/ha) and 1,800 lb/ac (2020 kg/ha) during the investigated period of 2021 and 2022. Organic production of hempseed had a slightly higher yields than conventional production with a weighted average of 940 lb/ac (1050 kg/ha) and 1030 lb/ac (1150 kg/ha) in 2021 and 2022.

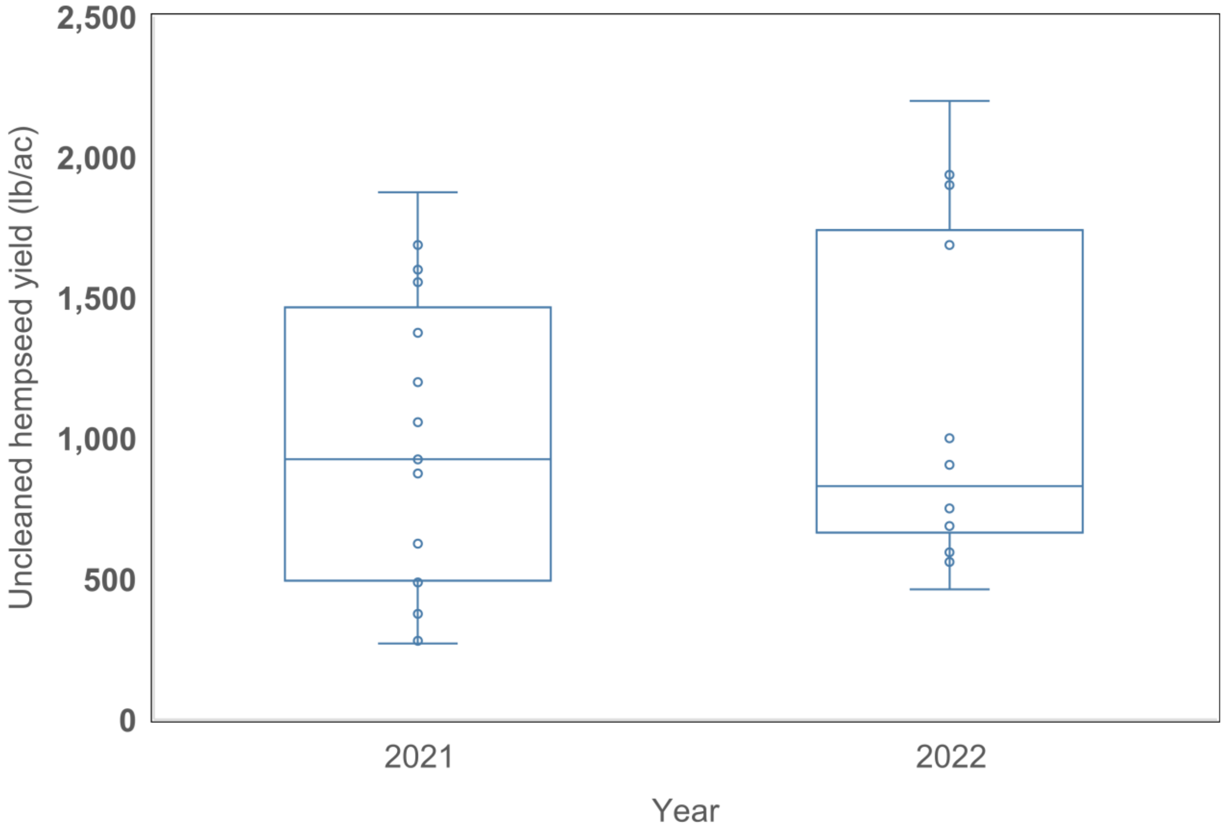

Figure 3.2 Box and Whisker plot of uncleaned hempseed yield in 2021 and 2022 from 27 production cases

[Open circles represent yield value reported by individual farmers, top and bottom end of whisker represent minimum and maximum value reported, box covers interquartile with 50% of data points and the median line]

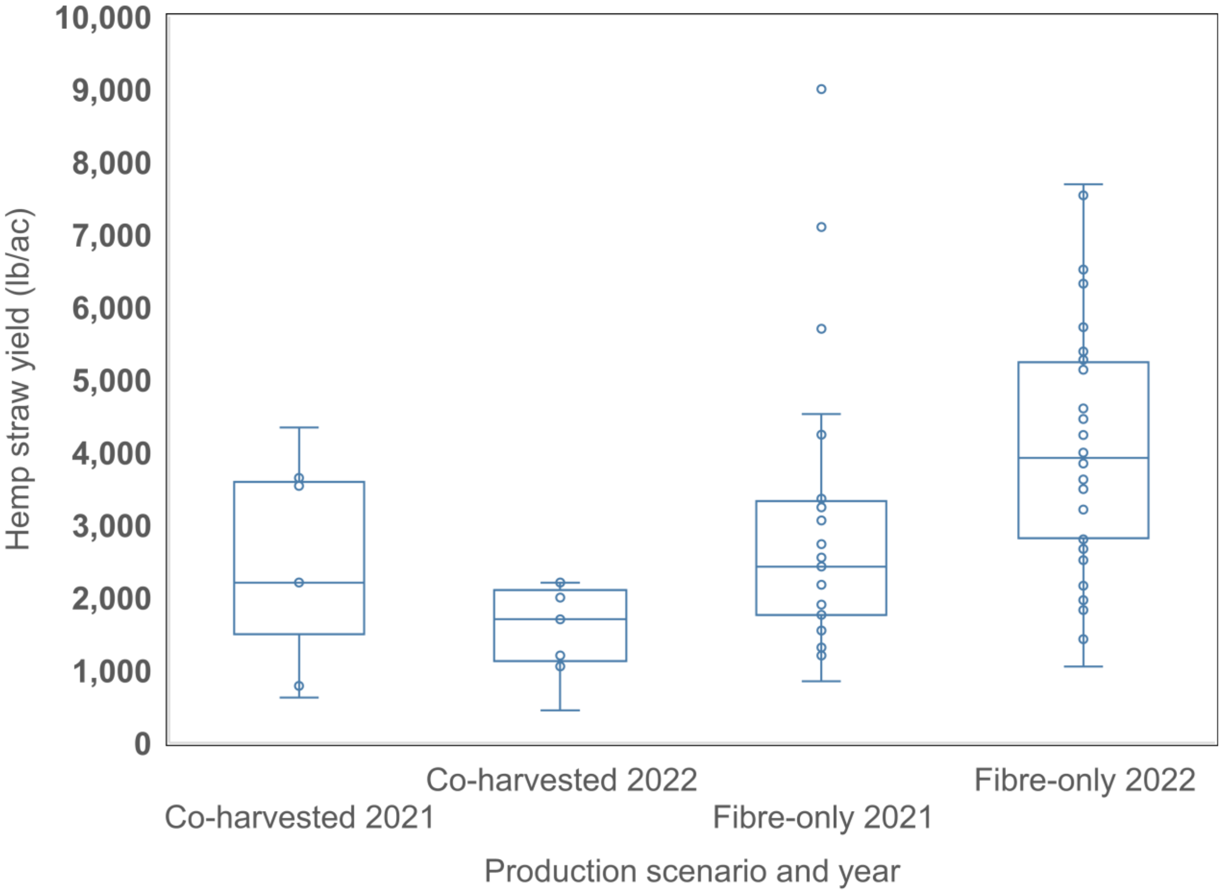

Figure 3.3 Box and Whisker plot of hemp straw yield in 2021 and 2022 from 14 co-harvested production cases and 63 fibre-only production cases

[Open circles represent yield value reported by individual farmers, top and bottom end of whisker represent minimum and maximum value reported, box covers interquartile with 50% of data points and the median line]

The yield variation of hemp straw is presented in Fig 3.2. Hemp straw harvested as a by-product from hempseed production was 2,500 lb/ac (2800 kg/ha) in 2021 and 1500 lb/ac (1680 kg/ha) in 2022. However, some farmers suggested that a significant amount of residue was left unharvested either in high stubble for soil protection, disposed of as waste during combined harvesting and worked into the soil later, or used for grazing cows. The weighted average yield of hemp straw from the fibre-only scenario was 1.27 tonne/ac (3.14 t/ha) in 2021 and 2.10 tonne/ac (5.19 t/ha) in 2022, as shown in Fig 3.3.

3.3.1.2 Environmental impacts of hemp production based on farms level dataset

Life cycle impact assessments were conducted with the ReCiPe 2016 Midpoint method. The average production footprint of hempseed and straw in 2021 and 2022 calculated using the LCI collected from farmer interviews are reported in Table 3.5 and Table 3.6. Generally, hempseed and straw produced in 2021 had higher footprints than in 2022 in most scenarios and impact categories. For hempseed, dual-purpose production of hempseed allocated by mass had the lowest footprints compared with grain-only production (no allocation) and dual-purpose production results allocated by economic value. For hemp straw, the production of dual-purpose hemp straw allocated by economic value had the lowest footprints, followed by fibre-only production and dual-purpose hemp straw allocated by mass.

Table 3.5 Average life cycle impact assessment results of hempseed produced in the prairie provinces

Year	2021			2022		
Production scenario	Grain-only without allocation	Dual-purpose with mass allocation	Dual-purpose with economic allocation	Grain-only without allocation	Dual-purpose with mass allocation	Dual-purpose with economic allocation
Ozone formation, Human health (kg NO_x eq)	5.39E-03	1.51E-03	4.25E-03	3.20E-03	1.49E-03	3.24E-03
Mineral resource scarcity (kg Cu eq)	1.59E-02	5.17E-03	1.36E-02	3.92E-03	4.57E-03	9.10E-03
Human carcinogenic toxicity (kg 1,4-DCB)	1.11E-01	3.25E-02	8.98E-02	2.86E-02	3.51E-02	7.55E-02
Terrestrial acidification (kg SO_2 eq)	4.95E-02	1.39E-02	3.33E-02	1.52E-02	1.41E-02	2.89E-02
Terrestrial ecotoxicity (kg 1,4-DCB)	9.30E+00	2.25E+00	6.21E+00	1.41E+00	2.38E+00	4.82E+00
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	5.64E-03	1.58E-03	4.46E-03	3.35E-03	1.55E-03	3.38E-03
Water consumption (m^3)	6.88E-01	2.15E-01	6.95E-01	6.50E-03	4.87E-01	1.21E+00
Land use (m^2a crop eq)	1.64E+01	4.64E+00	1.31E+01	1.18E+01	4.03E+00	8.76E+00
Marine ecotoxicity (kg 1,4-DCB)	1.75E-01	4.72E-02	1.32E-01	2.63E-02	5.55E-02	1.20E-01
Marine eutrophication (kg N eq)	3.65E-03	9.82E-04	2.74E-03	2.23E-03	9.50E-04	2.11E-03
Freshwater eutrophication (kg P eq)	2.08E-03	4.80E-04	1.66E-03	2.34E-03	3.60E-04	8.59E-04
Stratospheric ozone depletion (kg CFC11 eq)	2.37E-05	7.00E-06	2.03E-05	7.29E-06	1.09E-05	2.43E-05
Freshwater ecotoxicity (kg 1,4-DCB)	1.34E-01	3.72E-02	1.04E-01	2.33E-02	4.35E-02	9.40E-02
Human non-carcinogenic toxicity (kg 1,4-DCB)	2.91E+00	6.27E-01	1.73E+00	5.94E-01	7.22E-01	1.47E+00
Global warming (kg CO_2 eq)	1.79E+00	5.60E-01	1.52E+00	7.01E-01	6.38E-01	1.36E+00
Ionizing radiation (kBq Co-60 eq)	3.85E-02	1.25E-02	3.15E-02	1.81E-02	1.15E-02	2.33E-02
Fine particulate matter formation (kg PM2.5 eq)	7.49E-03	2.15E-03	5.26E-03	2.51E-03	2.14E-03	4.39E-03
Fossil resource scarcity (kg oil eq)	2.91E-01	1.11E-01	2.93E-01	1.00E-01	9.26E-02	1.84E-01

Table 3.6 Average life cycle impact assessment results of hemp straw produced in the prairie provinces

Year	2021			2022		
Production scenario	Straw-only without allocation	Dual-purpose with mass allocation	Dual-purpose with economic allocation	Straw-only without allocation	Dual-purpose with mass allocation	Dual-purpose with economic allocation
Ozone formation, Human health (kg NO_x eq)	1.10E-03	1.51E-03	2.14E-04	6.18E-04	1.49E-03	1.24E-04
Mineral resource scarcity (kg Cu eq)	2.82E-03	5.17E-03	6.84E-04	1.38E-03	4.57E-03	4.30E-04
Human carcinogenic toxicity (kg 1,4-DCB)	2.19E-02	3.25E-02	4.53E-03	1.18E-02	3.51E-02	3.18E-03
Terrestrial acidification (kg SO_2 eq)	1.12E-02	1.39E-02	1.68E-03	7.21E-03	1.41E-02	1.12E-03
Terrestrial ecotoxicity (kg 1,4-DCB)	1.01E+00	2.25E+00	3.13E-01	4.57E-01	2.38E+00	2.22E-01
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	1.16E-03	1.58E-03	2.25E-04	1.38E+00	1.55E-03	1.30E-04
Water consumption (m^3)	5.71E-03	2.15E-01	3.50E-02	3.50E-03	4.87E-01	3.89E-02
Land use (m^2a crop eq)	4.31E+00	4.64E+00	6.59E-01	2.73E+00	4.03E+00	3.63E-01
Marine ecotoxicity (kg 1,4-DCB)	2.53E-02	4.72E-02	6.66E-03	8.85E-03	5.55E-02	5.10E-03
Marine eutrophication (kg N eq)	8.24E-04	9.82E-04	1.38E-04	6.23E-04	9.50E-04	8.48E-05
Freshwater eutrophication (kg P eq)	1.13E-04	4.80E-04	8.37E-05	1.90E-03	3.60E-04	3.23E-05
Stratospheric ozone depletion (kg CFC11 eq)	3.45E-06	7.00E-06	1.02E-06	3.15E-03	1.09E-05	8.32E-07
Freshwater ecotoxicity (kg 1,4-DCB)	1.62E-02	3.72E-02	5.23E-03	1.15E-02	4.35E-02	3.97E-03
Human non-carcinogenic toxicity (kg 1,4-DCB)	3.12E-01	6.27E-01	8.71E-02	1.29E-01	7.22E-01	6.59E-02
Global warming (kg CO_2 eq)	3.06E-01	5.60E-01	7.66E-02	1.99E-01	6.38E-01	5.09E-02
Ionizing radiation (kBq Co-60 eq)	7.34E-03	1.25E-02	1.59E-03	4.02E-03	1.15E-02	1.02E-03
Fine particulate matter formation (kg PM2.5 eq)	1.68E-03	2.15E-03	2.65E-04	1.05E-03	2.14E-03	1.73E-04
Fossil resource scarcity (kg oil eq)	7.80E-02	1.11E-01	1.48E-02	4.72E-02	9.26E-02	8.04E-03

3.3.2 Impact results from field trial dataset (Approach B)

3.3.2.1 Hemp production based on field trial

The hempseed yield of the investigated cultivars from the NHVFT 2022, is presented in Fig 3.3. The maximum output was 1934.67 kg/ha of CFX-2 cultivar, recorded from Indian Head, SK. And the minimum yield was 518 kg/ha of Katani cultivar from Breton, AB. Hemp straw harvested from CRS-1 cultivar ranged from 1566 kg/ha to 6286.3 kg/ha.

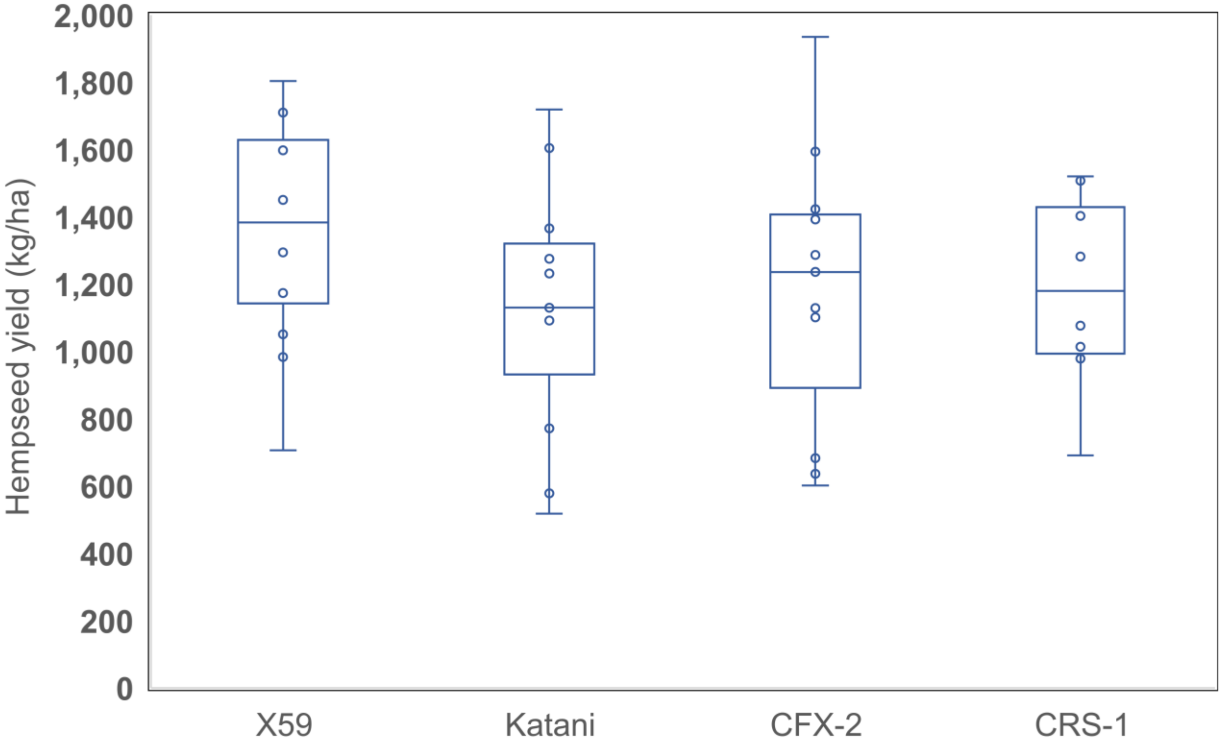

Figure 3.4 Box and Whisker plot of average hempseed yield from selected cultivars in the CHTA, NHVFT 2022 at 12 locations

[Note: Open circles represent yield value reported by individual farmers, top and bottom end of whisker represent minimum and maximum value reported, box covers interquartile with 50% of data points and the median line]

3.3.2.2 Life cycle impact assessment of hemp production from field trial

The average production footprints of hempseed and straw using the NHVFT 2022 data set are reported in Table 3.7. Grain-only production scenario had the highest environmental impacts in all categories, compared with dual-purpose production. Co-harvested hemp straw had the lowest footprints when allocated with economic value, followed by dual-purpose production of hempseed and straw with mass allocation.

