ABSTRACT

JASHI, NAZIA AFRIN. From Farm to Fiber: Evaluating the Environmental Performance of U.S. Hemp Cultivation Biomass for Packaging and Textile Applications (Under the direction of Dr. Lokendra Pal).

Industrial hemp (*Cannabis sativa L.*) is emerging as a sustainable crop in the United State due to its rapid growth, multipurpose applications, and potential to support circular bioeconomy systems. It produces valuable feedstocks including whole stems, bast fibers, hurds, dust particles, seeds, and extractives, that can be utilized in textiles, biocomposites, coatings, pulp and paper, construction materials, and other applications. As interest grows in leveraging hemp for sustainable materials, evaluating its environmental impact across its entire life cycle has become essential. Life Cycle Assessment (LCA) is a key tool for quantifying these impacts from farm to fiber. However, most existing hemp LCA studies are based on non-U.S. agronomic practices and often overlook whole-plant hemp systems or scenario-based variability. This research addresses these gaps by presenting a U.S.-based LCA of hemp biomass and its coproducts, incorporating scenario analysis to assess how agronomic practices, processing methods, and end-use applications influence environmental performance.

A comprehensive evaluation of the environmental performance of hemp-based products including bast fibers, hurds and dust, was conducted using an LCA framework that accounts for allocation methods, cultivation practices, fertilizer use, transportation, and yield variability. The results show that allocation choice strongly influences perceived impacts: under mass allocation, global warming potential (GWP) is distributed evenly among coproducts (~402 kg CO_2-eq per metric ton (MT)), whereas economic allocation concentrates emissions on high-value bast fibers (~1024 kg CO_2-eq per MT), with much lower burdens assigned to hemp hurd (~66 kg CO_2-eq per MT) and dust particles (~58 kg CO_2-eq per MT). Fertilizer use, particularly ammonium nitrate, was

identified as the primary emission source. Optimization can reduce GWP by ~5%, whereas excessive application increases emissions by ~10%. Sensitivity analysis demonstrates that transportation distance and crop yield significantly affect per-unit emissions: higher yields offset fixed environmental inputs, reducing GWP, whereas longer transport distances marginally increase emissions. Economic allocation also shifts GWP based on market value, emphasizing the need for transparent allocation methods in LCA.

Retted biomass shows a net carbon footprint of −330 MT CO_2-eq per hectare over 25 years. Comparative evaluation against cotton and wood chips confirms hemp's environmental advantages, with net carbon sequestration of −61 MT CO_2-eq per hectare over 25 years for bast fiber and −189 MT CO_2-eq per hectare over 25 years for hemp hurds, surpassing conventional alternatives. This trend aligns with the quantified GWP data: cotton lint and cotton yarn generate 2,036 kg CO_2-eq per MT and 8,600 kg CO_2-eq per MT, respectively, whereas bast fiber after decortication and bast fiber yarn emit only 402 kg CO_2-eq per MT and 5,200 kg CO_2-eq per MT, respectively. Thus, bast fiber yarn production has approximately 40% lower GWP compared to cotton yarn.

Hemp hurd, under economic allocation, exhibits a GWP of ~66 kg CO_2-eq per MT, compared with ~74 kg CO_2-eq per MT for wood chips. For retted biomass, the North Carolina Mountain Research Station (NCRS)-Synthetic Fertilizer (SF) scenario results in ~152 kgCO_2-eq per MT, with the lowest impacts observed in the NCRS- Without Fertilizer (WF) scenario (~47 kg CO_2-eq per MT) and the highest in the Mountain (SF) scenario (~583 kg CO_2-eq per MT). After fiber processing, coproducts (hemp hurd, bast fiber, dust) produced under organic fertilizer (OF) and fertilizer-free systems achieved a 45–50% reductions in GWP. Under varying allocation approaches, bast fiber recorded GWP values between ~631–2038 kg CO_2-eq per MT, hemp hurd between ~41–131 kg

CO_2-eq per MT, and dust between ~36–116 kg CO_2-eq per MT. These results indicate that without synthetic fertilizer, the GWP of hemp hurd (~41 kg CO_2-eq per MT) is 45% lower than that of wood chips (74 kg CO_2-eq per MT).