Table 3.7 Average life cycle impact assessment results of hempseed and straw produced in 12 research sites in NHVFT 2022 in Canada

Production scenario	Grain-only without allocation (all 4 cultivars)	Grain-only without allocation (CRS-1)	Dual-purpose hempseed with mass allocation	Dual-purpose hempseed with economic allocation	Dual-purpose hemp straw with mass allocation	Dual-purpose hemp straw with economic allocation
Ozone formation, Human health (kg NO_x eq)	3.24E-03	2.76E-03	6.25E-04	2.10E-03	6.25E-04	2.33E-04
Mineral resource scarcity (kg Cu eq)	1.74E-02	1.70E-02	3.49E-03	1.17E-02	3.49E-03	1.30E-03
Human carcinogenic toxicity (kg 1,4-DCB)	9.75E-02	8.15E-02	1.75E-02	5.87E-02	1.75E-02	6.52E-03
Terrestrial acidification (kg SO_2 eq)	1.56E-02	1.54E-02	3.17E-03	1.06E-02	3.17E-03	1.18E-03
Terrestrial ecotoxicity (kg 1,4-DCB)	4.24E+00	4.32E+00	8.91E-01	2.99E+00	8.91E-01	3.33E-01
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	2.99E-03	2.91E-03	6.56E-04	2.20E-03	6.56E-04	2.44E-04
Water consumption (m^3)	2.12E-01	2.11E-01	4.14E-02	1.45E-01	4.14E-02	1.61E-02
Land use (m^2a crop eq)	9.42E+00	9.15E+00	1.86E+00	6.23E+00	1.86E+00	6.92E-01
Marine ecotoxicity (kg 1,4-DCB)	1.06E-01	1.03E-01	2.14E-02	7.18E-02	2.14E-02	7.98E-03
Marine eutrophication (kg N eq)	2.24E-03	2.06E-03	4.16E-04	1.38E-03	4.16E-04	1.54E-04
Freshwater eutrophication (kg P eq)	6.02E-04	6.38E-04	1.21E-04	4.28E-04	1.21E-04	4.76E-05
Stratospheric ozone depletion (kg CFC11 eq)	3.53E-05	3.64E-05	7.46E-06	2.24E-05	7.46E-06	2.49E-06
Freshwater ecotoxicity (kg 1,4-DCB)	8.10E-02	7.92E-02	1.64E-02	5.51E-02	1.64E-02	6.12E-03
Human non-carcinogenic toxicity (kg 1,4-DCB)	1.42E+00	1.38E+00	2.91E-01	9.77E-01	2.91E-01	1.09E-01
Global warming (kg CO_2 eq)	1.75E+00	1.76E+00	3.65E-01	1.16E+00	3.65E-01	1.28E-01
Ionizing radiation (kBq Co-60 eq)	3.37E-02	3.30E-02	7.03E-03	2.36E-02	7.03E-03	2.62E-03
Fine particulate matter formation (kg PM2.5 eq)	3.42E-03	2.85E-03	6.00E-04	2.01E-03	6.00E-04	2.23E-04
Fossil resource scarcity (kg oil eq)	2.76E-01	2.68E-01	5.83E-02	1.96E-01	5.83E-02	2.17E-02

3.3.3 Hemp production results from cultivation guides (Approach C)

The typical yield of hempseed implemented for LCA modelling were similar, as shown in Table 3.3. Alberta (dryland) and Saskatchewan farmers expect an output around 1200 kg/ha. Meanwhile, results from Ontario and Manitoba were lower, close to 900 kg/ha.

The global warming potential of hempseed calculated from provincial production guides ranges from 0.88 to 3.26 kg CO_2 eq/kg cleaned seed. Dryland production from AB has the lowest GWP, followed by SK production with 1.02 kg CO_2 eq and MB with 1.86 kg CO_2 eq/kg cleaned seed. Production footprint in ON was significantly higher than other locations, with greater emissions from soil and field operations.

3.3.4 Global warming potential (GWP)

Greenhouse gas emissions are the primary driver of global warming and climate change. Therefore, a detailed analysis regarding the major contributor of GWP was performed. As shown in Fig 3.5 and Fig 3.6, carbon footprints of hempseed produced by individual farmers (Approach A) were quite variable especially in 2021. In general, GHG emissions of hempseed production had the same trend as discussed in Chapter 3.3.1, that dual-purpose production of hempseed had the lowest GWP while allocation by mass. Hempseed from Approaches B and C are shown in Fig 3.7 and had somewhat higher carbon footprints at around 1.75 kg CO_2 eq/kg grain, which is higher than the results generated from farmer input (Approach A). By covering 12 locations across Canada, GHG emissions from each site in the NHVFT 2022 were distributed in a wide spectrum.

Moisture and nutrient management practices, such as irrigated and organic production, had mixed results on the GHG emissions of hempseed compared with dryland and conventional production. Due to the limited and mixed sample size, the weighted average results were presented without allocation. Hempseed produced organically in 2021 had a carbon footprint of 1.04 kg CO_2 eq/kg grain, lower than the conventional system's 1.16 kg CO2 eq/kg grain. Irrigated hempseed had slightly higher GHG emissions at 1.15 kg CO_2 eq/kg grain than the 1.08 kg CO_2 eq/kg hempseed produced on dryland. There were overlaps between the two categories. Hempseed produced in 2022 had the same pattern, while irrigation significantly increased the carbon footprint to 1.38 kg CO_2 eq/kg grain, while dryland produced a lower footprint at 0.78 kg CO_2 eq/kg hempseed. The GHG emissions of organic and conventional hempseed were close, with 0.91 and 0.99 kg CO_2 eq/kg grain.

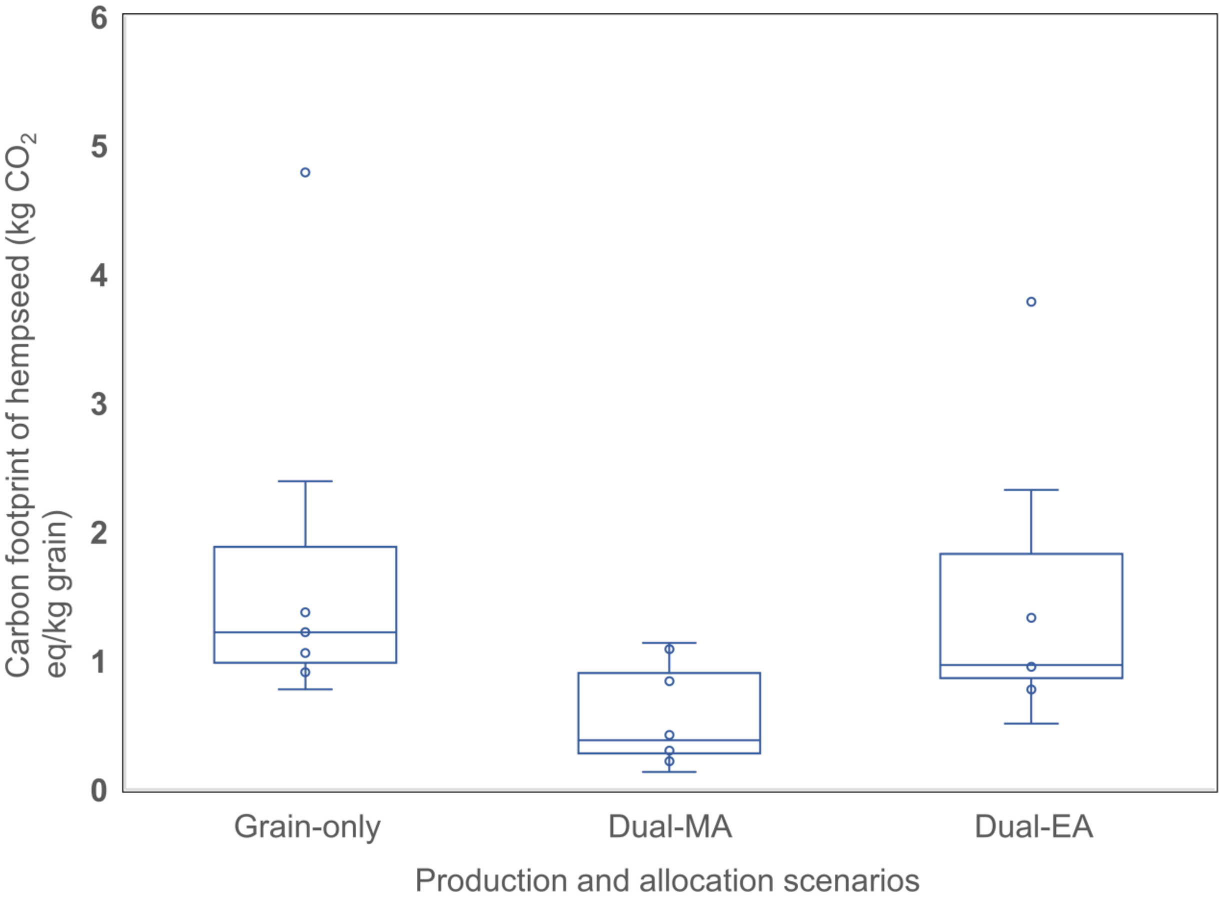

Figure 3.5 Box and Whisker plot of hempseed carbon footprint from farm level dataset in 2021. Approach A

[Open circles represent carbon footprints from individual farmers, top and bottom end of whisker represent minimum and maximum value reported, box covers interquartile with 50% of data points and the median line]

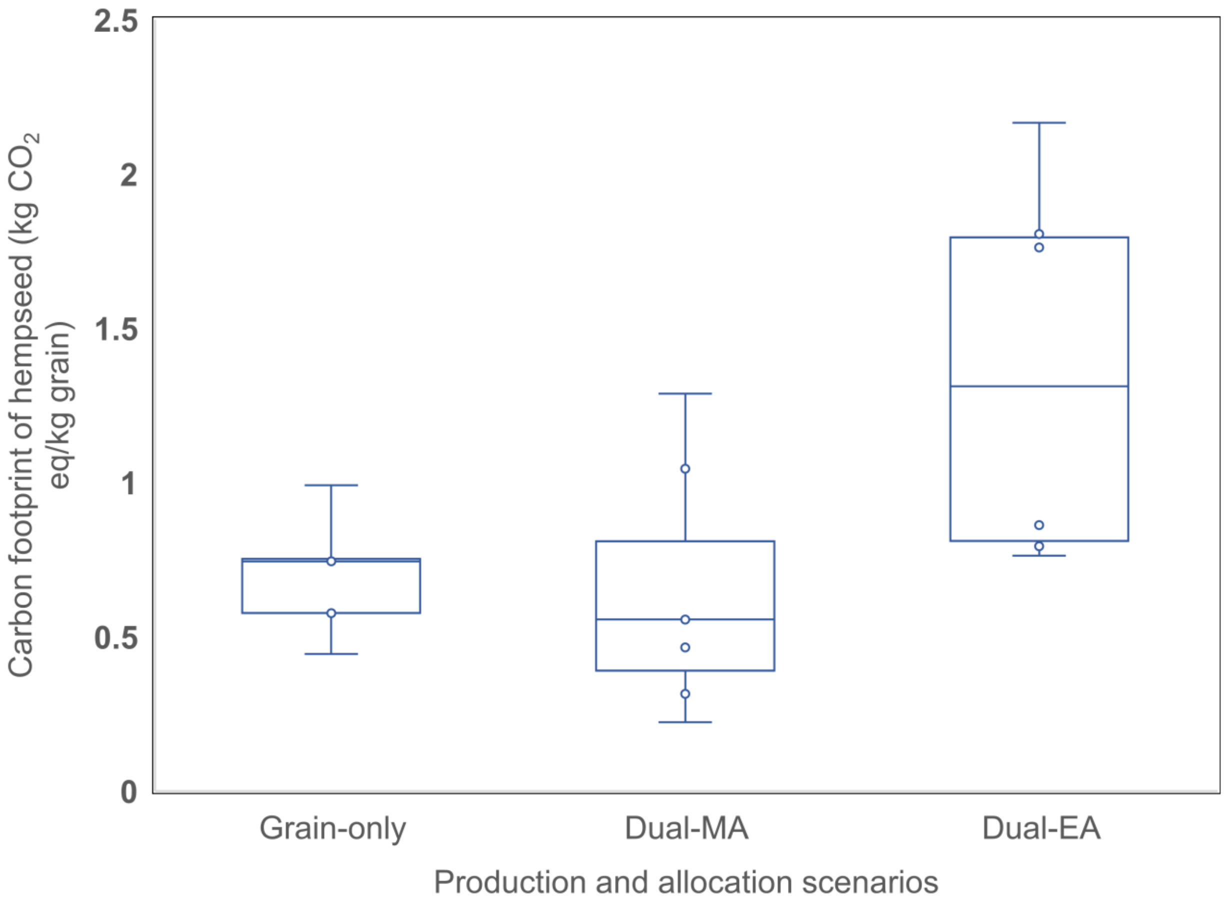

Figure 3.6 Box and Whisker plot of hempseed carbon footprint from farm level dataset in 2022. Approach A

[Open circles represent carbon footprints from individual farmers, top and bottom end of whisker represent minimum and maximum value reported, box covers interquartile with 50% of data points and the median line]

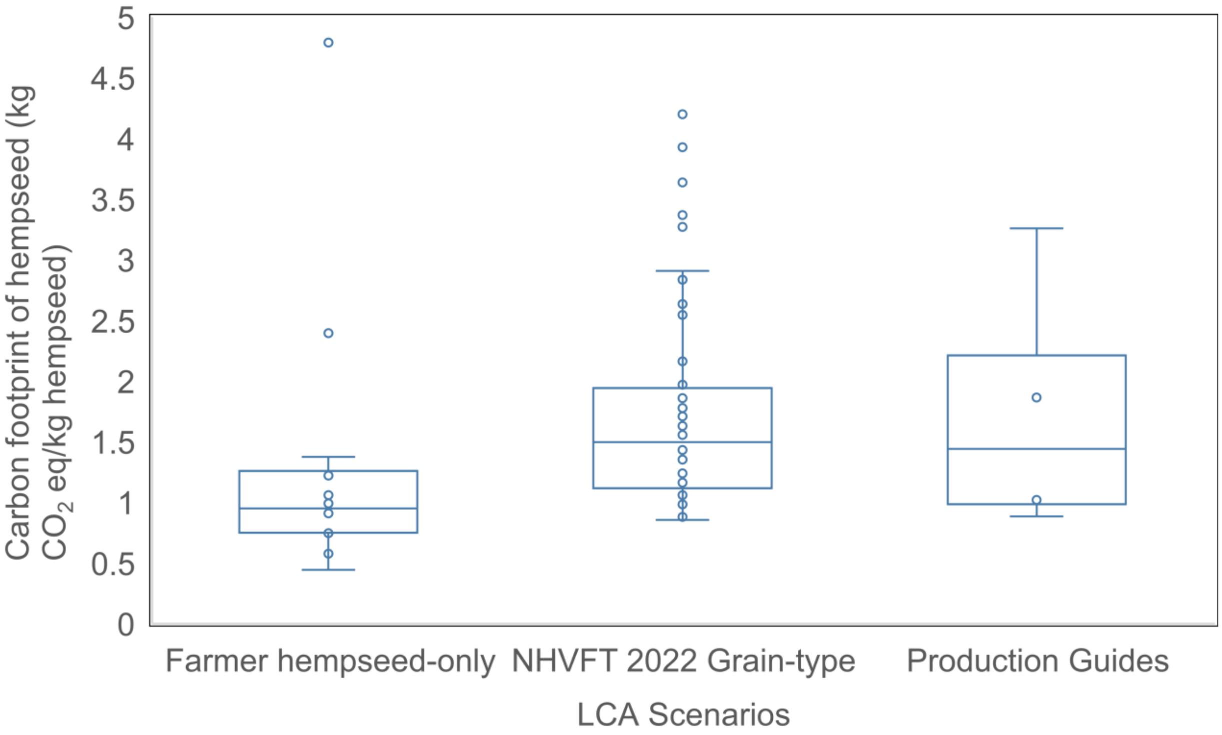

Figure 3.7 Box and Whisker plot of hempseed carbon footprint from farmer interview, NHVFT 2022 and provincial production guides. Approach A (hempseed-only), B (grain-type production) and C

[Open circles represent carbon footprints from individual cases, top and bottom end of whisker represent minimum and maximum value reported, box covers interquartile with 50% of data points and the median line]

Since the NHVFT 2022 produced hemp at various locations across Canada with similar practice, the difference in LCIA results were mostly driven by environmental conditions such as precipitation and soil texture. The GHG emissions of grain-only hempseed were categorized by ecozones in Canada and presented in Fig 3.8. Hempseed produced in the prairies generally had the lowest GHG emissions and had closer distribution. Hempseed produced in mixwood plains (QC) had the highest carbon footprints. The relationship between hempseed yield and its GHG emissions was presented in Fig 3.9, and an inversely proportional trend was observed. Higher hempseed yield was associated with lower carbon footprints, except for a few outliers representing mainly production in QC.

Main contributors of GHG emissions have been distributed into four categories: field emission (most N2O with other GHG emissions associated with burning of residue, urea fertilization, and liming); fertilizer production (emissions associated with the extraction and production of mineral and organic fertilizers); field operations (fieldwork and post-harvesting handling of the products); other (mostly herbicide and other chemicals, as well as process that contribute less than 1% to overall GWP). The proportion of carbon footprint associated with each category is presented in Table 3.8 and Table 3.9. Field emissions and fertilizer production contribute about 90% of GHG emissions in NHVFT 2022. In contrast, production guides and farmer interviews suggested that field operations contributed significantly more GHG and became one of the major contributors. Field emissions associated with irrigation were higher than that in dryland conditions. GHG emissions from organic fertilizer production were much lower than mineral fertilizers used in conventional production. Organic production also required more field operations to transport and broadcast livestock or turn green manure into the soil.

Therefore, carbon footprints associated with fieldwork were higher in organically produced hemp than in conventional production.

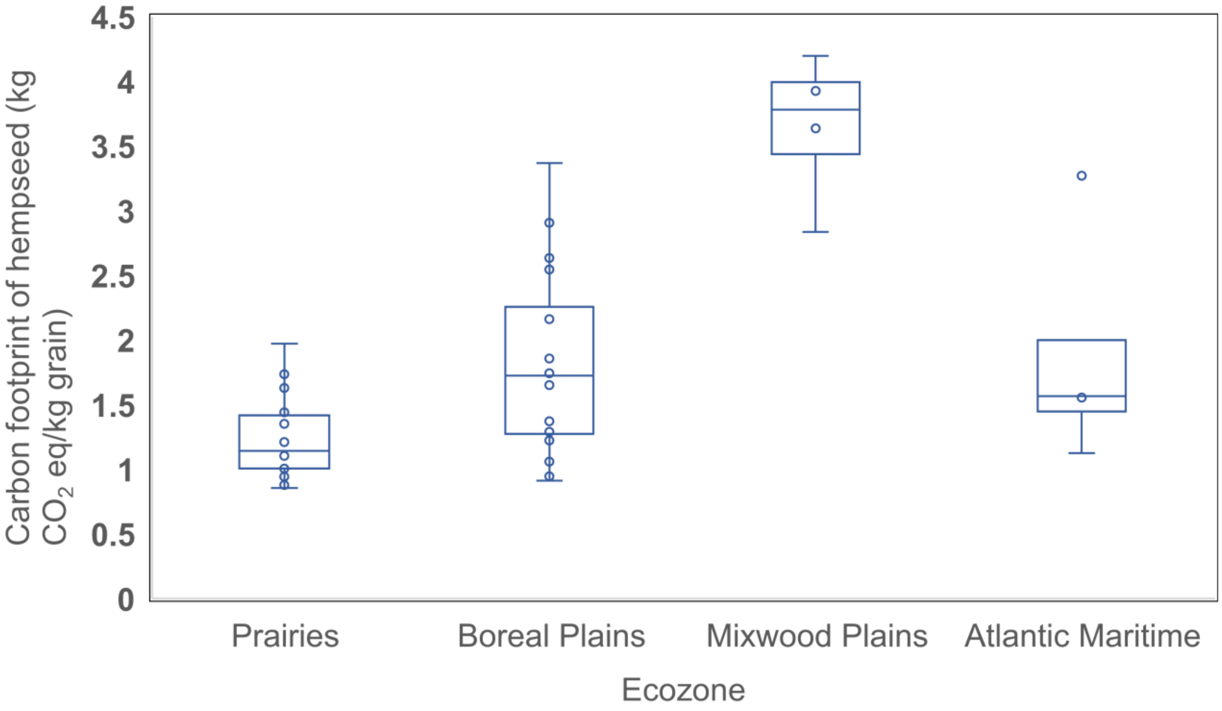

Figure 3.8 Box and Whisker plot of hempseed carbon footprint from NHVFT 2022 in different ecozones in Canada. Approach B

[Open circles represent carbon footprints from individual research sites, top and bottom end of whisker represent minimum and maximum value reported, box covers interquartile with 50% of data points and the median line]

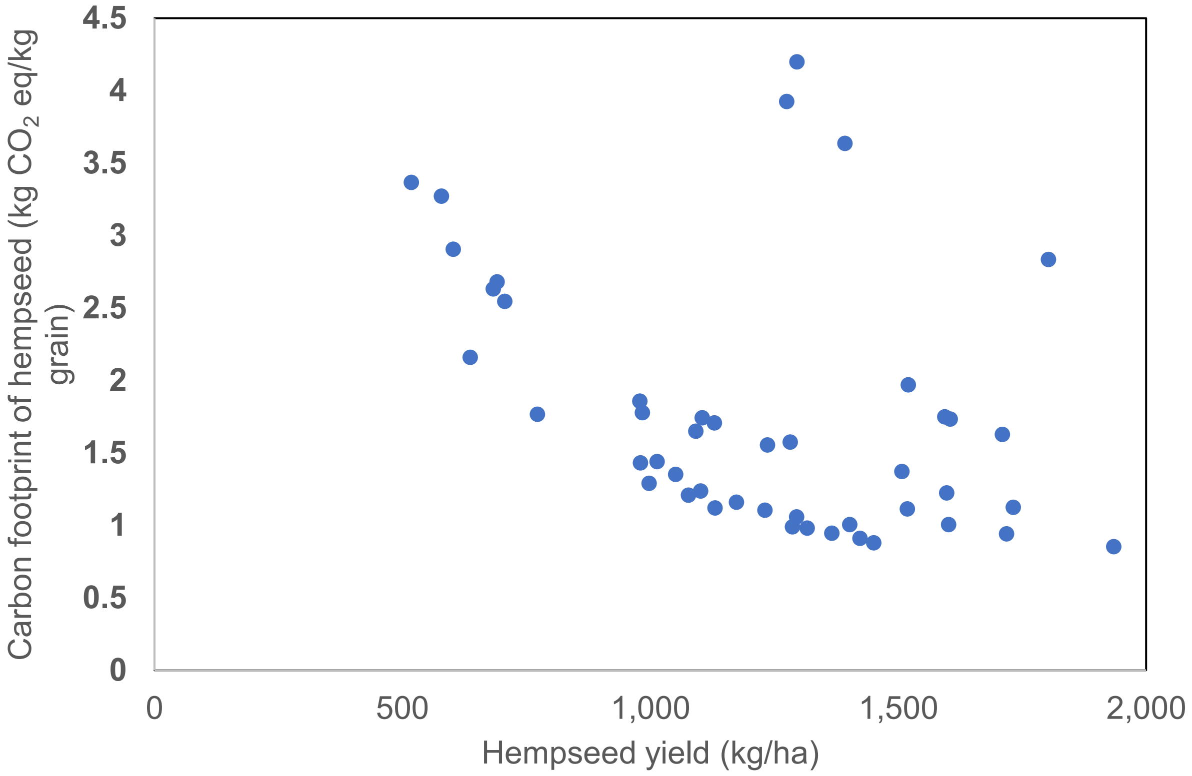

Figure 3.9 Carbon footprint of hempseed produced in the NHVFT 2022 related to yield (n=46)

Table 3.8 Average GHG emissions contributed by each category during the production of hemp

Contributors/production scenarios	Field emissions (%)	Fertilizers production (%)	Field operations (%)	Others (%)
2021 hempseed	38.8	34.2	24.9	2.1
2022 hempseed	35	30.2	32.2	2.6
NHVFT 2022 grain-only	46.7	43	7.9	2.4
NHVFT 2022 dual-purpose	42.6	43.8	11	2.7
Production guide grain-only	44.7	33.6	20.1	1.6

Table 3.9 Proportion of GHG emissions contributed by each category in different production scenarios, based on farm level dataset (Approach A)

Contributors/production scenarios	Field emissions (%)	Fertilizers production (%)	Field operations (%)	Others (%)
2021 irrigated	46.8	27.8	23.9	1.4
2022 irrigated	48.7	30	18.8	2.5
2021 dryland	33.4	38.5	25.6	2.5
2022 dryland	28.1	30.3	38.9	2.7
2021 organic	47.4	20.5	31.2	0.9
2022 organic	32.3	14.5	50.7	2.5
2021 conventional	35.6	39.2	22.6	2.5
2022 conventional	36.9	41.4	19	2.8

3.3.5 Sensitivity analysis of yield and harvested portion

A sensitivity analysis was performed using the models developed for Approaches B (field trials) and C (guidelines) to better understand the sensitivity of yield on carbon footprint. As shown in Fig 3.10 the GHG emissions of hempseed in Approach C were more sensitive to yield reduction by increasing at a greater rate. The degree of variation was similar among the four production guides, especially in response to increased yield.

For Approach B, a 50% reduction in straw yield was applied to the dual-purpose production of the CRS-1 cultivar, and the remaining straw was left on the field as residue. The percentage change in GHG emissions is presented in Table 3.10. Reducing prospected yield of hemp straw increased the environmental impact of all categories at each production and allocation scenario. Compared with grain-only production of the same cultivar, harvesting 50% of hemp straw still performed better in all impact categories. The theoretical case with 50% straw collected was used as default in Table 3.10 and experienced a 100% change in the harvested straw in both directions. The 100% reduction in straw was represented by grain-only production, while the 100% increase in straw was the default dual-purpose production. Harvesting hemp straw has significantly reduced the GHG emissions of hempseed. Maximizing straw yield had a lower influence on carbon footprint but still had a positive effect.

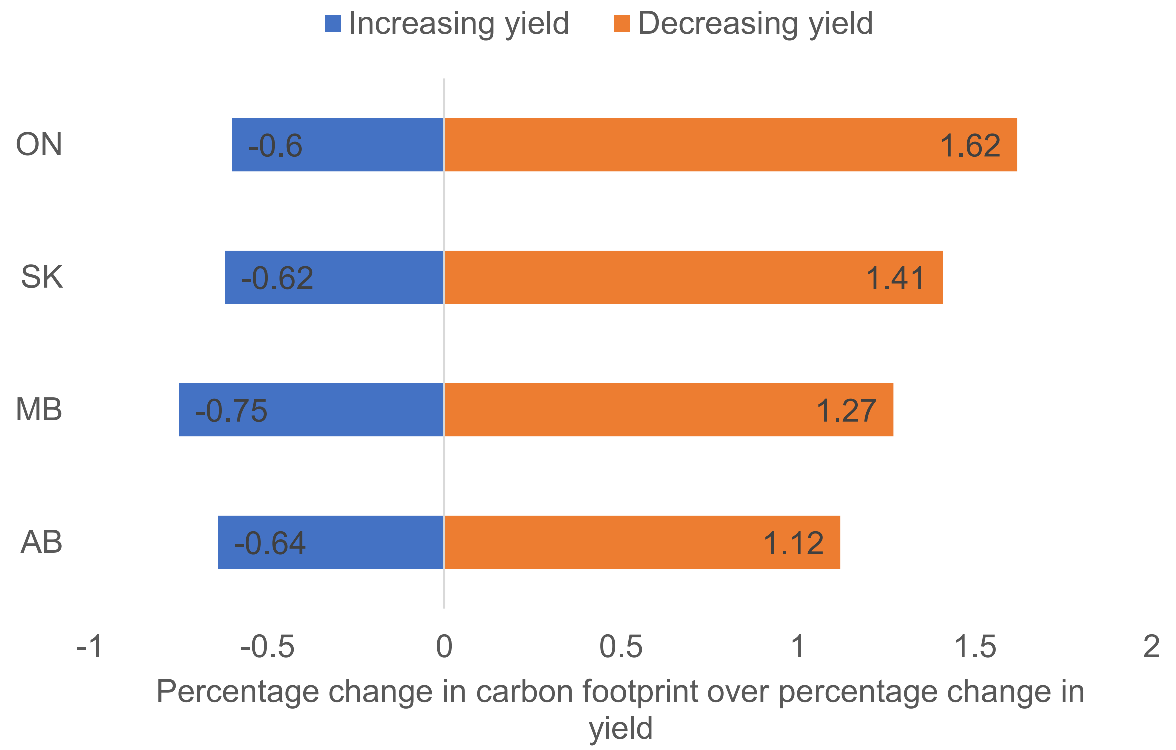

Figure 3.10 Changes in hempseed carbon footprint to changes in yield (Approach C)

Table 3.10 Changes in carbon footprints (kg CO2 eq/kg products) of hempseed and straw from changes in the amount of straw collected, based on field trial (Approach B)

	Mass allocation		Economic allocation	
	Hempseed	hemp straw	Hempseed	hemp straw
Grain without straw	1.76		1.76	
Default with 50% straw collected	0.6	0.6	1.4	0.16
Dual with 100% co-harvested straw	0.36	0.36	1.16	0.13

3.4 Discussion

3.4.1 Difference in study definition and LCI

The present study implemented LCI information from three primary sources: farmer interviews (Approach A), trial experiment results (Approach B), and cultivation guidelines (Approach C). Practices adopted by other LCA studies are presented in Table 3.11. It was common to evaluate hemp production from cradle to gate and use an aggregated LCI for analysis. However, individual cases under more extreme conditions were reported alongside the industrial average environmental footprint using a bottom-up approach. The variation in agriculture's footprint was highlighted.

Farming input contributes significantly to the overall cost and environmental footprints, especially the production of inorganic fertilizers. The farming system requirements of other hemp LCA studies are presented in Table 3.12. Canadian farmers generally use more N fertilizers and herbicides than suggested practices in other jurisdictions. However, liming with CaO wasn't common in Canada, especially in the prairies.

Table 3.11 Goal and scope of published LCA studies investigating the production of primary hemp materials

Literature	van der Werf, 2004 [19]	Gonzalez-Garcia et al., 2010 [20]	Zampori et al., 2013 [21]	Andrianandraina et al., 2015 [108]	Rodrigues et al., 2019 [111]	Scrucca et al., 2020 [12]	Campiglia et al., 2020 [24]	Todde et al., 2022 [25]
Country of cultivation	France	Spain	Italy	France	Homecourt (France)	France	Italy, Mediterranean	Italy
Functional unit	per ha	1 ton of fibre ready to be processed in a pulp mill	1 ha hemp cultivation	production and harvesting of 1 kilogram (kg) of hemp straw	reclaim 1 ha of degraded land and produce biomass equivalent	1 kg hurds	1 kg of seeds produced	1 kg of dry matter industrial hemp product (kg DM hempseed/hemp straw)
Allocation method	N/A	economic	mass and economic	N/A	system expansion	mass	N/A	economic
System boundary	cradle to gate	cradle to gate	cradle to gate	cradle to gate	cradle to gate	cradle to gate	cradle to gate	cradle to gate

Table 3.12 Farming system inputs of published LCA studies investigating the production of primary hemp materials

Literature	**Information source (cultivation)**	**LCI database**	**N**	**P (as P2O5)**	**K (as K2O)**	**Seeding rate**	**Chemicals**	**Irrigation**	**Production mode**
van der Werf, 2004 [19]	van der Werf, 2002	BUWAL 250 database	75 kg/ha (ammonium nitrate as N)	38 kg/ha (triple superphosphate as P2O5)	113 kg/ha (potassium chloride as K2O)	55 kg/ha	333 kg/ha CaO	N/A	Good agricultural practice; reduced tillage; less leaching
			N/A	N/A	51 kg/ha (potassium chloride as K2O)				Pig slurry
Gonzalez-Garcia et al., 2010 [20]	Spanish growers, bibliographic	Ecoinvent	85 kg N/ha (ammonium nitrate)	65 kg P2O5/ha (triple superphosphate)	125 kg K2O/ha (Potassium chloride)	50 kg/ha	N/A	N/A	Conventional
Zampori et al., 2013 [21]	official Italian association of hemp cultivation	Ecoinvent	~81 kg N	300 kg/ha (ammonium nitrate phosphate [27-12-0-4.5] as P2O5) ~36 kg P	200 kg/ha (potassium chloride as K2O)	50 kg/ha	N/A	N/A	Conventional
Andrianandraina et al., 2015 [108]	French national hemp producer federation (FNPC, 2005)	Ecoinvent	70; 100; 120 kg/ha	30; 50; 60 kg/ha	114; 150; 200 kg/ha	40-50 kg/ha	300; 500; 600 kg/ha of lime	N/A	Variable

Rodrigues et al., 2019 [111]	N/A	Ecoinvent v.3.3	70 kg/ha	50 kg/ha	20 kg/ha			N/A	Conventional
Scrucca et al., 2020 [12]	interview with farmers and producers (averaged from 20 main actors of hemp production in France, covering 95% of cultivated surfaces and 95% of produced volumes); InterChanvre, 2017; TerresInovia Institut, 2017	Ecoinvent v.3.4	0.21 kg/FU (N)	0.0989 kg/FU (P2O5)	0.076 kg/FU (K2O)		1.636E-5 kg/FU (Pomarsol [Thirame])	N/A	Conventional
Campiglia et al., 2020 [24]	Campiglia et al., 2017	Agri-footprint, ELCD, Ecoinvent	50 or 100 kg/ha			40/80/120 plants/m2		N/A	Conventional
Todde et al., 2022 [25]	collected under the "CANOPAES" project at two experimental sites	Ecoinvent	60 kg/ha			40 kg/ha (Futura 75)		4500 m3/ha (450 mm, 17.72 in)	Conventional (medium contaminated soil)
									Conventional (high contaminated soil)

Hempseed yield in Canada was compatible with other jurisdictions. A maximum output of 2.44 t/ha was suggested by Campiglia et al. [24] in the Mediterranean environment. Yield on the lower end of 500 kg/ha in the Czech Republic was reported [25], and 300 kg/ha in Italy on highly contaminated soil [112]. The yield of co-harvested hemp straw was compatible with Jasinskas et al., [113] who suggested that the dry mass of Finola cultivar ranging from 3245 to 3406 kg/ha, but lower than 9000 kg/ha from dual-purpose industrial hemp reported by Bernas [114].

The average yield in the fibre-only production scenario was significantly lower than in other studies. Still, some fields produced a comparable amount of biomass as high as 10 tonne/ha. Zampori et al. [21] presented one of the highest mass outputs of biomass at 15 t/ha, referring to the Carmagnola variety in Italy; Butkute et al. [113] reported 9063 kg/ha DM yield of hemp stem; Hansen et al., [41] reported 8 t/ha with 15% moisture, similar to 7500 kg/ha straw yield suggested by Schulte et al., [43]. Hemp production guides from AB [74], and ON [2] reported a maximum output of 14-16 tonne/ha of straw, producing more biomass than most studies. The average amount of hemp straw harvested from some locations in the NHVFT 2022, was compatible with the reported yield by these studies at more than 6000 kg/ha [89]. The biomass was collected at the same site but before seed development. Therefore, the weight of the straw was determined in the form of a fibre-only production scenario and maximized the overall yield. It might overestimate the yield since a proportion of straw was wasted during the combing of hempseed and lost as aboveground residue in commercial production.

3.4.2 Influence of allocation

LCA studies commonly use allocation methods for processes that generate multiple products [21]. As indicated in Table 3.11, mass and economic allocations were widely used in hemp-related LCA studies. System expansion was implemented more on secondary and further processing of hemp materials. Energy allocation was used in studies on generating energy from biomass and transportation. The current research adopted mass and economic allocation for scenarios that produced hempseed and straw, aggregated results from Approach A and B are presented in Fig 3.11. In both approaches, hempseed produced in dual-purpose scenarios had lower GHG emissions with mass allocation than that of economic allocation. Mass allocation distributes the environmental burden toward hemp straw, which has greater mass but low market value, therefore favors hempseed. Economic allocation is heavily influenced by price fluctuation, but it can reflect the motivation of farming activities. It distributes the majority of production footprint toward hempseed and align with the proportion of hempseed acreages in Canada.

The distribution of data points in Approach B are closer to the median value comparing to that of Approach A, since the NHVFT 2022 provided detailed guideline for hemp production and most of the input parameters are the same in the farming system. Data collected from Approach A includes various scenarios such as organic and irrigated production, therefore showing greater variability. However, results from Approach B have showed more outliers since it covers a wider geographical area and more diverse climate conditions. Some farmers suggest that the lack of market and processing capacity dictates their willingness and ability to harvest hemp straw alongside hempseed production. If market access of co-harvest hemp straw is more available, farmers might produce more dual-type hemp cultivars.

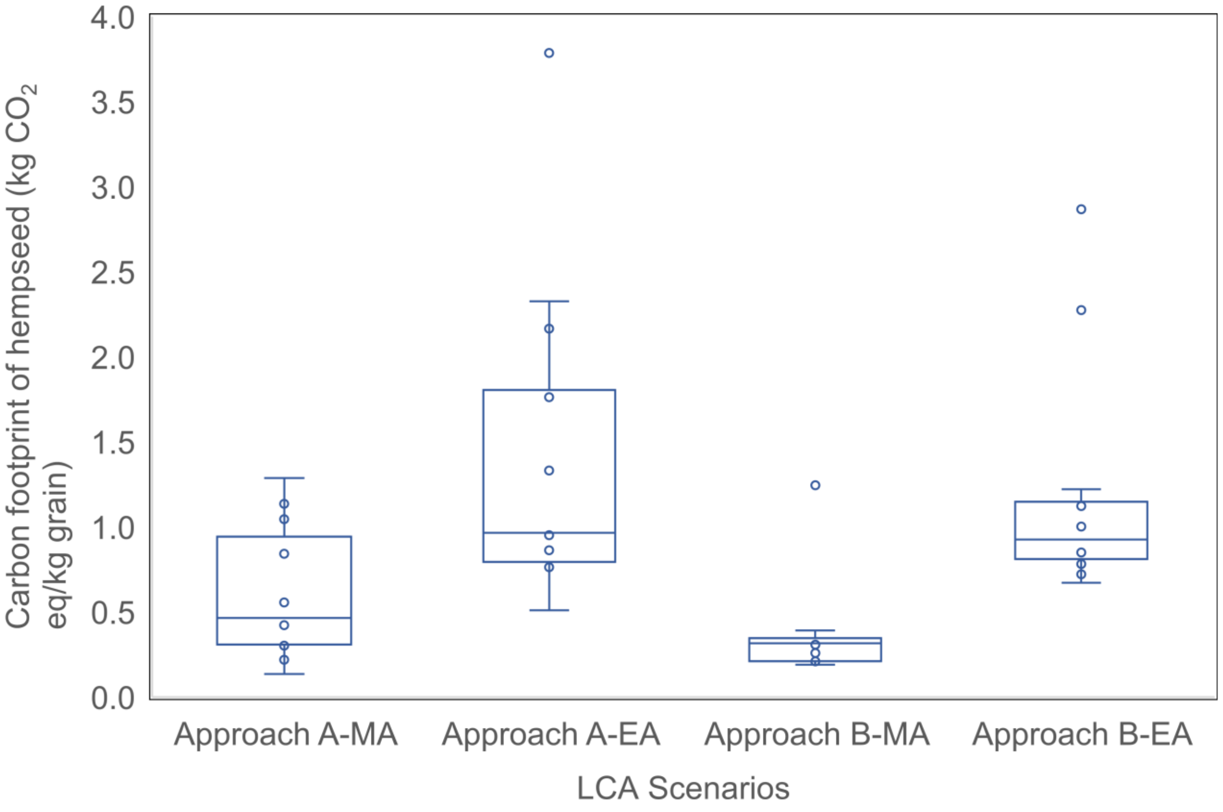

Figure 3.11 Box and Whisker plot of dual-type hempseed carbon footprints from farm level dataset (Approach A) and NHVFT 2022 (Approach B)

[Open circles represent results from individual farmers (Approach A) and average footprints from individual research sites (Approach B), top and bottom end of whisker represent minimum and maximum value reported, box covers interquartile with 50% of data points and the median line]

3.4.3 Influence of input variables of the farming system (Approach A)

The LCIA results were aggregated when analyzing the influence of input variables such as moisture management and nutrient management, due to low sample size. Irrigated production has slightly lower environmental footprints in most impact categories than that of dryland production, but only significantly better in land use category. However, it also used significantly more water resources as expected. Organic production of hempseed had slightly better environmental impacts in half of the categories evaluated than that of conventional production. However, its production used slightly more water resources, likely due to distribution of irrigated production cases in a small sample size (5 out of 9 cases). Dual-purpose production of hempseed without allocation wasn't significantly different from grain-only production, results are provided in Appendix B. Some farmers mentioned that dual-purpose production of hempseed and straw exported more nutrients out of the system. As a result, producing the following crop might require more fertilizer and not providing benefits to the complete crop rotation sequence.