In summary, this study demonstrates that industrial hemp offers substantial environmental advantages over traditional raw materials such as cotton and wood. Across multiple scenarios and allocation methods, hemp-based products show lower greenhouse gas emissions, strong carbon-sequestration capacity, and improved sustainability performance when optimized cultivation practices, particularly reduced synthetic fertilizer use, are implemented. Sensitivity analyses reveal that fertilizer intensity, yield variability, allocation choice, and transportation distance are key drivers of GWP impacts, with organic and fertilizer-free systems reducing GWP by up to 50%. Bast fiber yarn exhibits approximately ~40% lower GWP than cotton yarn, and hemp hurd outperforms wood chips under reduced-input conditions. Collectively, these results position industrial hemp as a climate-positive, low-impact bioresource with strong potential to support sustainable textile, packaging, construction, and advanced biomaterials industries.

While environmental assessments provide critical insights, the commercial viability of hemp-based materials must also be evaluated through techno-economic analysis (TEA). Future research should examine the cost-effectiveness of hemp production systems by assessing input costs, processing technology requirements, product pricing, and supply chain logistics. Policy tools such as carbon credits, renewable material incentives, green procurement standards, and farm subsidies should also be evaluated for their potential to support broader adoption. Integrating LCA with TEA and policy modeling will enable holistic evaluations that align environmental benefits with economic feasibility and regulatory pathways, supporting the transition toward sustainable material systems at scale.

From Farm to Fiber: Evaluating the Environmental Performance of U.S. Hemp Cultivation Biomass for Packaging and Textile Applications

by
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DEDICATION

I dedicate this thesis to my beloved parents, whose unwavering support, unconditional love, and constant encouragement have been the foundation of my academic and personal journey. I am also thankful to Dr. Lokendra Pal for providing me with this opportunity to work with the Department of Forest Biomaterials.

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CHAPTER 1

Introduction and Objectives

1.1. Introduction

To meet the fast-growing demand for paper packaging to take place of plastic in the consumer market, driven by industrialization, population growth and urbanization, there is a need for paper with versatile characteristics designed for specific functions such as packaging and hygiene products [1] . This has led pulp and paper industry to carefully consider the selection of the best renewable natural fibers, focusing not only on the final applications but also on social, economic, and environmental aspects [2]. Wood, non-wood, and recycled fibers are the best renewable natural fibers [3], [4].

Even though the ecological impacts of wood cultivation in forestry management are lower than those of most non-wood biomass, due to long-term CO_2 sequestration over time, most non-wood biomass consists of agricultural residues incorporated into waste minimization practices, which help balance net carbon dioxide emissions [5],[6]. Hardwood and softwood are the primary wood types used in the pulp and paper industry, each offering distinct fiber characteristics that influence pulp properties and final product performance [7].

Softwood provides long fibers (2.5–4.5 mm) that contribute high strength, making it ideal for packaging and reinforcing papers, while hardwood offers short fibers (0.7–1.5 mm) that enhance smoothness and printability, used in printing, writing, and coated papers. Despite these benefits, wood-based pulping has significant environmental impacts due to the intensive use of chemicals, high energy, and water consumption, as well as GWP [2]. On average, the U.S. pulp and paper industry generates its steam and power using approximately 44% black liquor, around 20% waste wood, and about 36% fossil fuels, which include natural gas (24%), coal (6%), and other sources (6%) [8], [2]. To reduce this impact, the industry is adopting sustainable forestry, increased use of sustainable fibers, recycled fibers, cleaner technologies, and renewable energy sources.

The use of non-wood biomass, often blended with wood, is increasingly being considered as an alternative fiber source to mitigate environmental challenges. This approach ensures the production of high-yield cellulose for versatile papermaking applications while maximizing the utilization of agro-residues [9]. Globally, approximately 90% of raw material for papermaking originates from wood chips, while non-wood raw material accounts for less than 10% of total pulp and paper production. These non-wood sources consist of 44% straw, 18% bagasse, 14% reeds, 13% bamboo, and 11% other materials, including hemp and cotton, which contribute less than 2%, primarily for specialty and archival papers [10].

The limited use of hemp in modern papermaking contrasts with its long-standing history as one of the earliest cultivated fiber crops. Hemp (*Cannabis sativa* L.), originally native to the Himalayas, spread to India and East Asia during the Neolithic period, with China being the earliest center of cultivation [11]. In the U.S., hemp was grown as early as the 1600s for rope, sails, and textiles but was later restricted under the Marihuana Tax Act of 1937 and then fully banned under the Controlled Substances Act of 1970 [12]. It was reintroduced and legalized as an agricultural commodity under the 2018 Federal Farm Bill [13]. Hemp containing less than 0.3% or 0.2% Δ9-THC is classified as nonpsychoactive, greatly increasing farmers' interest in its cultivation [14].