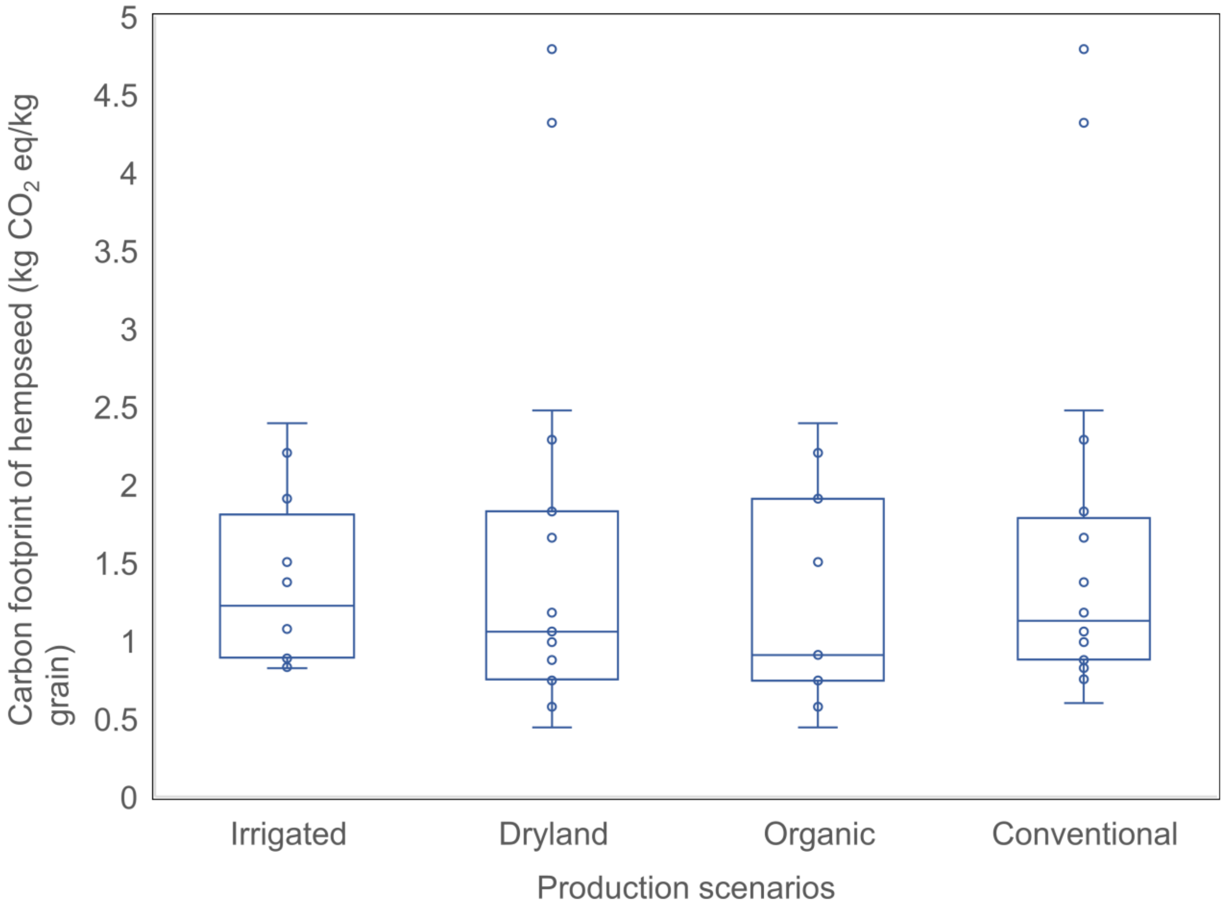

Figure 3.12 Box and Whisker plot of integrated hempseed carbon footprints from farm level dataset (Approach A) from four production scenarios

[Open circles represent results from individual farmers without allocation (hempseed contributes to all emissions), top and bottom end of whisker represent minimum and maximum value reported, box covers interquartile with 50% of data points and the median line]

3.4.4 Comparison of carbon footprints with literature and other sources

3.4.4.1 Comparing carbon footprints of hempseed and straw

It is often quite difficult to directly compare all environmental impacts from an LCA study with other of studies in the literature due to differences in modeling approaches, assumptions, system boundaries, and LCIA methods. However, GHG emissions are made comparable since most studies refer to IPCC guidelines while estimating global warming potential or climate change indicators, and the results are reported in CO_2 equivalent. Hempseed from the current study had a similar carbon footprint as suggested by Todde et al., [25] which reported an average of 1514.44 g CO_2 eq per kg DM from the conventional dual-type production on contaminated soil in Italy. Campiglia et al. [24] showed significant variation in the GWP of hempseed, ranging from 0.161 to 18.72 kg CO2 eq/kg for grain-only production. The GWP results from the current study fit in the range and show similar variation. Hemp straw from the current study also had a comparable footprint compared to the EU countries (except for co-harvested hemp straw allocated by mass). A comparison of the carbon footprint of hemp straw from other studies is presented in Table 3.13.

As presented in Fig 3.8, the carbon footprint in the current study (Approach B) was influenced by environmental conditions in different locations. Agriculture and Agri-Food Canada reported similar results by estimating GHG emission intensities for field crops produced in Canada [115]. The CO_2 equivalent to producing oilseed and cereals was higher in BC, ON, QC, and Atlantic provinces, while lower in prairie provinces including AB, SK, and MB [115]. The weighted average carbon footprint of hempseed produced in Canada was slightly higher than the average GHG emission intensities of oilseed estimated by AAFC in 2011. The mass-allocated results were better than the footprint of major oilseeds such as canola, flaxseed and sunflower but not as good as soybean.

Table 3.13 Carbon footprint of hemp straw estimated by published LCA studies investigating the production of primary hemp materials

Literature	**Scenario**	**Production mode**	**GHG reported (CO_2 eq)**	**kg CO_2 eq/kg hemp straw converted**
van der Werf, 2004 [19]	Good agricultural practice	Straw only	2330 kg/ha	0.35
	Reduced tillage		2200 kg/ha	0.33
	Less leaching		2090 kg/ha	0.31
	Pig slurry		1770 kg/ha	0.26
Zampori et al., 2013 [21]		Straw only	1.57 t/ha	0.1
Andrianandraina et al., 2015 [108]	(Default mean, from supporting information)	Straw only		0.24
Todde et al., 2022 [25]	Hemp straw (medium contaminated soil)	Dual type	53.88 g/kg	0.05
	Hemp straw (high contaminated soil)	Dual type	84.74 g/kg	0.08

3.4.4.2 Comparing major contributors of GHG emission

Major GHG contributors include fertilizer production, field emissions, and footprint associated with field activities and post-harvesting operations. Other studies have shown a similar trend, as presented in Table 3.14. In general, no-till and minimum tillage were widely adopted in Canada. Therefore, the GHG associated with soil preparation is significantly lower than conventional tillage since tillage is the most energy-consuming activity compared to other operations, such as spraying and harvesting [116]. For organic production, the footprint of livestock and green manure contributes much less GHG than in conventional production. Studies investigating other crops produced organically had mixed conclusions. Clark and Tilman [117] suggest that organic production emits a similar amount of GHG per unit of food but requires more land. Hillier et al. [118] found that 75% of greenhouse gas emissions resulted from using nitrogen fertilizer over the production of all crops. At the same time, organic farms had significantly lower carbon footprints than conventional and integrated farms. However, Tuomisto et al. [119] indicated that organic production has lower environmental impacts per unit area but doesn’t necessarily apply to unit products, due to problems such as lower yield, nutrient deficiencies, pest, diseases and weeds.

Irrigated production had higher GHG emissions due to increased field emissions. Higher soil moisture causes greater microbial activities and releases more N_2O from denitrification [66]. However, irrigation provides sufficient moisture to crops, which ensures a steady yield and mitigates the negative impact of drought. Therefore, reducing irrigation isn’t a viable option for farmers who produces hemp in drier area, achieving optimal yield ensures the financial sustainability without substantially increase the carbon footprints of hempseed. Field emissions from Approach B and C were higher than that from Approach A, as shown in Table 3.8, because target nutrient levels were used in the modelling, overestimating emissions associated with fertilizer and contributing a greater proportion of the overall carbon footprints. Another reason for the observation was attributed to the lack of organic production, which accounted for a substantial proportion of hempseed production in Approach A. Table 3.9 indicates that the GHG emissions associated with organic fertilizer production were lower than that of conventional production, and reduces the contribution of fertilizers in Approach A. Conversely, organic production requires extensive fieldworks includes manure application and cultivating, contributing greater amount of GHGs that conventional production. Studies that investigate hemp straw production didn't show similar results as expected [12, 19-20, 108], since straw production requires less management and densely seeded hemp often outcompete weeds during its growth phase.

Table 3.14 Proportion of GHG emissions contributed by each category during the production of hemp

Literature	Field emission (%)	Fertilizer production (%)	Field operations (%)
van der Werf, 2004 [21]	41.1	43.1	15.8
Gonzalez-Garcia et al., 2010 [20]	~36	~33	~21
Zampori et al., 2013 [18]	5.38	~31.82	~42.3
Andrianandraina et al., 2015 [50]	27.7	47.5	24.4
Scrucca et al., 2020 [55]	8.2	70.8	12.2

("~" indicates data that are estimated from a graphical source or summation of minor contributors)

The present study investigated hemp produced in the Canadian prairies during 2021 and 2022, and the NHVFT 2022 from the bottom-up. Long-term tracking of hemp produced in Canada is highly recommended to mitigate the variation in production input, yield and climate conditions. Regionalized information is also crucial in estimating the production footprint of crops since field emissions are heavily influenced by moisture and soil texture [65]. More research is required to determine the nutrient returned to the soil from straw residue decomposition.

3.5 Conclusions

The present study estimated the environmental impacts associated with producing hempseed and straw in the prairies in Canada via life cycle assessment. Information was collected from farmer interviews, the CHTA National Hemp Variety Field Trial 2022, and production guides. The investigation comprised processes from raw material extraction to the farm gate.

The results indicated that hempseed and hemp straw have comparable footprints compared to other studies conducted in the EU. Other oilseeds produced in Canada had similar or slightly better GHG emission intensities than hempseed. Agricultural production of a multi-purpose crop is complicated due to variables in environmental conditions and production practices. Dual-purpose production of hempseed did not always have lower environmental impacts than grain-only production. Mass and economic allocation distribute footprints between coproducts and significantly affect the results. Mass allocation distributed less footprint to hempseed while assigning more emissions to hemp straw while economic allocation had the opposite effect (Mass allocation favors hempseed, economic allocation distributes more footprints toward hempseed and favors co-harvested hemp straw). Field emissions and fertilizer production were the major contributors to GHG emissions, followed by fieldwork. Harvesting more hemp straw while maintaining hempseed yield will lower the environmental footprint for both products. Extensive tracking and analysis of industrial hemp production in the future will provide more definitive results and include farmers who collects hemp fractions in their operations.

Chapter 4 : Life cycle assessment of hemp straw decortication and non-woven textile production in Canada

4.1 Introduction

Industrial hemp has been used by humans for thousands of years as a fibre crop, providing durable products such as rope, sail and textiles [1]. Countries, including Canada, reintroduced industrial hemp cultivation in the late 1990s [74]. The European Union has allowed legal cultivation of industrial hemp with a 0.3% or lower THC content for decades [7]. Even though the traditional fibre market has been dominated by cotton and synthetic materials since the 20th century, hemp straw provides specialty fibre for a niche market. Usually, hemp has been cultivated for fibre in the EU and China while grown for hempseed in Canada. FAOSTAT indicates that more than 74,000 ha and 287,000 tonnes of raw or retted hemp were produced in 2021 [8]. Other than fibre, the entire hemp plant can be used in more than 25,000 products [1]. Therefore, there is increasing interest in Canada and other major hemp-producing countries to explore industrial hemp, such as the rapid expansion in the market for Cannabidiol (CBD) and other extracts [7, 87].

Besides the benefits from the production system, hemp material has high carbon storage potential in both soil and long-lived products [14]. Several studies have explored the low-carbon material in products such as hempcrete, insulation and biocomposites. In various applications, hemp-based materials have a significantly lower carbon footprint than conventional materials [14, 21]. Besides the ability to mitigate global warming, experiments also confirmed that hemp could be used as a bioremediation solution on sites polluted by heavy metals and radioactive materials [1, 84].

To quantify the environmental footprints and benefits of the complex production system, many researchers have implemented the life cycle assessment (LCA) method. Studies have evaluated the production of hemp straw and its primary products, including bast fibre and hurd. These previous studies have been primarily conducted in European countries by authors such as Gonzales-Garcia et al. [20], Zampori et al. [21], and Sinka et al. [32]. Some researchers have considered the biogenic carbon contained in the hemp biomass, which could reduce the carbon footprint significantly [21, 84]. However, LCA studies on Canadian hemp straw are limited to just a few articles, while thousands of acreages is dedicated to hemp fibre production in Canada, alongside significant amount of co-harvested hemp straw from hempseed production [85]. Pervaiz and Sain [21] assessed the performance of hemp-based composite produced in Ontario and suggested that implementing hemp fibre in the auto industry could reduce significant amount of greenhouse gas (GHG) emissions. George and Bressler [50] evaluated the footprints of the chemical treatment process of hemp fibre and the composite material production in Alberta. Utilizing treated hemp fibre as feedstock reduces the carbon footprint associated with input material comparing to glass fibre. Both studies have investigated the utilization of hemp bast fibre and leaving hemp hurd unattended, which represents a significant proportion of straw-derived by-product alongside dust. With limited dataset on hemp straw processing, there is an increasing need to assess the production footprints of hemp straw-derived materials in Canada and explore the potential of all fractions.

A life cycle assessment was carried out to assess the processing of hemp straw in Canada, including the secondary production of consumer goods. The present work discussed the production of hemp bast fibre, hurd, and nonwoven mats. The results were categorized by different production scenarios and compared with similar LCA studies from the EU. Production footprints of co-products were allocated by mass and economic value. Environmental hotspots and major contributors to GHG emissions in the production system were identified. Sensitivity analysis were conducted to evaluate the impact of alternatives that can be implemented in the near future, and the effectiveness to reduce production footprints.

4.2 Materials and Methods

Life cycle assessment was performed following the ISO 14040 and ISO 14044 [16-17]. The LCA study consists of four phases: Goal and scope definition; Life Cycle Inventory (LCI); Life Cycle Impact Assessment (LCIA); and interpretation.

4.2.1 Goal and Scope Definition

This study aimed to investigate the environmental sustainability of processed hemp straw products and non-woven hemp fibre mats in Canada through a cradle-to-gate LCA. The global warming potential of Canadian hemp products was compared with other studies.

The LCA model was based on production operations of the BioComposites Group (BCG) located in Drayton Valley, AB, Canada. Hemp straw processing was associated with two co-products, bast fibre and hurd, as well as dust as a potential by-product or waste material. The production of non-woven mat consists of three different thicknesses, including 300, 500 and 1000 grams per sq. meter (GSM). The hemp fibre mat was produced in roll form and is being marketed directly in erosion control blanket for slope stabilization applications. Cutting and packaging of these stock rolls are also used to manufacture dozens of other consumer goods such as plant growth mats, weed suppression squares, animal liners and nesting sheets [120].

4.2.2 Functional Unit and System Boundary

This study considered 1 tonne of bast fibre and hurd as the functional unit for straw processing. Dust was treated as waste material since the utilization wasn't available at the facility during the investigation. The functional unit selected to assess the nonwoven mat was 1 m^2 since it was marketed to customers based on area. One tonne of mat was implemented as secondary functional unit and compares to other products.

The system boundary of this study was defined as cradle-to-gate, including all upstream material inputs such as fertilizers, herbicides, fuel, and electricity consumed during farming operations, transportation, and processing of straw. The present study did not include sizing and packaging for the hurd, as well as cutting and packaging of the mats.

4.2.3 Life Cycle Inventory

4.2.3.1 Hemp straw production

Primary data regarding hemp straw feedstock were collected from farmers who supply hemp straw to the BCG facility. The previous study in Chapter 3 assessed the production footprints of hemp straw in various scenarios, and its results were used in Chapter 4. In total, three scenarios in the supply of hemp straw were assessed: 1) Sampled 2021 co-harvested hemp straw feedstock (from hempseed production, processed in 2022 by BCG); 2) Sampled 2022 co-harvested hemp straw feedstock (from hempseed production, processed in 2023); 3) Hemp straw from fibre-only production sources.

As recorded by BCG, 43.2% of straw processed was supplied by farmers who participated in the previous study in Chapter 3. All suppliers prioritized hempseed production, while collected hemp straw as a co-product for additional income. Feedstock produced in 2021 were used in the analysis as default, and suppliers of the hemp stalk were located in two of the prairie provinces in Canada (AB, SK). Hemp straw produced in 2022 was modelled as an alternative in the second scenario, from the same suppliers. The weighted average footprints of hemp straw from interviewed suppliers were used to represent the overall feedstock and used in the analysis. Hemp cultivars include X59 and Picolo; other potential suppliers also produce Canda, Altair, and Henola. Both X59 and Picolo were popular among growers, as shown by the production acreages published by Health Canada [5].

Beside co-harvested hemp straw from hempseed production, fibre-only production scenarios were discussed in section 4.2.5 and modelled as a potential source of input material in the third scenario. It comprised 61 production cases the Canadian Rockies Hemp Corporation (CRHC) provided and was analyzed in Chapter 3. On average, hemp straw harvested as a by-product from hempseed production was 1 tonne/ac, approximately 2.47 tonne/ha. CRHC reported that the weighted average yield of the fibre-only production was 1.26 tonne/ac in 2021 and 2.10 tonne/ac in 2022, significantly higher than co-harvested hemp straw.

4.2.3.2 Decortication

Hemp processing via decortication operations was investigated from available data from Jan 2022 to Dec 2022, representing year-round operation and variable feedstock quality. The decorticator was integrated with the following cleaning operations and analyzed as an integrated unit process. It consumed 88.8 kWh of electricity per hour and was designed with a processing capacity of 1 tonne of straw per hour. It should be noted, however, that the equipment did continuously consumes power even in downtimes (i.e. maintenance, production stoppages). Therefore, the actual processing efficiency was lower than the system design. The material and energy flow to process 1 tonne of hemp straw is presented in Table 4.1.