By 2024, the U.S. became a major player in global hemp production, with approximately 78,176 acres cultivated across all 50 states. Production parameters, such as final yield, fertilizer use, and land management, vary regionally. Hemp has recently gained renewed attention as a sustainable alternative to wood chips and cotton fibers, with the aim of reducing chemical use and promoting resource efficiency [15].

On the other hand, cotton cultivation poses significant environmental challenges due to high water consumption, pollution, soil degradation, GWP, and heavy use of pesticides and fertilizers. Cotton accounts for approximately 6% of global pesticide use and 16% of all insecticides, the highest of any crop [16]. About 53% of global cotton fields are irrigated, primarily using low-efficiency flood or furrow systems, which improve yields but contribute to soil salinization [17]. Bast fiber crops such as hemp have gained popularity as sustainable alternatives to cotton, whereas utilizing hemp hurds as a raw material for the paper industry is of increasing importance [18].

Hemp is valued for its multiple components including bast fibers, hurds, grain, and flowers, which can be used in textiles, bio composites, insulation, construction materials, bedding, and paper production [19], [20]. Hemp grain is widely used for human consumption and animal feed in the form of edible seeds and hemp oil [21]. These diverse applications have made hemp attractive to farmers, and cultivation methods, especially field inputs, directly influence environmental performance. As a cover crop, hemp can contribute to biodiversity conservation and soil improvement. Unlike conventional crops such as cotton and corn, hemp generally requires fewer pesticides, herbicides, and synthetic fertilizers. Its dense canopy suppresses weeds naturally, while irrigation improves soil organic matter[22].

The growing importance of hemp cultivation has increased awareness of the environmental impacts associated with agricultural inputs, particularly concerning GWP. The agricultural sector contributes nearly 23% of global anthropogenic GWP, primarily due to fertilizer use, land-use changes, soil degradation, and livestock emissions [23] Increasing global temperatures, changing rainfall patterns, and more frequent extreme weather events are posing serious threats to agricultural yields, food security, and the stability of ecosystems [24].

As a result, multipurpose crops such as hemp are increasingly recognized as key components of climate-resilient agriculture, owing to their low input requirements, ability to remediate contaminated soils, and strong carbon sequestration potential. Hemp biomass can sequester approximately 1.63–1.8 tons of CO_2-eq per ton of dry hemp produced [25]. Producing 1 kg of hemp hurd results in a net CO_2 uptake of –1.29 kg CO_2-eq, with a total carbon footprint of 0.975 kg CO_2-eq, of which 0.69 kg CO_2-eq originates from fertilizer use [26]. Another study reported that one hectare of hemp production generated a GWP of 2,330 kg CO_2-eq [27], while the production of 1 kg of bast fiber emitted 7.634 kg CO_2-eq [28]. Hemp's ability to store carbon in soil through residual biomass left after harvest has been estimated at approximately –2.7 kg CO_2-eq per hectare per year, resulting in a net carbon impact of around –0.27 kg CO_2-eq per hectare per year [29].

GWP for hemp cultivation varies widely depending on field inputs, processing infrastructure, and regional conditions. Previous studies show that producing 1 ton of bast fiber can generate 1,600 kg CO_2-eq in emissions [30]. Such variations arise from differences in fertilizer use, soil type, climate, and cultivation practices, all of which are considered in the present study through multiple regional scenarios.

This study aimed to assess the environmental performance of hemp production within a circular bioeconomy framework through a regionalized LCA across various U.S. regions (mountain, coastal, inland), using the North Carolina mountain region as a baseline. By benchmarking hemp against conventional raw materials like cotton and wood chips, this work seeks to identify the conditions under which hemp can serve as a sustainable, low-emission alternative in the textile and paper industries. The overarching goal is to inform assessments of hemp production as a low-impact, renewable resource that supports climate mitigation and sustainable material transitions, taking into account region-specific conditions, fertilizer inputs, and allocation methods.

1.2. Current Practices of Biomass Cultivation in the U.S.

Biomass cultivation in the United States is a cornerstone of the emerging bioeconomy, leveraging a diverse array of feedstocks including forest residues, fast-growing short-rotation woody crops such as poplar and willow, agricultural byproducts like sugarcane bagasse and cotton stalks, as well as innovative crops like industrial hemp to sustainably supply raw materials for bioenergy, bioproducts, and industrial applications [31], [32]. The U.S. policy framework, anchored by the Renewable Fuel Standard (RFS) and the 2018 Farm Bill, has supported biomass expansion, particularly in biofuel and fiber markets. As of 2022, total biomass feedstock use in the U.S. was approximately 342 million dry tons**,** comprising 144 million tons of forest and woody biomass**,** 162 million tons of agricultural biomass, and thirty-seven million tons from waste biomass (**Figure 1.1**) [33], [34].