Table 4.1 Material and energy flow in hemp straw decorticating and cleaning

Input	
Hemp straw bale	1 tonne
Electricity	326.49 kWh
Output	
Bast fibre	211.1 kg
Hurd	487 kg
Dust	301.9 kg

4.2.3.3 Mat production

The production of non-woven mats consists of two input materials: hemp bast fibre from the decorticator in the same facility and cellulose-based rayon fibre scrim (recycled pulp tissue). The standard roll of non-woven mat measured 2.4 m x 30.5 m (8 ft x 100 ft). The 300 GSM, 500 GSM and 1000 GSM mats have thicknesses of 0.52 cm (0.205 in), 0.64 cm (0.25 in) and 1.27 cm (0.5 in), respectively. The composition of the mats produced is presented in Table 4.2. The hourly output of this operation and the material flow was consistent according to company record.

Table 4.2 Material and energy requirements for non-woven mat production (per m^2)

Products	300 GSM	500 GSM	1,000 GSM
Hemp bast fibre	0.26 kg	0.45 kg	0.90 kg
Scrim backing	0.04 kg	0.05 kg	0.10 kg
Electricity	7.08 kWh	5.67 kWh	12.17 kWh

(Note: the 1,000 GSM mats contain recycled mats from the cutting process and are calculated based on 30% recycled 300 GSM mat, 30% recycled 500 GSM mat, and 40% bast fibre)

4.2.3.4 Secondary data

Secondary data, such as transportation and electricity, were obtained from the Ecoinvent v3.7 database. Electricity dedicated to the Alberta grid in 2020 was used to process hemp material based on the facility's location. The MROE (MRO East, East Wisconsin) [121] grid mix was used in the production of scrim since the manufacturer was located in Wisconsin, USA. Canadian-specific data was used as default in modelling, followed by North American data (RNA), Global dataset without EU (Row) and Global source (GLO).

4.2.3.5 Biogenic carbon

Biogenic carbon was reported separately, as both bast fibre and hurd could produce long-lasting products, including textile, composite material, insulation and hempcrete. Several studies acknowledged that hemp captures a significant amount of carbon dioxide during its growth phase and has the potential to store the GHG temporarily or longer for up to 100 years [12, 32]. The present study assumes that hemp straw and its products contain 1.63 kg of CO_2 equivalent per kg, as reported by Seile et al. [53].

4.2.4 Life Cycle Impact Assessment

The present study implemented an attributional approach regarding environmental impacts and implemented the ReCiPe 2016 Midpoint (H) LCIA method. It consists of 18 impact categories: Ozone formation, Human health (kg NO_x eq); Mineral resource scarcity (kg Cu eq); Human carcinogenic toxicity (kg 1,4-DCB); Terrestrial acidification (kg SO_2 eq); Terrestrial ecotoxicity (kg 1,4-DCB); Ozone formation, Terrestrial ecosystems (kg NO_x eq); Water consumption (m^3); Land use (m^2a crop eq); Marine ecotoxicity (kg 1,4-DCB); Marine eutrophication (kg N eq); Freshwater eutrophication (kg P eq); Stratospheric ozone depletion (kg CFC11 eq); Freshwater ecotoxicity (kg 1,4-DCB); Human non-carcinogenic toxicity (kg 1,4-DCB); Global warming (kg CO_2 eq); Ionizing radiation (kBq Co-60 eq); Fine particulate matter formation (kg PM2.5 eq); and Fossil resource scarcity (kg oil eq). LCIA results were calculated using the software OpenLCA v1.10.3.

4.2.5 Allocation of feedstock and products

Allocation was required since decorticating hemp straw produces more than one product stream from the production system [16]. Therefore, mass allocation and economic allocation were used for the processing of hemp straw. As suggested by the BCG, the market value of hemp bast fibre and hurd was in a 2 to 1 ratio. Dust from the decortication process currently had no market value; therefore, not allocated with other co-products. Allocation of feedstock was performed in Chapter 3; the same allocation was followed in the current analysis. Thus, production footprints allocated by mass in the foreground system also implemented the mass-allocated feedstock in the background, and the same practice was repeated in economic allocation.

4.2.6 Sensitivity Analysis

A sensitivity analysis was conducted to evaluate the impact of various data and assumptions based on existing alternative inputs [108]. Changes in the following parameters were analyzed: decorticating and cleaning efficiency; sourcing hemp straw from fibre-only production; using a low-carbon electrical grid mix; sourcing hemp straw with higher bast fibre and hurd content; and utilizing dust. Only positive changes that has the potential to improve the production footprints in these variables were considered in the analysis.

4.2.7 Study Limitations

The life cycle analysis of straw processing was challenging due to various production scenarios. This study sourced co-harvested straw from hempseed production and fibre-only production of straw. There are other cultivation approaches beyond the scope. The following assumptions could influence the assessment results: 1) The present study used results form Chapter #3 as the source of hemp straw, and the limitations from the previous study were inherited as part of the feedstock. 2) The cost of transportation limited the hemp straw supply chain, as mentioned by the BCG. The facility studied only purchased hemp straws from farmers in AB and SK. Therefore, inputs were limited geographically in central Alberta and its surrounding area. Several decorticators are in operation or under construction in different parts of the country and use various feedstock and electrical grids. The sensitivity analysis was conducted to address some variables but couldn’t cover all production scenarios in Canada.

4.3 Results

4.3.1 Environmental impacts

Results regarding 18 environmental impact categories calculated using the ReCiPe 2016 Midpoint method are reported in Table 4.3 and Table 4.4., based on mass and economic allocation. Hemp straw was produced in 2021 and processed in the facility in 2022. The production footprint of bast fibre and hurd with mass allocation was significantly higher than that of economic allocation. The environmental footprint of hurd was about 50% of the footprint of bast fibre while allocated by market value.

Table 4.3 Life cycle impact assessment results of hemp bast fibre and hurd produced in Alberta, Canada

Allocation methods	MA		EA	
Coproducts	Bast fibre	Hurd	Bast fibre	Hurd
Ozone formation, Human health (kg NO_x eq)	4.41E+00	4.41E+00	2.40E+00	1.20E+00
Mineral resource scarcity (kg Cu eq)	1.93E+01	1.93E+01	3.76E+00	1.88E+00
Human carcinogenic toxicity (kg 1,4-DCB)	1.52E+02	1.52E+02	8.27E+01	4.14E+01
Terrestrial acidification (kg SO_2 eq)	2.20E+01	2.20E+01	5.89E+00	2.95E+00
Terrestrial ecotoxicity (kg 1,4-DCB)	1.31E+04	1.31E+04	4.18E+03	2.09E+03
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	4.59E+00	4.59E+00	2.45E+00	1.23E+00
Water consumption (m^3)	2.34E+02	2.34E+02	4.34E+01	2.17E+01
Land use (m^2a crop eq)	1.01E+04	1.01E+04	1.69E+03	8.44E+02
Marine ecotoxicity (kg 1,4-DCB)	2.45E+02	2.45E+02	9.96E+01	4.98E+01
Marine eutrophication (kg N eq)	2.33E+00	2.33E+00	4.45E-01	2.22E-01
Freshwater eutrophication (kg P eq)	1.05E+00	1.05E+00	1.09E+00	5.44E-01
Stratospheric ozone depletion (kg CFC11 eq)	1.39E-02	1.39E-02	2.55E-03	1.28E-03
Freshwater ecotoxicity (kg 1,4-DCB)	1.86E+02	1.86E+02	7.57E+01	3.79E+01
Human non-carcinogenic toxicity (kg 1,4-DCB)	3.78E+03	3.78E+03	1.38E+03	6.89E+02
Global warming (kg CO_2 eq)	1.80E+03	1.80E+03	1.02E+03	5.11E+02
Ionizing radiation (kBq Co-60 eq)	4.02E+01	4.02E+01	1.24E+01	6.18E+00
Fine particulate matter formation (kg PM2.5 eq)	4.17E+00	4.17E+00	1.48E+00	7.42E-01
Fossil resource scarcity (kg oil eq)	4.22E+02	4.22E+02	2.73E+02	1.37E+02

Table 4.4 Life cycle impact assessment results of hemp-based nonwoven mats produced in Alberta, Canada

Allocation methods	MA			EA		
Nonwoven mats	300 GSM	500 GSM	1000 GSM	300 GSM	500 GSM	1000 GSM
Ozone formation, Human health (kg NO_x eq)	1.83E-03	2.74E-03	5.10E-03	1.31E-03	1.84E-03	3.16E-03
Mineral resource scarcity (kg Cu eq)	7.03E-03	1.12E-02	2.05E-02	2.98E-03	4.17E-03	5.47E-03
Human carcinogenic toxicity (kg 1,4-DCB)	8.03E-02	1.14E-01	1.96E-01	6.23E-02	8.27E-02	1.29E-01
Terrestrial acidification (kg SO_2 eq)	6.88E-03	1.12E-02	2.27E-02	2.70E-03	3.91E-03	7.18E-03
Terrestrial ecotoxicity (kg 1,4-DCB)	4.39E+00	7.11E+00	1.36E+01	2.07E+00	3.08E+00	4.95E+00
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	1.89E-03	2.83E-03	5.28E-03	1.33E-03	1.87E-03	3.21E-03
Water consumption (m^3)	7.03E-02	1.17E-01	2.35E-01	2.07E-02	3.10E-02	5.08E-02
Land use (m^2a crop eq)	2.65E+00	4.58E+00	9.75E+00	4.73E-01	8.02E-01	1.66E+00
Marine ecotoxicity (kg 1,4-DCB)	1.10E-01	1.61E-01	2.92E-01	7.18E-02	9.62E-02	1.51E-01
Marine eutrophication (kg N eq)	6.39E-04	1.08E-03	2.30E-03	1.48E-04	2.35E-04	4.73E-04
Freshwater eutrophication (kg P eq)	7.14E-04	9.23E-04	1.65E-03	7.23E-04	9.40E-04	1.69E-03
Stratospheric ozone depletion (kg CFC11 eq)	3.72E-06	6.37E-06	1.36E-05	7.74E-07	1.27E-06	2.61E-06
Freshwater ecotoxicity (kg 1,4-DCB)	8.27E-02	1.22E-01	2.21E-01	5.41E-02	7.24E-02	1.15E-01
Human non-carcinogenic toxicity (kg 1,4-DCB)	1.75E+00	2.58E+00	4.50E+00	1.12E+00	1.50E+00	2.18E+00
Global warming (kg CO_2 eq)	8.02E-01	1.16E+00	2.19E+00	6.00E-01	8.14E-01	1.44E+00
Ionizing radiation (kBq Co-60 eq)	1.88E-01	2.40E-01	1.95E-01	1.81E-01	2.27E-01	1.68E-01
Fine particulate matter formation (kg PM2.5 eq)	1.53E-03	2.38E-03	4.57E-03	8.33E-04	1.17E-03	1.98E-03
Fossil resource scarcity (kg oil eq)	1.99E-01	2.84E-01	5.28E-01	1.60E-01	2.17E-01	3.85E-01

The environmental footprint associated with 1 m^2 of nonwoven mats increased as the weight increased from 300 GSM to 1000 GSM. At the same time, results allocated by economic value were lower than that distributed by mass, similar to the footprint of bast fibre and hurd. The LCIA results were presented by 1 tonne of mats in Appendix C, where the opposite trend was observed, and the environmental impacts of 1000 GSM were the lowest, followed by 500 and 300 GSM in most categories, except land use.

4.3.2 Global warming potential

Greenhouse gas emissions are the primary driver of global warming and climate change. Therefore, a detailed analysis identifying major contributors to GWP was performed. Table 4.5 and Table 4.6 show that mass allocation distributed the same production footprint between hempseed and straw in a dual-purpose production scenario. The environmental impact of hemp straw production accounted for more than 70% of the overall footprint.

The production of nonwoven mats had a similar proportion, where the content of bast fibre increased from 300 GSM to 1000 GSM, and the footprint contributed by bast fibre also increased accordingly. On the other hand, the footprint associated with hemp straw production was less significant when allocated by economic value; the GHG emissions from electricity took a more substantial share. The scrim accounted for about 10% of the weight in nonwoven mats, and its production footprint contributed between 8% to 13% of the overall GHG emissions.

Table 4.5 Major contributors in GHG emissions from the production of bast fibre, hurd, and nonwoven mats (mass allocation)

Products/contributors	Bast fibre & hurd	300 GSM nonwoven mat	500 GSM nonwoven mat	1000 GSM nonwoven mat
Hemp straw production (%)	70.7	58.3	69.6	75.2
Transportation (%)	5.6			
Decortication (%)	23.8			
Scrim production & transportation (%)		9.4	8.1	9
Mat production (%)		32.2	22.2	15.8

Table 4.6 Major contributors in GHG emissions from the production of bast fibre, hurd, and nonwoven mats (economic allocation)

Products/contributors	Bast fibre & hurd	300 GSM nonwoven mat	500 GSM nonwoven mat	1000 GSM nonwoven mat
Hemp straw production (%)	20.7	44.3	56.6	63.3
Transportation (%)	15			
Decortication (%)	64.3			
Scrim production & transportation (%)		12.6	11.6	13.4
Mat production (%)		43.1	31.8	23.4

4.3.3 Sensitivity analysis results

The sensitivity analysis consists of four scenarios, and the results are presented in Table 4.7 and Table 4.8. Generally, five scenarios reduced the carbon footprint of bast fibre, hurd, and nonwoven mats at various degrees, except when comparing the fibre-only feedstock with the current supply of co-harvested straw with economic allocation. Using electrical energy with a lower carbon footprint had the most significant environmental benefits and reduced the GHG emissions associated with the production of nonwoven mats from 30-65%.

Table 4.7 Sensitivity analysis of carbon footprint regarding the production of bast fibre and hurd (kg CO2 eq/tonne products)

Allocation methods	MA		EA	
Coproducts	Bast fibre	Hurd	Bast fibre	Hurd
Base case	1799.7	1799.7	1023	511.4
Increasing decortication efficiency	1586.3	1586.2	695.2	347.6
Processing fibre-only hemp straw	904.2	904.1	1388.5	694.2
Using low carbon electrical grid	1413.1	1413.1	429.3	214.6
Higher bast fibre and hurd content	1439.6	1439.6	818.3	409.1
Utilization of dust	1256.4	1256.4		

Table 4.8 Carbon footprint reduction from the base scenario of nonwoven mats production according to sensitivity analysis

Allocation methods	MA			EA		
Nonwoven mats	300 GSM	500 GSM	1000 GSM	300 GSM	500 GSM	1000 GSM
Increasing decortication efficiency	6.9%	8.3%	8.9%	14.2%	18.1%	20.3%
Processing fibre-only hemp straw	29%	34.7%	37.4%	-15.8%	-20.2%	-22.6%
Using low carbon electrical grid	41.7%	35.1%	30.2%	64.7%	61.6%	57.6%
Higher bast fibre and hurd content	11.7%	13.9%	15.1%	8.8%	11.3%	12.7%
Utilization of dust	17.6%	21%	22.7%			

The analysis started with improving processing efficiency, as the actual processing speed was 0.27 tonne/hour, much lower than the rated 1 tonne of hemp straw per hour. Scenario A reduced the overall processing time by 50%, which increased the processing capability to approximately 0.54 tonne/hour. The fibre-only production model in scenario B had a lower carbon footprint than the co-harvested straw when using mass allocation. Using low-carbon electrical power in scenario C modelled a similar facility operating in Manitoba, and it experienced a significant reduction in carbon footprint for all the products. Scenario D has implemented better-quality co-harvested straw and contains 25% more bast fibre and hurd. The carbon footprints of products were lower than the base case, while mass-allocated nonwoven mats experienced a more significant reduction than that allocation by economic value. At last, dust accounts for 30% of the weight of feedstock, and its utilization reduced the footprint of bast fibre and hurd proportionally. However, the market value of dust was close to non without secondary processing and not included in the economic allocation.

4.4 Discussion

4.4.1 Production of hemp straw, bast fibre and hurd

Hemp straw produced in 2022 was included as feedstock for production in 2023, and the results are available in Appendix C. The yield of hempseed and hemp straw fluctuates every year, which influences the footprint of co-harvested straw, as suggested by the previous study in Chapter 3.

Co-harvested hemp straw yield in Canada was compatible with other jurisdictions. The suppliers reportedly baled nearly 1 tonne/ac, approximately 2.2 tonne/ha. Todde [25] reported a similar yield from contaminated soil, while 2600 kg/ha and 5000 kg/ha of co-harvested straw were collected. Other studies have reported a greater yield of 8000-9000 kg/ha [12, 108, 114].

The alternative feedstock dedicated to hemp straw production had comparable output, as suggested by Gonzales-Garcia [20], who reported 3 tonne/ha. Many researchers indicated variation in the fibre-only production of hemp straw. The dry mass of straw ranging from 3245 to 3406 kg/ha was suggested by Jasinskas et al. [112]. In his LCA analysis, Van der Werf [19] modelled with 6720 kg/ha DM. Zampori et al. [21] reported one of the highest yields at 15 tonne/ha producing Carmagnola cultivar. When a greater yield was achieved, it would likely have a lower production footprint per tonne of straw.

Hemp straw comprises three components: bast fibre, hurd, and dust. In general, hemp hurd is the co-product with the greatest proportion produced from the decortication process, followed by bast fibre and dust. The ratio of each fraction investigated in the present study is mentioned in Table 4.1. Compared with similar studies listed in Table 4.9, the current feedstock had inferior quality due to the relatively lower composition of bast fibre and hurd. Most studies assume that bast fibre accounts for 30-33% of straw mass, higher than the 21% recorded in the present study [12, 20, 30, 33, 38, 43]. However, similar yields were recorded, such as the 20% fibre yield assumed by Zampori et al. [21], 22% fibre mentioned by Hansen et al. [41], and 20-25% implemented by Pennacchio et al. [42]. Hemp hurd could represent up to 65-75% of hemp straw, as suggested by Shen et al. [38] and Zampori et al. [10]. Meanwhile, lower hurd composition, about 48-50%, was used by Gonzalez-Garcia et al. [20] and Kiesae et al. [30], which is similar to the present study. LCA studies that collected processing information from hemp processors were more likely to conclude a lower yield of bast fibre and hurd. More studies that implemented data from literature and industry associations were likely to use a more optimistic composition for their calculation. As a result, bast fibre and hurd are likely to have a lower production footprint with a greater share of products and less waste.

Electricity is the primary energy input in the decorticating and mat production process. The separation of hemp straw consumed 326 kWh per tonne of feedstock in the present study. Gonzales-Garcia et al. [20] reported similar energy consumption at 336 kWh per tonne of fibre. While Scrucca et al. [12] and Shen et al. [38] implemented lower electrical energy, with 0.233 kWh per kg of hurd and 1816.43 kWh for 8.44 tonnes of straw. Kiesae et al. [30] and Seile et al. [53] suggested even lower energy requirements at 79, 107, and 112 kWh per tonne of straw. The processing line investigated in the present study was designed to operate at 88.8 kWh per tonne of straw, similar to the most efficient system in other studies.

Table 4.9 Inventory data from LCA studies estimating the production footprint of hemp products

Literature	Allocation method	Hemp straw	Bast fibre	Hurd	Dust	Information source (cultivation)	Information source (processing)
Gonzalez-Garcia et al., 2010 [20]	mass (flax) and economic (hemp)	3 t (11-14% moisture)	1 t	1.5 t	0.5 t	Spanish growers, bibliographic	Van der Werf, 2022
Zampori et al., 2013 [21]	mass and economic	15 t/ha (Carmagnola)	3 t/ha (20%)	11.25 t/ha (75%)	0.75 t/ha (5%)	official Italian association of hemp cultivation	N/A
Scrucca et al., 2020 [12]	mass	8000 kg/ha (9000 kg/ha gross production)	2400 kg/ha	4400 kg/ha	1200 kg/ha	interview with farmers and producers (averaged from 20 main actors of hemp production in France, covering 95% of cultivated surfaces and 95% of produced volumes); InterChanvre, 2017; TerresInovia Institut, 2017	
Pretot et al., 2014 [27]	mass	8 t/ha	0.25	0.6	0.15	French producers	the average value of the three major French producers (LCDA, PDM industrie and Eurochanvre), Boutin et al.,
Arrigoni et al., 2017 [29]	economic	15 t/ha (Carmagnola)	3 t/ha (20%)	11.25 t/ha (75%)	0.75 t/ha (5%)	producer, Zampori et al., 2013, ecoinvent	Zampori et al., 2013, ecoinvent

Sinka et al., 2018 [32]	economic	16500 kg/ha (Bialobrezskie variety)		54% (1.7% fiber, 96.2% shives, 2.2% dust)		Stramkale V., 2012, 2015; Turunen and van der Werf, 2006. hemp growers and processors	producer “z/s Rudeņi”
Heidari et al., 2019 [33]	mass and economic	8000 kg/ha	2745.1 kg/ha	3764.7 kg/ha	1490.2 kg/ha	Van der Werf, 2002	Kiesse et al., 2017
DI CAPUA et al., 2021 [35]	economic for seed and straw, mass for fibre and hurd	8 ton/ha (dried)	2 ton/ha	6 ton/ha		The national hemp association (AssoCanapa)	The national hemp association (AssoCanapa)
Sinka et al., 2022 [37]	N/A	16500 kg/ha (Bialobrezskie variety)		72.5% 1-20 mm, 20.5% 20-40 mm		Sinkaa et al., 2018	Lithuania (Naturalus Plostas)
Shen et al., 2022 [38]	system expansion		30%	65%	5%	Ventura et al., 2015	Norton et al., 2009
Hansen et al., 2016 [41]	system expansion	8 t/ha with 15% moisture	22%	57%		Carus et al., 2014; Bos et al., 2010	Carus et al., 2014
Pennacchio et al., 2017 [42]			20%	75%	5%	industrial partners, ecoinvent	N/A
			20-25%	60-65%	10-20%		AssoCanapa

Kiesae et al., 2017 [30]	mass and economic	7000 (6000-9500) kg/ha straw, 1000 (800-1200) seed	30%	55%	15%	Ventura et al., 2013; Andrianandraina et al., 2015	Van der Werf et al., 1994
		6-8 ton/ha straw, 0.8-1 ton/ha seed	35%	48%	17%		Federation Nationale des Producteurs de Chanvre, France; Boutin et al., 2005; Turunen and van der Werf, 2006
Schulte et al., 2021 [43]	economic	7500 kg/ha (15% moisture)	0.3	0.65	0.05	Beus and Piotrowskim 2017; Beus et al., 2019	Gusovius and Pecenka, 2008
Pervaiz and Sain, 2003 [14]			15-25%, 2.95 t bast and tow fibre 25% yield @ 12% moisture			Ministry of Agriculture and Food, Ontario	N/A
		3-4 tonnes of dry retted straw	1 tonne	2-3 tonne			Ministry of Agriculture and Food, Ontario
Mungkung et al., 2018 [52]	N/A	18750-25000 kg/ha		70% hemp axis		N/A	N/A
Seile et al., 2022 [53]	econmic		38.8-40.4%	51.1-59.7		Barth et al., 2015 (NOVA institut)	Barth and Carus, 2015; Sinka et al., 2018

Gonzalez-Garcia et al., 2010 [54]	economic	3000 kg/ha	1000 kg/ha	1500 kg/ha	500 kg/ha	from grower (González-García et al., 2010), bibliographic, database	The pulp mill provided average annual data from several years. Dones et al., 2007
Vieira et al., 2010 [55]	system expansion	6.72 t/ha	34.30%			van der Werf et al., 2005?	Dutt et al. 2008; Harris et al. 2008
Van der Werf and Turunen, 2008 [56]	economic	6480 kg/ha (8000 kg/ha green stem)	583 kg long fibre, 1490 kg short fibre	2592 kg/ha		previous study HEMP-SYS project, Amaducci 2005; Turunen and van der Werf 2006; van der Werf 2004	previous study HEMP-SYS project, Amaducci 2005; Turunen and van der Werf 2006; van der Werf 2005
		8000 kg/ha green stem	1000 kg long fibre, 1000 kg short fibre, 658 kg long fibre after retting	3600 kg/ha			
		3250 kg/ha retted stem	293 kg long fibre, 748 kg short fibre	1300 kg/ha			
Gonzalez-Garcia et al., 2010 [57]	mass and system expansion	2.6 t/ha (oven dry)	0.33	0.5	0.167	field data, literature	research reports, literature (Aden et al., 2022)
Gonzalez-Garcia et al., 2012 [58]	mass and economic	3000 kg/ha (11-14% moisture)	0.33	0.5	0.167	González-García et al., 2010	González-García et al., 2010

4.4.2 Effect of allocation methods

Allocation is commonly used in LCA studies for manufacturing that produces more than one product [16]. As presented in Table 4.9, mass allocation, economic allocation and system expansion were widely used in LCA studies investigating hemp straw-based products. Some studies have implemented two allocation methods and evaluated the footprint with different priorities. The current research includes mass and economic allocation for processing hemp-based products, following the same allocation methods implemented from feedstock production. As a result, mass allocation distributes the environmental burden toward hemp straw and hurd, which has greater mass but low market value. Economic allocation is heavily affected by price fluctuation, but it can reflect the motivation of farmers and manufacturers. It assigns more footprints to hempseed in the background system and bast fibre in the present study since both have greater market value than their co-products.

4.4.3 Carbon footprint of hemp-based products

It wasn't easy to compare the environmental impacts of hemp products between different studies due to variations in assumptions and LCIA methods. However, GHG emissions are comparable since most studies and LCIA methods refer to IPCC and report in CO_2 eq. The carbon footprint of hemp bast fibre and hurd estimated by other researchers are presented in Table 4.10. The present study showed a similar footprint as suggested by Gonzalez-Garcia et al. and Scrucca et al. [12, 20]. Zampori et al. reported in both mass and economic allocation, where the GHG emissions of bast fibre and hurd had a similar ratio as estimated in the present study [21]. However, the absolute carbon footprint presented by Zampori is significantly lower than that in Table 4.3.

Table 4.10 GHG emissions of bast fibre and hurd estimated by LCA studies (without biogenic carbon)

Literature	**Allocation**	**GHG reported (CO_2 eq)**	**kg CO_2 eq/kg bast fibre converted**	**kg CO_2 eq/kg hemp hurd converted**
Gonzalez-Garcia et al., 2010 [20]	Economic	1600 kg/t	1.6	
Zampori et al., 2013 [21]	Mass	1.17 t woody core, 0.31 t fiber, 0.08 t dust	0.1	0.1
	Economic	0.96 t woody core, 0.61 t fibre, 0 t dust	0.2	0.085
Scrucca et al., 2020 [12]	Mass	0.975 kg/kg hurd (without -1.29 CO2 uptake)		0.975

Major contributors to GHG emissions include the production of hemp straw and electricity used in material processing and non-woven manufacturing. Other studies have highlighted hemp cultivation as the primary source of GHG emissions [12, 20-21], as presented in Table 4.11. Transportation has been mentioned in several studies as a minor GHG contributor, but it depends on feedstock availability and transportation distance. Electricity consumed by the decortication of straw was considered a minor source of GHG emissions by Gonzalez-Garcia et al. [20] and Scrucca et al. [12]. However, transportation and processing contribute a greater footprint, as Zampori et al. suggested [21]. The processing efficiency and carbon intensity of electrical grids significantly influence their contribution to the processing footprint, which was also confirmed by the sensitivity analysis in the present study.

Table 4.11 Contributors of GHG emissions in the production of hemp-based products estimated by LCA studies

Literature	Hemp cultivation	Straw transportation	Straw processing
Gonzalez-Garcia et al., 2010 [20]	~95%	~2%	~3%
Zampori et al., 2013 [21]	0.428 kg CO2 eq/FU	0.131 kg CO2 eq/FU	
Scrucca et al., 2020 [12]	0.951 kg CO2 eq/FU		0.012 kg CO2 eq/FU

Some studies indicated the power consumption of the decortication process, as shown in section 4.4.1. Production of bast fibre and hurd in LCA studies conducted by Gonzalez-Garcia et al. [20] and Scrucca et al. [12] have consumed a similar amount of electricity. However, the proportion of GHG emissions associated with straw processing is low than in the present study, as presented in Table 4.5 and Table 4.6. The difference in the contribution is likely due to the electrical grid mix, where the mentioned studies were conducted in Spain and France. The carbon footprint of electricity is less than 200 g CO_2 eq/kWh in these two countries and 590 g CO_2 eq/kWh in Alberta in 2020 [122-123].

4.4.4 Biogenic carbon

Hemp straw contains a significant amount of carbon that was captured during its growth period. Therefore, many LCA studies have reported that hemp-based products have negative carbon footprints. The carbon footprint of hemp products with 1.63 kg CO_2 equivalent uptake per kg in the present study is presented in Table 4.12. The overall GHG emission of nonwoven mats was mostly positive due to primary and secondary processing that consumed large amounts of electrical energy. The carbon footprint of bast fibre and straw was negative only with economic allocation. However, Zampori et al. [21] reported that fibre and woody cores had a negative carbon footprint with either mass or economic allocation [21]. Scrucca et al. [12] suggested that hemp hurd had a negative carbon footprint with a 1.29 kg CO2 uptake based on mass allocation.

Crop production also helps mitigate climate change by increasing soil organic carbon (SOC). Even though the present study doesn't quantify the influence of SOC, many studies have highlighted its positive impact, especially in organic production. Gomiero et al. [124] found that the increase of SOC in organic systems was significantly higher than in conventional. In the case of a dual-purpose production scenario, 22% of wheat straw removal reduced the C input by 13%, while a significant reduction in soil C wasn't observed. However, removing 50% of straw would likely have a detectable impact on SOC accumulation, and 95% residue removal will decrease SOC substantially [125].

Table 4.12 Carbon footprint of hemp products with biogenic carbon (kg CO2 eq/tonne product)

Allocation methods/products	Mass	Economic
Bast fibre	169.7	-607
Hurd	169.7	-1118.6
300 GSM nonwoven	1045.8	370.9
500 GSM nonwoven	698	-2.9
1000 GSM nonwoven	519.8	-179.2

4.4.5 Effect of variables in the sensitivity analysis

The sensitivity analysis lists several potential production scenarios in the future. Improving efficiency for the decortication process reduces the electricity consumption and the production footprint for both bast fibre and hurd. The increased efficiency could be achieved by using higher-quality feedstock and commissioning the equipment. However, the Government of Alberta is reducing the carbon footprint of its electrical grid [126], and the benefits of increased processing efficiency will diminish.

Processing hemp straw from fibre-only production had mixed outcomes since it only reduced GHG emissions with mass allocation. Co-harvested hempseed and straw had the same footprint, more than 1 kg CO2 eq/kg straw. On the other hand, hempseed has a much greater market value, resulting in a minimal footprint assigned for co-harvested straws. Therefore, the co-harvested hemp straw had a lower carbon footprint than fibre-only hemp while allocated with economic value, resulting in a better environmental burden. Scenario B also partially represents the changes in overall results when the carbon footprint of co-harvested hemp straw was reduced. Except that mass and economic allocation will respond in the same way.

According to the Canada Energy Regulator [123], Alberta's electrical grid comprised 54% natural gas, 36% coal and coke in 2019. Its carbon intensity was much greater than that of a cleaner grid in other provinces in Canada, such as British Columbia, Manitoba, and Quebec. The electrical grid in Manitoba [127] consists of 97% hydro and 3% wind, making its carbon footprint ten times less than in AB. As a result, the GHG emission associated with producing hemp straw fractions and non-woven mats was reduced significantly. And the effect of a cleaner grid is even more significant with economic allocation since electricity surpasses feedstock production, becoming the major contributor to GHG emissions. The carbon footprint of products investigated in the present study will reduce in the future, alongside the government project for a greener electrical source.

Scenario D increased the bast fibre and hurd content in the feedstock while reducing the proportion of waste. The analysis simulated the lower waste content implemented by most LCA studies. The results indicated positive outcomes as the carbon footprint of hemp-based materials decreased proportionally to the composition.

If the hemp straw processor collects and utilizes the dust, it will reduce the footprint of bast fibre and hurd. The effect is greater with mass allocation, as the distributed footprint reduces proportionally with its weight fraction. However, the influence on economic allocation is negligible because the market value of dust is extremely low compared to other coproducts.

Since the sensitivity analysis was conducted with parameters that reflect real-world practices, the changes in each variable were disproportional. The sensitivity to each variable was adjusted to the ratio between changes in GHG emissions of the induced process to the changes in overall carbon footprints. The results are presented in Fig 4.1 and Fig 4.2. Mass-allocated footprints of primary products were more sensitive to the utilization of dust, higher bast fibre and hurd content, and sourcing fibre-only hemp straw. However, secondary products had weaker responses to fibre-only straw but were sensitive to electrical energy with lower carbon intensity. Allocation driven by market value had results sensitive to all variables except the fibre-only straw. Modifications such as utilizing dust and higher bast fibre and hurd content had a greater influence on the overall GHG emissions of hemp-based products than other variables. However, these improvements have lower ceilings and will soon hit the limit. The amount of dust utilized and reduced waste material are limited, which was 30%, as suggested by the present study. Yet the achievable reduction in grid carbon intensity is more than 90%. Thus, GHG emissions reduced by the transition to greener electricity will be the most significant, as presented in Table 4.7 and Table 4.8.

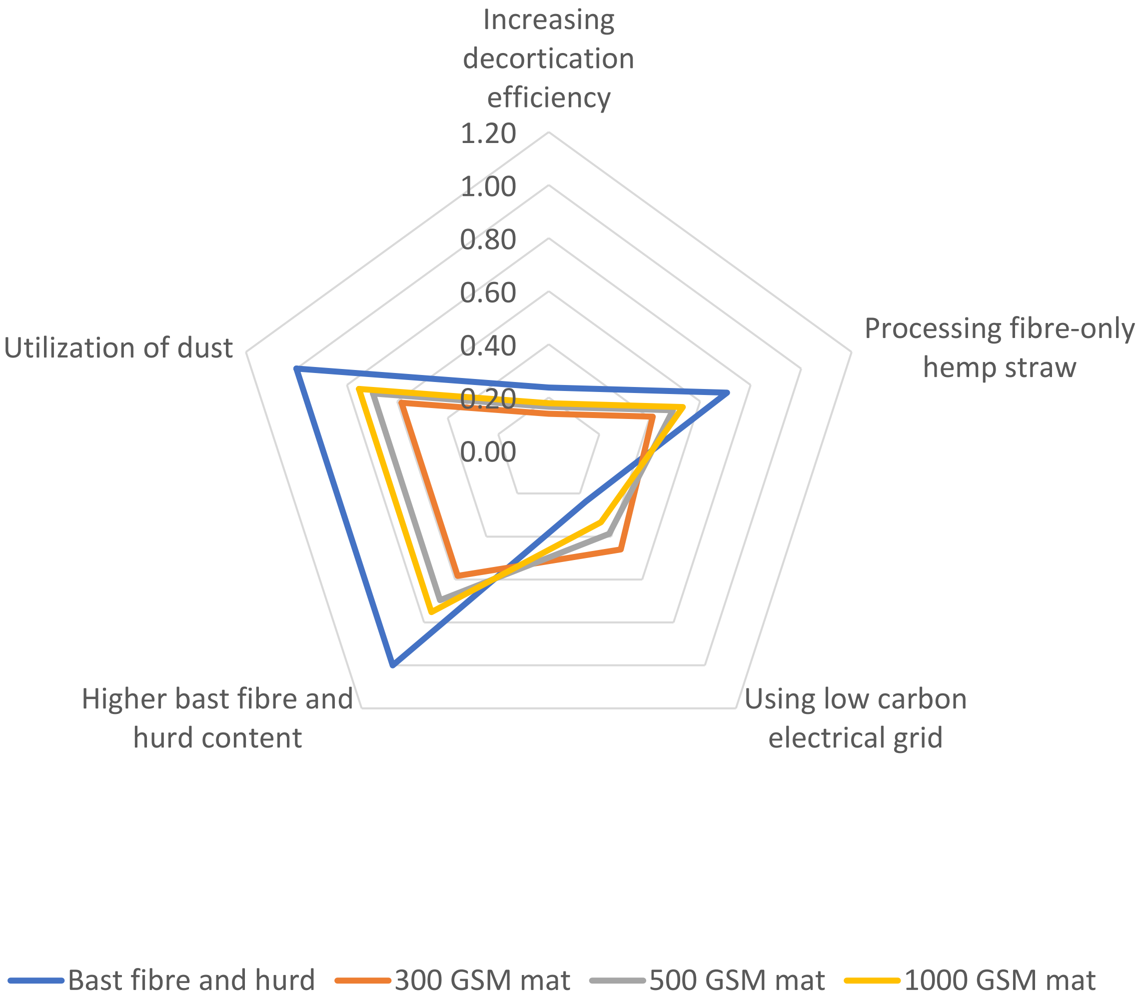

Figure 4.1 Percentage reduction in the carbon footprint of hemp-based products to the percentage change in variables (mass allocation)

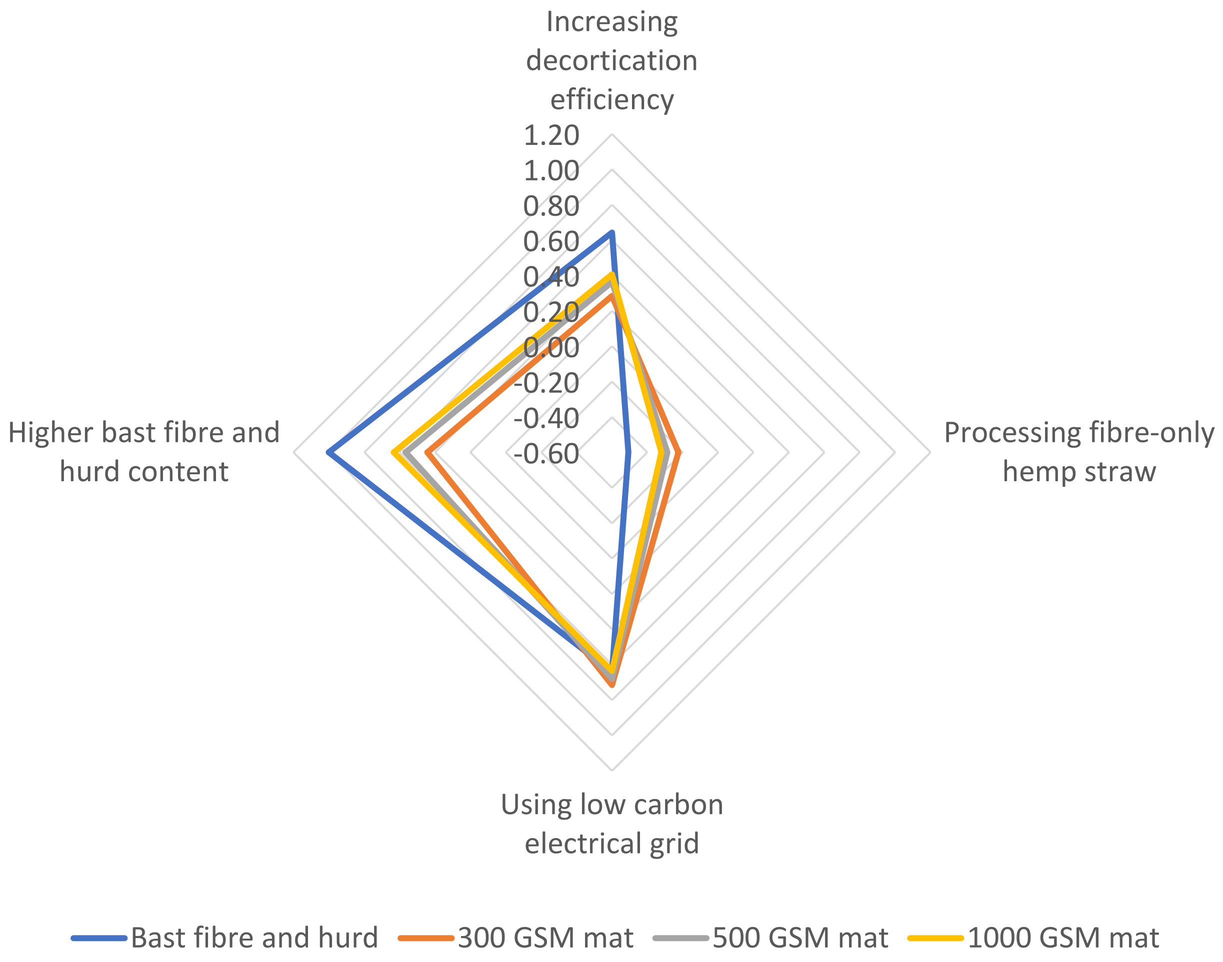

Figure 4.2 Percentage reduction in the carbon footprint of hemp-based products to the percentage change in variables (economic allocation)

4.5 Conclusions

The present study evaluated the environmental impacts associated with the decortication of hemp straw in western Canada and the production of hemp-based nonwoven mats. The investigation covered processes from raw material extraction in the background to producing hemp straw and manufacturing consumer goods.

The results suggest that hemp bast fibre and hurd have a comparable footprint as produced in the EU. Hemp straw production was the major contributor to GHG emissions when allocating the footprint by mass. Electricity consumed during processing was another major contributor to the carbon footprint, accounting for a greater proportion of economic allocation. Various allocation methods have distributed footprints between co-products differently, significantly affecting the results. If biogenic carbon stored in hemp material is accounted for, bast fibre and hurd are seen to have low or negative carbon footprint. At the same time, the GHG emissions associated with nonwoven mats produced was reduced significantly. The overall carbon footprint of hemp-based products is sensitive to the carbon intensity of feedstock and electricity and the proportion of products obtained from the straw. These products have great potential to reduce GHG emissions and contribute to the green economy.

Chapter 5 : Conclusions and future research opportunities

5.1 Summary of key findings

This thesis evaluated the production footprint of hempseed, straw and hemp-based products such as bast fibre, hurd, and nonwoven mats using a life cycle approach. Chapter 3 used information collected from farmer interviews, the NHVFT 2022, and hemp production guides to establish LCA models from the bottom-up and top-down. Three common production systems were compared, including grain-only production of hempseed, fibre-only production of straw, and dual-purpose production of both materials. Other variables include organic production and irrigation. Mass and economic allocation methods were implemented to distribute environmental impacts for the dual-purpose scenarios. As a result, farmer interviews (Approach A) had the lowest average footprint among the three data sources. Targeted nutrient input from Approach B and C overestimated the actual usage and likely resulted in greater production footprints. The greenhouse gas (GHG) emissions from producing hempseed and straw were similar to the reported value from LCA studies conducted in the EU. However, the carbon footprint of hempseed was slightly higher than major oilseeds produced in Canada due to lower average yield per hectare. Organically grown hempseed had slightly lower GHG emissions than conventional production with mineral fertilizer. Irrigation ensures a steady yield but also increases the carbon footprint of hempseed than dryland production. Collecting straw from a grain-only production of hempseed will decrease its footprint, but the impact on nutrient balance wasn’t investigated. Field emission and fertilizer production were the major contributors to GHG emissions, followed by fieldwork. Organic fertilizer had a lower contribution to GHG, but the production system requires more field operations to supply nutrients and control weeds. Field emission in irrigated production took a greater proportion due to enhanced soil microbial activity. Mass allocation distributed a lower footprint to dual-purpose hempseed than grain-only production. Economic allocation distributed less footprint to co-harvested straw, making it lower than fibre-only production. As a results, industrial he can be produced with lower inputs and maintenance. However, hemp farmers invested in fertilizers and appropriate fieldworks to ensure optimum yield, which makes its production align with other cash crops.

The production of bast fibre, hurd and nonwoven mats in Alberta was investigated in Chapter 4. The current manufacturing process used co-harvested hemp straw and had similar GHG emissions to bast fibre and hurd produced in the EU. Allocation methods significantly influenced the production footprint and showed much lower environmental impacts with economic allocation due to lower footprint associated with hemp straw feedstock. Mass allocation is more common, but it didn’t differentiate bast fibre from hurd, and inherited greater footprint from straw production. The production of feedstock and electricity were the major contributors to GHG emissions, and their contribution changes from the primary processing of bast fibre and hurd to the secondary production of nonwoven mats. Multiple alternative input parameters were selected to reduce the carbon footprint of hemp straw derived products, such as using low-carbon electrical energy, sourcing high-quality feedstock with higher content of bast fibre and hurd, increasing production efficiency with less downtime, and utilizing dust. All changes have successfully reduced GHG emissions, except one. Using straw from the fibre-only production system had mixed outcomes, as it had a lower footprint than co-harvested straw when allocated by mass but had a higher footprint if economic allocation is the preferred method. A large amount of biogenic carbon is stored in bast fibre and hurd, which could lower the carbon footprint to negative numbers.

Based on this research's findings, the environmental impacts of producing hempseed and straw in the prairies and other locations in Canada were assessed. Researchers who investigate the environmental footprints of industrial hemp and its primary products such as hempseed, straw (including bast fibre and hurd) could implement life cycle inventory (LCI) and life cycle impact assessment (LCIA) results from Chapters 3 and 4 for further analysis. Farmers who produce hemp under similar environmental conditions and production practices mentioned in Chapter 3 could expect similar footprints and hotspots in their production system. Manufacturers who process hemp straw into secondary products could benefit from Chapter 4, which identifies major contributors to GHG emissions and mitigation practices. Consumers who interested in the production of industrial hemp will get a holistic view of the Canadian hemp industry and how it's been produced alongside other crops. The results inform hemp growers, product manufacturers, and potential customers that hemp could contribute to the green economy and help mitigate climate change.

5.2 Novelty of work and future research opportunities

The present study filled the data gap in the Canadian hemp industry regarding its various production scenarios and coverage from coast to coast. Many researchers have investigated hemp produced in the EU, focusing on using bast fibre and hurd. The present work has evaluated hempseed produced in Canada with different practices alongside hemp straw. The advantage of various approaches to the same objective is that the influence of several parameters was evaluated, including differences in the data source, production system, locations, and result allocation. It is contrary to most LCA studies which had limited variability.

The sensitivity analysis conducted in Chapters 3 and 4 provides additional variables and the influence on overall results. Parameters were selected to simulate feasible strategies hemp growers and manufacturers can adopt. Changes with more significant benefits were identified to help in decision-making.

Finally, there are a number of potential research opportunities that can extend this work:

- Investigating hemp production in Canada in the longer term (since agricultural outputs can vary year to year) and covering more producers. It will provide a more accurate evaluation and identify differences among various practices and regions.
- Measuring and tracking nutrient content in manure and green manure can provide LCIA results with better accuracy. Since hemp farmers usually take what is available in their local area and does not have access to precise nutrient content as artificial fertilizers.
- Quantifying carbon and nitrogen content of hemp biomass and root system. There is a lack of hemp-specific information in general and dedicated to Canadian hemp.
- Evaluating the nutrient returned to soil with and without hemp straw being harvested and removed from the production system. Some farmers don't harvest hemp straw by prioritizing soil health and nutrients.
- Measuring root biomass of various hemp cultivars and observing the relationship between aboveground and belowground biomass. Grain-type cultivars like Finola had lower heights and produced less biomass. Other dual-type cultivars might produce a higher quantity of biomass and a greater root system.

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Appendix A

Table A-1 Hemp and hemp-based products evaluated by LCA studies (n=56)

Application/processing level	Primary	Secondary	Service	End of life
Cultivation	6	2		
Hempcrete		16		
Insulation mat		5		
Reinforced plastic		12		
Pulp & paper		2		
Textile		1		
Bioenergy (biomass)		5	2	
Bioenergy (hempseed)			1	
Food		2		
Feed		1		
End of life				1

Table A-2 Scope and life cycle stages of hemp LCA studies (n=56)

Application/scope	Cradle to gate	Cradle to use	Cradle to grave	End of life
Cultivation	8			
Hempcrete	9	4	3	
Insulation mat	3		2	
Reinforced plastic	5		7	
Pulp & paper	2			
Textile	1			
Bioenergy (biomass)	2		5	
Bioenergy (hempseed)			1	
Food	2			
Feed	1			
End of life				1

Table A-3 Source of hemp production information from previous LCA studies (n=51)

Application/source of LCI data	Original	Cultivation studies	Previous LCA studies	Combined	Database	N/A
Cultivation	5	2				1
Hempcrete	3	1	7	4	1	
Insulation mat	1	1	1			
Reinforced plastic	1	1	3	2	1	3
Pulp & paper		1	1			
Textile			1			
Bioenergy (biomass)	1	2	1	2		
Bioenergy (hempseed)	1					
Food		1				
Feed		1				
End of life						1

Table A-4 Meta data of hemp LCA (n=56)

Category	**Reference**	**Functional unit**	**System boundary**	**Location of hemp production**	**Data source of hemp production**	**LCIA method**
Cultivation	[19]	per ha	cradle to gate	France	Van der Werf, 2002	literature (Guinee et al., 2002; Huijbregts, 1999), IPCC
	[20]	1 ton of fibre ready to be processed in a pulp mill	cradle to gate	Spain	spanish growers, bibliographic	CML baseline 2000
	[21]	1 ha hemp	cradle to gate	Italy	official Italian association of hemp cultivation	GGP, CED, Ecoindicator 99 H
	[22]	production and harvesting of 1 kilogram (kg) of hemp straw	cradle to gate	France	French national hemp producer federation (FNPC, 2005)	CML 2001, CED, ILCD
	[23]	Reclaim 1 ha of degraded land, produce biomass equivalent	cradle to gate	Homecourt (France)	N/A	IPCC 2013 GWP 100, CED
	[12]	1 kg hurds	cradle to gate	France	interview with farmers and producers; InterChanvre, 2017; TerresInovia Institut, 2017	IPCC 2013 GWP 100, CED
	[24]	1 kg of seeds produced	cradle to gate	Italy, Mediterranean environment	Campiglia et al., 2017	ReCiPe 2016 (22 mid-point, 3 end-point)

Table A-4 cont. Meta data of hemp LCA (n=56)

Category	**Reference**	**Functional unit**	**System boundary**	**Location of hemp production**	**Data source of hemp production**	**LCIA method**
Cultivation	[25]	1 kg of dry matter industrial hemp product (kg DM hempseed/hemp straw) and 1 ha of phytoremediated area	cradle to grave	Italy	collected under the "CANOPAES" project at two experimental sites	CED, IPCC
Hempcrete	[13]	a 1 m × 1 × 0.3 m (thick) vertical hemp–lime wall and has a density of 275 kg/m3	cradle to gate	UK	hemp growers and manufacturers, Van der Werf 2004, ecoinvent	IPCC
	[26]	1 m2 exterior wall, with U value – 0.18 W/M2k, and life cycle is set to 60 years	cradle to gate	UK	ICE 2011 and literature	Inventory of Carbon and EnergyV2.0 (ICE 2011)
	[27]	per square meter, with heat transfer coefficient to 0.36 W/m2/K, and 100 years of lifespan	cradle to grave	France	French producers	N/A
	[28]	prototype building with HL walls, simulated residential unit is 110 m2 in floor area, and a 50-year life-cycle period	cradle to use	France, UK	Israeli Ministry of Energy and Water Resources, ecoinvent, Ip and Miller, 2012; Zampori et al., 2013	N/A

Table A-4 cont. Meta data of hemp LCA (n=56)

Category	Reference	Functional unit	System boundary	Location of hemp production	Data source of hemp production	LCIA method
Hempcrete	[29]	one square meter of non-load-bearing wall made of hempcrete blocks. With heat transfer coefficient (U-value) of 0.27 W/(m2*K)	cradle to use	Italy	producer, Zampori et al., 2013, ecoinvent	CML-IA Baseline (version 3.04), CED, version 1.09, GGP, version 1.02
	[30]	1 m2 of hemp concrete with a thermal resistance 2.36Km2/Wand 50 years duration, 1 m2 of insulating board with a thermal resistance of 2.44Km2/W and 100 years duration	cradle to gate	France	Ventura et al., 2013; Andrianandraina et al., 2015	CML 2001, Cumulative Energy Demand (CED)
	[31]	magnesium-hemp construction panel with U value – 0.18 W/m2K.	cradle to gate	Latvia	literature, local cultivator enterprises	IPCC 100a
	[32]	1 m2 of wall	cradle to gate	Latvia	Stramkale V., 2012, 2015; Turunen and van der Werf, 2006. hemp growers and processors	CML 2

Table A-4 cont. Meta data of hemp LCA (n=56)

Category	Reference	Functional unit	System boundary	Location of hemp production	Data source of hemp production	LCIA method
Hempcrete	[33]	1 kg of hemp shiv and sol-gel coating material produced. per one squaremeter of insulation wall with a U-value of 0.15 W/m2K for one year of its service life	cradle to grave	France	Van der Werf, 2002	ReCiPe 2016 midpoint and endpoint (H), CML-IA baseline, IMPACT 2002+ method
	[34]	1 m2 of non-load bearing insulation made with hempcrete cast on-site between temporary formwork, heat transfer coefficient of 0.27 W/(m2K)(R-20).	cradle to gate + use	Italy	Zampori et al., 2013	NUFCCC
	[35]	one m2 of wall	cradle to gate	North of Italy	The national hemp association (AssoCanapa)	Ecoindicator 99; CED, IPCC
	[36]	1 kg of material	Gate to gate	N/A	KBOB database	NRE, CED, GWE
	[37]	1 m2 of wall with a U-value of 0.180 or 0.105 W/m2*K	Gate to gate	Lithuania	Sinkaa et al., 2018	GWP 100a

Table A-4 cont. Meta data of hemp LCA (n=56)

Category	**Reference**	**Functional unit**	**System boundary**	**Location of hemp production**	**Data source of hemp production**	**LCIA method**
Hempcrete	[38]	Annual management of 1 ha of representative CV (carbon-vulnerable) land, used to produce hempcrete (as insulation)	cradle to grave	France	Ventura et al., 2015	Environmental Footprint v2.0 life cycle impact assessment method
	[39]	A prototypical single-family one-story house, made with a different uniform envelope (walls and ceiling)	cradle to use	N/A	Ip and Miller, 2012; Zampori et al., 2013; Florentin et al., 2017	N/A
	[40]	1 m2 of a wall, with an overall heat transfer coefficient equal to 0.19 W/m2*K	cradle to gate	UK	Ip and Miller, 2012	N/A
Insulation mat	[21]	1 m2 of hemp mat to be inserted in a wall having a thermal transmittance (U) equal to 0.2 W/m2-K.	cradle to gate	Italy	official Italian association of hemp cultivation	GGP, CED

Table A-4 cont. Meta data of hemp LCA (n=56)

Category	**Reference**	**Functional unit**	**System boundary**	**Location of hemp production**	**Data source of hemp production**	**LCIA method**
Insulation mat	[41]	one square meter of insulation material (A = 1 m2) with the specific heat transfer coefficient U = 0.2W / m2K	cradle to grave	Germany	Carus et al., 2014; Bos et al., 2010	IPCC
	[42]	1 kg of product, thermal resistance of 2.5 m2k/W, for m2 of surface	cradle to gate	Italy	industrial partners, ecoinvent	Cumulative Energy Demand (CED)
	[30]	1 m2 of hemp concrete with a thermal resistance 2.36Km2/Wand 50 years duration, 1 m2 of insulating board with a thermal resistance of 2.44Km2/W and 100 years duration	cradle to gate	France	Ventura et al., 2013; Andrianandraina et al., 2015	CML 2001, Cumulative Energy Demand (CED)
	[43]	Insulating 1 m2 of external wall of a residential building with 0.24W/M2K for 70 years	cradle to grave	Central Europe	Beus and Piotrowskim 2017; Beus et al., 2019	ReCiPe

Table A-4 cont. Meta data of hemp LCA (n=56)

Category	**Reference**	**Functional unit**	**System boundary**	**Location of hemp production**	**Data source of hemp production**	**LCIA method**
Reinforced plastic	[44]	a side panel of the AUDI A3	cradle to gate	Baden-Wu¨rttemberg (South-West-Germany)	not specified	Eco-indicator 95, UBA, CED
	[14]	one metric ton of hemp-based thermoplastic (65% fiber content)	cradle to grave	Canada	Ministry of Agriculture and Food, Ontario	N/A
	[45]	a body component casing the middle section between the head lights above the fender of a MAN-passenger-bus of the series A10/A11 with the MAN-reference number 81.79.201-6017	cradle to grave	Germany	TLL, 2003; Stolzenburg, 2001	Ecoindicator 99, CED
	[46]	A composite panel made of plant-based epoxy resin and hemp fibre, production of 1kg of glass-fibres and 1 kg of hemp mat	cradle to grave	UK	not specified	N/A

Table A-4 cont. Meta data of hemp LCA (n=56)

Category	Reference	Functional unit	System boundary	Location of hemp production	Data source of hemp production	LCIA method
Reinforced plastic	[47]	the function of one elbow fitting used in the sea water cooling pipeline of a Sicilian chemical plant, with an estimated life of 20 years.	cradle to grave	UK	González-García et al., 2010	ReCipe Endpoint, IPCC, CED
	[48]	An eco-sandwich panel sized (0.400*0.400*0.02 m)	cradle to gate	UK	González-García et al., 2010; La Rosa et al., 2013	CML 2000 v2.0/West Europe
	[49]	(300mmX300mm X15mm) of material, 40:60 fiber to polymer ratios. a beam with a uniform load of 0.0024 MPa, span length of 305mm, width of 100mm, and a variable depth calculated based on an allowable deflection of span length/360 ("l/360")	cradle to grave	China	Struik, 2000; Karus and Vogt, 2004; van der Werf, 2004; Turunen and van der Werf, 2006	IPCC, Eco-Indicator 99, BEES

Table A-4 cont. Meta data of hemp LCA (n=56)

Category	**Reference**	**Functional unit**	**System boundary**	**Location of hemp production**	**Data source of hemp production**	**LCIA method**
Reinforced plastic	[50]	1 kg of chemically treated hemp fibre that will be subsequently used for reinforcing polymers (PLA and PP).	Cradle to gate	Canada	Alberta Hemp Growers Association, González-García et al., 2010	ReCipe Endpoint (H)
	[51]	1 kg part	cradle to grave	N/A	MBase database	TRACI
	[52]	a Hempstone sheet (W 0.82 x L 3.04 x H 0.012 m)	cradle to gate	Thailand	not specified	ReCiPe
	[53]	A 1000*500 mm large composite with ultimate tensile stress of 18.24 Mpa or thickness of 4.5 mm	cradle to gate	Zemgale region, Lativa	Barth et al., 2015 (NOVA institut)	CML 2 baseline
	[38]	Annual management of 1 ha of representative CV (carbon-vulnerable) land, used to produce car panel structures	cradle to grave	France	Ventura et al., 2015	Environmental Footprint v2.0 life cycle impact assessment method

Table A-4 cont. Meta data of hemp LCA (n=56)

Category	**Reference**	**Functional unit**	**System boundary**	**Location of hemp production**	**Data source of hemp production**	**LCIA method**
Pulp & paper	[54]	1 tonne of non-wood paper pulp (90% air dried) from Hemp (Cannabis sativa, 50%) and Flax (Linumusitatissimum, 50%) fibres	cradle to gate	Spain	from grower (González-García et al., 2010), bibliographic, database	CML 2 baseline 2000 V2.1 method
	[55]	1 t of white printing and writing paper produced from Kraft pulp.	cradle to gate	Portugal	van der Werf et al., 2005	IPCC, literature
Textile	[56]	per 100 kg of yarn of a metric count number (Nm) of 26 (a g of 26Nmyarn is 26mlong)	cradle to gate	Hungary, Italy	previous study HEMP-SYS project, Amaducci 2005; Turunen and van der Werf 2006; van der Werf 2004	IPCC
Bioenergy (hempseed)	[62]	consumption of 44.80 L of diesel oil or 47.04 L of bio-diesel in an 18 ton PMA rubbish collection lorry in an urban circuit of 50 km	cradle to grave	Spain	local data, personal interview, literature	N/A

Table A-4 cont. Meta data of hemp LCA (n=56)

Category	Reference	Functional unit	System boundary	Location of hemp production	Data source of hemp production	LCIA method
Bioenergy (biomass)	[57]	1 km distance driven by a FFV	cradle to grave	Spain	field data, literature	CML
	[58]	distance travelled by vehicles with the vehicle tank full of CG, If 36 kg of CG fills up the tank of an FFV, it drives for 545 km. Driving this distance with E10 and E85 would require about 37.6 kg and 50.2 kg, respectively.	cradle to grave	Spain	González-García et al., 2010	CML
	[59]	kW h net energy content in processed fuels (pellets ready for use in boilers)	cradle to grave	Ireland	Crowley, 2001; Finnan and Burke, 2013; Institut Technique du Chanvre, 2007	IPCC 2007
	[60]	1 hectare over a time period of 1 year	cradle to gate	Ireland	nitrogen response trials in Ireland in 2008, 2009, 2010	IPCC 2006
	[15]	1 GJ of upgraded and pressurised biogas	cradle to gate	southern Sweden	Gissen et al., 2014	IPCC
	[61]	1 ha of arable land	cradle to gate/grave	Germany	lab results, personal information, literature, GaBi 6	TRACI, ReCiPe 2008

Table A-4 cont. Meta data of hemp LCA (n=56)

Category	Reference	Functional unit	System boundary	Location of hemp production	Data source of hemp production	LCIA method
Bioenergy (biomass)	[25]	1 kg of dry matter industrial hemp product and 1 ha of phytoremediated area	cradle to grave	Italy	collected under the "CANOPAES" project at two experimental sites	IPCC 2014, CED
Food	[63]	1 m3 of food oil; area unit (land demand for generating the same yield of food oil)	cradle to gate	Czech Republic	Field investigation and Outlook Report on oil crops prepared by the Ministry of Agriculture of the Czech Republic	ReCiPe Midpoint, Hierarchical (H) perspective V1.13/Europe Recipe H
	[38]	Annual management of 1 ha of representative CV (carbon-vulnerable) land, used to extract hemp oil	cradle to gate	France	Ventura et al., 2015	Environmental Footprint v2.0 life cycle impact assessment method
Feed	[64]	1 kg of fat and protein corrected milk (FPCM), 1 m2 of UAL	cradle to gate	Italy	Baldini et al., 2018; Amaducci et al., 2008, Amaducci et al., 2015	CML-IA baseline V3.05, IPCC
End of life	[18]	disposal kg of biorefinery feedstock	end of life	N/A	Cultivation not included	N/A

Appendix B

Primary data collection questionnaire

Table B-1. Farm inputs information

Farm information							
	Unit		**Area**	**Soil structure**	**Shape**	**Location**	**Comments**
Hemp field							
Farming inputs							
Irrigation	**Unit (volume/area)**		**Volume**	**Source (waterbody)**	**Supplier**	**Transportation**	**Comments**
Seeding	**Unit (mass/area)**		**Mass**	**Seed variety**	**Supplier**	**Transportation**	**Comments**
Inorganic Fertilizers							
Nutrients	**Unit (mass/area)**		**Mass**	**Variety**	**Supplier**	**Transportation**	**Comments**
N							
P							
K							
S							
Organic Fertilizers (estimation)							
Nutrients	**Unit (mass/area)**		**Mass**	**Variety**	**Supplier**	**Transportation**	**Comments**

To add							
Chemicals							
Type	**Unit (mass/area)**		**Mass**	**Variety**	**Supplier**	**Transportation**	**Comments**
Herbicide							
Lime							
To add							

Table B-2. Field operations information – Soil preparation

Unit Process	**# of repetition**	**Equipment**	**Implementation**	**Comments**
1.1 Harrowing				
1.2 Disking				
1.3 Vertical tillage				
1.4 Herbicide application				
1.5 Fertilization				
1.6 Manure application				
1.7 Lime application				
1.8 Mulching				
To add (as required)				

Table B-3. Field operations information – Seeding

Unit Process	# of repetition	Equipment	Implementation	Comments
2.1 Seeding/Seed drilling				
2.2 Fertilization				
2.3 Transplanting seedlings				
To add (as required)				

Table B-4. Field operations information – Crop management

Unit Process	# of repetition	Equipment	Implementation	Comments
3.1 Pesticide application				
3.2 Fertilization				
3.3 Irrigation/fertigation				
To add (as required)				

Table B-5. Field operations information – Harvesting

Unit Process	# of repetition	Equipment	Implementation	Comments
4.1 Swathing				
4.2 Combining				
4.3 Burning				
4.4 Stalk cutting				
4.5 Retting				
4.6 Tedding				
4.7 Raking				
4.8 Baling				
4.9 Harrowing				
4.10 Bud cutting/stripping				
4.11 Whole plant cutting				
To add (as required)				

Table B-6. Field operations information – Post-harvest processing

Unit Process	# of repetition	Equipment	Implementation	Comments
5.1 Bale collecting				
5.2 Transportation (in farm)				
5.3 Grain cleaning (pre-screening)				
5.4 Grain drying/storage				
5.5 Retting (other methods)				
5.6 Bud drying/curing				
To add (as required)				

Table B-7. Farm outputs information

Material	Unit (mass/area)		Mass	Buyer/location	Transportation	Comments
Stalk						
Hempseed						
Hemp chaff						

Methods to calculate N_2O emissions

Emissions associated with direct and indirect N_2O emissions from agricultural soil were calculated using NIR 2022 report section A3.4.5 equations [1]. The current work assumes no topological differences exist among hemp fields, and the area under the lower section of the toposequence is zero. Therefore, the base N_2O emission factor (EF_Base) equation A 3.4-12 becomes:

$$EF\_Base_i = EF\_CT_{i,P} * RF\_TX_i$$

Hemp produced annually in crop rotation was investigated in this study. Therefore, the perennial crop was excluded, and the ratio factor for the cropping system between annual and perennial crops was eliminated from the equation A3.4-14 when calculating emissions associated with organic N fertilizers:

$$N_2O_{ON} = \sum[F_{ON(i,m)} * (EF\_Base_i * RF\_NSE * RF\_NS_{k=ON,m})] * 44/28$$

The same changes also applied to the equation A3.4-17 for emissions associated with inorganic N fertilizers:

$$N_2O_{SFN} = \sum[F_{FERT(i,m)} * (EF\_Base_i * RF\_NSE * RF\_NS_{k=IN,m})] * 44/28$$

The ratio factor was removed from equation A3.4-22 for emissions associated with crop residue decomposition:

$$N_2O_{CRN} = \sum[F_{CR(i,m)} * (EF\_Base_i * RF\_NSE * RF\_NS_{k=CN,m})] * 44/28$$

Meanwhile, $F_{ON(i,m)}$, $F_{FERT(i,m)}$, and $F_{CR(i,m)}$ no longer represent the source of N in an ecodistrict. It was replaced by actual N input from LCI data and calculation.

To estimate the crop residue N returned to the soil during the production of hemp, equations A3.4-23 and A3.4-24 were adopted:

$$F_{CR(i,m)} = P_{H,i} * (R_{AG,H} * N_{AG,H} + R_{BG,H} * N_{BG,H})$$

$$P_{H,I} = P_{H,p} * (1-H_2O_H)$$

Hemp is the only crop under investigation in the present study, represented by H. However, industrial hemp has significant variation regarding the ratio between hempseed and straw. For scenarios that prioritize hempseed production, $R_{AG,H}$ represents "overall available hemp straw/harvested hempseed" and could be derived from the Harvest Index (HI) of specific hemp cultivar:

$R_{AG,H} = (1-HI_H) / HI_H$

$R_{BG,H}$ was estimated based on the ratio between aboveground and belowground biomass of 5.46, suggested by Amaducci et al., [2]:

$R_{BG,H} = R_{AG,H} / 5.46$

The default water content of hempseed was 9% and 15% for hemp straw in long-term storage, according to the cultivation guide published by the Government of Alberta [3].

Another equation adapted for the field production of hemp was A3.4-28. All parameters associated with ecodistrict were replaced by input dedicated to hemp production at the individual farm. No-till and reduced tillage are common practices in the prairies [4], and the fraction of land on conservational tillage is one since it applied to the entire field:

$N_2O_{TILL} = \sum[(N_2O_{k=IN,m=A,i} + N_2O_{k=ON,m=A,i} + N_2O_{k=CN,m=A,i}) * (RF\_Till_z – 1)]$

A similar change was also applied to equation A3.4-29, where the ratio factor for irrigation is 1 for irrigated hemp field:

$N_2O_{IRRI} = \sum(N_2O_{k,i}) * (RF_{IRRI,i} – 1)$

Changes were made to equations calculating emissions associated with indirect N_2O emissions. Since the production of field crop doesn't involves manure N deposited on pasture, range, and paddock. It was removed from equation A3.4-31:

$N_2O_{VD} = \sum[(N_{FERT,TN,i} * FRAC_{GASF\ NT,i}) + (F_{ON,i} * FRAC_{GASM,i})] * EF_4 * 44/28$

The same change was applied to equation A3.4-33 to remove urine and dung deposited N from field crop production:

$N_2O_L = \sum[(N_{FERT,i} + N_{MAN\text{-}CROPS,i} + N_{RES,i}) * FRAC_{LEACH,i} * EF_5] * 44/28$

Other equations implemented from section A3.4.5 remain unchanged.

Crop burning is rarely utilized by Canadian farmers nowadays [1]. However, a few hemp producers still use this practice because large amounts of hemp straw residue can be problematic. To calculate CH4 and N2O emissions from field burning of agricultural residues, equations from section A3.4.7. were implemented. The percentage of crop residue subject to burning was 100% for farmers who burnt leftover hemp straw:

$$Q_{BURN} = (PRODUCTION_H * (1 - MOISTURE_H) * RatioAR/P_H * RATIO_{SCALE})$$

The intensity factor and fuel efficiency of wheat were used in the calculation due to the lack of hemp-specific data.

Liming is a common practice in hemp production in the EU, as suggested by number of LCA studies [5, 6]. However, limestone application isn't common in the Canadian hemp industry, especially in the prairies. The emission associated with liming and urea fertilization were calculated according to equations from sector A3.4.8.

Table B-8 Harvesting Index of 12 industrial hemp cultivars at Vegreville, AB [7]

Variety	**Harvest Index**
Canda	0.23
CFX-1	0.36
CFX-2	0.35
CRS-1	0.24
Delores	0.22
Finola	0.36
Grandi	0.35
Joey	0.21
Katani	0.35
Picolo	0.28
Silesia	0.17
X59	0.37

Environmental information used in LCA modelling

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Table B-9 Economic value of hempseed and straw

Products	Market price range	Value used in calculation
Conventional hempseed	0.68-0.96 C$/lb	0.9 C$/lb
Organic hempseed	1.5-2.03 C$/lb	1.9 C$/lb
Hemp straw	74-100 C$/tonne	100 C$/tonne

Table B-10 Integrated LCIA results from Approach A (without allocation)

Production scenario	Grain-only	Dual-purpose	Dryland	Irrigated	Conventional	Organic
Ozone formation, Human health (kg NO_x eq)	4.47E-03	4.26E-03	4.85E-03	3.53E-03	4.56E-03	3.96E-03
Mineral resource scarcity (kg Cu eq)	1.09E-02	1.32E-02	1.68E-02	4.37E-03	1.71E-02	2.44E-03
Human carcinogenic toxicity (kg 1,4-DCB)	7.64E-02	8.95E-02	9.73E-02	6.05E-02	1.01E-01	4.91E-02
Terrestrial acidification (kg SO_2 eq)	3.52E-02	4.16E-02	3.83E-02	3.95E-02	4.19E-02	3.24E-02
Terrestrial ecotoxicity (kg 1,4-DCB)	6.02E+00	5.54E+00	7.93E+00	2.05E+00	7.81E+00	1.64E+00
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	4.69E-03	4.47E-03	5.10E-03	3.65E-03	4.79E-03	4.12E-03
Water consumption (m^3)	4.04E-01	8.72E-01	2.32E-02	1.75E+00	4.33E-01	1.13E+00
Land use (m^2a crop eq)	1.45E+01	1.30E+01	1.74E+01	7.32E+00	1.47E+01	1.15E+01
Marine ecotoxicity (kg 1,4-DCB)	1.13E-01	1.27E-01	1.41E-01	8.68E-02	1.53E-01	5.77E-02
Marine eutrophication (kg N eq)	3.06E-03	2.76E-03	3.50E-03	1.86E-03	3.11E-03	2.44E-03
Freshwater eutrophication (kg P eq)	2.19E-03	1.30E-03	2.13E-03	9.45E-04	1.98E-03	1.12E-03
Stratospheric ozone depletion (kg CFC11 eq)	1.69E-05	2.35E-05	1.77E-05	2.54E-05	1.99E-05	2.19E-05
Freshwater ecotoxicity (kg 1,4-DCB)	8.80E-02	1.01E-01	1.10E-01	7.05E-02	1.19E-01	4.73E-02
Human non-carcinogenic toxicity (kg 1,4-DCB)	1.95E+00	1.60E+00	2.27E+00	8.86E-01	2.17E+00	9.18E-01
Global warming (kg CO_2 eq)	1.34E+00	1.63E+00	1.56E+00	1.39E+00	1.61E+00	1.27E+00
Ionizing radiation (kBq Co-60 eq)	3.00E-02	3.25E-02	3.89E-02	1.86E-02	3.77E-02	1.89E-02
Fine particulate matter formation (kg PM2.5 eq)	5.41E-03	6.29E-03	6.02E-03	5.69E-03	6.42E-03	4.87E-03
Fossil resource scarcity (kg oil eq)	2.12E-01	2.89E-01	3.08E-01	1.64E-01	3.23E-01	1.18E-01

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Appendix C

Table C-1 LCIA results of 1 tonne nonwoven mats

Allocation methods	MA			EA		
Nonwoven mats	300 GSM	500 GSM	1000 GSM	300 GSM	500 GSM	1000 GSM
Ozone formation, Human health (kg NO_x eq)	6.10E+00	5.48E+00	5.10E+00	4.36E+00	3.68E+00	3.16E+00
Mineral resource scarcity (kg Cu eq)	2.34E+01	2.23E+01	2.05E+01	9.94E+00	8.33E+00	5.47E+00
Human carcinogenic toxicity (kg 1,4-DCB)	2.68E+02	2.28E+02	1.96E+02	2.08E+02	1.65E+02	1.29E+02
Terrestrial acidification (kg SO_2 eq)	2.29E+01	2.23E+01	2.27E+01	8.99E+00	7.83E+00	7.18E+00
Terrestrial ecotoxicity (kg 1,4-DCB)	1.46E+04	1.42E+04	1.36E+04	6.89E+03	6.17E+03	4.95E+03
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	6.29E+00	5.66E+00	5.28E+00	4.43E+00	3.74E+00	3.21E+00
Water consumption (m^3)	2.34E+02	2.34E+02	2.35E+02	6.90E+01	6.21E+01	5.08E+01
Land use (m^2a crop eq)	8.85E+03	9.15E+03	9.75E+03	1.58E+03	1.60E+03	1.66E+03
Marine ecotoxicity (kg 1,4-DCB)	3.65E+02	3.23E+02	2.92E+02	2.39E+02	1.92E+02	1.51E+02
Marine eutrophication (kg N eq)	2.13E+00	2.17E+00	2.30E+00	4.94E-01	4.69E-01	4.73E-01
Freshwater eutrophication (kg P eq)	2.38E+00	1.85E+00	1.65E+00	2.41E+00	1.88E+00	1.69E+00
Stratospheric ozone depletion (kg CFC11 eq)	1.24E-02	1.27E-02	1.36E-02	2.58E-03	2.53E-03	2.61E-03
Freshwater ecotoxicity (kg 1,4-DCB)	2.76E+02	2.44E+02	2.21E+02	1.80E+02	1.45E+02	1.15E+02
Human non-carcinogenic toxicity (kg 1,4-DCB)	5.82E+03	5.16E+03	4.50E+03	3.74E+03	3.00E+03	2.18E+03
Global warming (kg CO_2 eq)	2.67E+03	2.33E+03	2.19E+03	2.00E+03	1.63E+03	1.44E+03
Ionizing radiation (kBq Co-60 eq)	6.27E+02	4.80E+02	1.95E+02	6.03E+02	4.55E+02	1.68E+02
Fine particulate matter formation (kg PM2.5 eq)	5.11E+00	4.75E+00	4.57E+00	2.78E+00	2.33E+00	1.98E+00
Fossil resource scarcity (kg oil eq)	6.62E+02	5.67E+02	5.28E+02	5.33E+02	4.33E+02	3.85E+02

Table C-2 LCIA results of co-harvested hemp straw feedstock (1 tonne) produced in 2021 and 2022

Allocation methods	Mass allocation		Economic allocation	
Year of production	2021	2022	2021	2022
Ozone formation, Human health (kg NO_x eq)	2.23E+00	2.29E+00	2.42E-01	1.95E-01
Mineral resource scarcity (kg Cu eq)	1.32E+01	1.39E+01	1.43E+00	1.18E+00
Human carcinogenic toxicity (kg 1,4-DCB)	7.68E+01	8.14E+01	8.32E+00	6.92E+00
Terrestrial acidification (kg SO_2 eq)	1.42E+01	1.13E+01	1.56E+00	9.60E-01
Terrestrial ecotoxicity (kg 1,4-DCB)	8.13E+03	8.53E+03	8.78E+02	7.25E+02
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	2.34E+00	2.41E+00	2.55E-01	2.05E-01
Water consumption (m^3)	1.62E+02	1.55E+02	1.84E+01	1.33E+01
Land use (m^2a crop eq)	7.03E+03	7.32E+03	7.62E+02	6.22E+02
Marine ecotoxicity (kg 1,4-DCB)	1.41E+02	1.49E+02	1.52E+01	1.26E+01
Marine eutrophication (kg N eq)	1.60E+00	1.62E+00	1.74E-01	1.38E-01
Freshwater eutrophication (kg P eq)	2.68E-01	2.83E-01	2.90E-02	2.41E-02
Stratospheric ozone depletion (kg CFC11 eq)	9.58E-03	1.00E-02	1.04E-03	8.55E-04
Freshwater ecotoxicity (kg 1,4-DCB)	1.07E+02	1.13E+02	1.16E+01	9.61E+00
Human non-carcinogenic toxicity (kg 1,4-DCB)	2.26E+03	2.38E+03	2.44E+02	2.02E+02
Global warming (kg CO_2 eq)	8.88E+02	8.89E+02	9.63E+01	7.57E+01
Ionizing radiation (kBq Co-60 eq)	2.52E+01	2.67E+01	2.73E+00	2.27E+00
Fine particulate matter formation (kg PM2.5 eq)	2.51E+00	2.18E+00	2.74E-01	1.86E-01
Fossil resource scarcity (kg oil eq)	1.91E+02	1.86E+02	2.08E+01	1.58E+01