In terms of GWP, agricultural activities (crop and livestock production) contributed about 9.4% of total U.S. GWP in 2022, driven by emissions from cropland soils, livestock, and fertilizer use. LCAs of woody biomass for electricity generation report GWP in the range of 0.124–0.143 kg CO_2-eq per kWh, depending on factors like feedstock type (pulpwood vs. residues) and transportation distance [35]. Despite this large biomass production base, economic, logistical, and regulatory barriers still limit the full utilization of these resources. As environmental pressures and sustainability targets mount, interest in diversified and low-carbon biomass systems continues to increase.

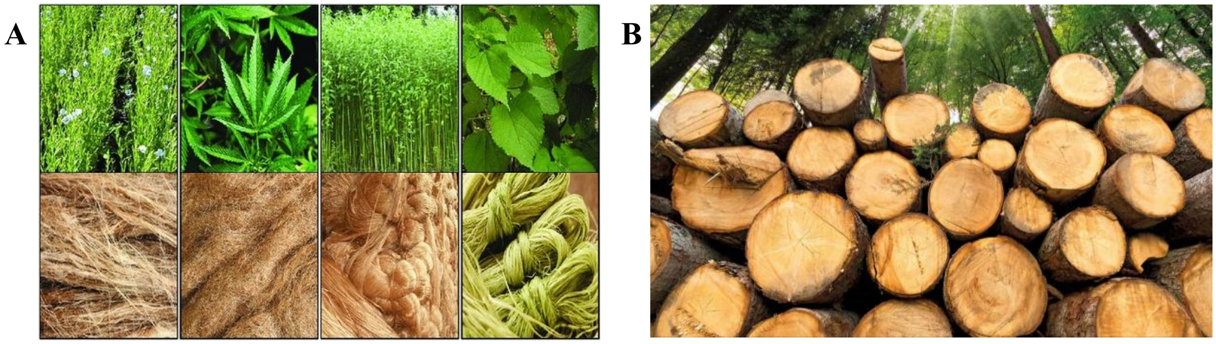

Figure 1.1: Diverse types of (A) non-wood biomasses and extracted fibers in the U.S. and (B) woody biomasses [36].

1.3. Introducing Hemp Cultivation in the U.S.

European settlers brought hemp to the U.S. in the early 1600s, cultivating it for its strong fiber, which was essential for producing ropes, sails, and fabrics. Recognizing its economic value, the Virginia Assembly enacted legislation in 1619 mandating that farmers grow hemp [37]. By the 18th and 19th centuries, hemp became a key cash crop in states such as Kentucky and Missouri, with influential figures like George Washington and Thomas Jefferson promoting its cultivation [38].

In the early 1900s, hemp lost its prominence due to the rise of cotton and synthetic fibers, alongside increasing legal restrictions associated with psychoactive cannabis. Although hemp contains very low levels of THC, the Marihuana Tax Act of 1937 imposed strict limitations on its cultivation [39]. During World War II, the U.S. government temporarily revived hemp cultivation through the "Hemp for Victory" campaign to meet military material demands. After the war, production declined again until widespread legalization and renewed interest returned in the 21st century with the 2018 Farm Bill [40], [41].

1.4. Hemp Compared to Other Biomass Feedstocks

Hemp crops stand out among biomass feedstocks such as cotton and wood chips due to their rapid growth, sustainability, and multipurpose utility. Unlike cotton, which primarily produces fiber for textiles but requires high water usage and extensive pesticide application, hemp is more environmentally friendly, needing less water and fewer chemicals, resulting in a smaller ecological footprint [37]. Additionally, hemp produces both strong bast fibers and woody core hemp hurds, making it more versatile than cotton, which only yields soft textile fibers.

Compared to wood chips, a traditional biomass source for paper, bioenergy, and composites, hemp grows far more quickly, maturing in 3 to 4 months rather than decades. This allows for rapid biomass turnover and more frequent harvests [41] While wood chips generally have higher lignin content suitable for certain industrial processes, hemp's lower lignin and higher cellulose content make it easier to process for paper and textile applications with less chemical input [42]. Furthermore, hemp grows quickly and produces versatile fibers, offering environmental benefits such as minimizing soil erosion and enhancing nutrient cycling, which makes it an excellent sustainable alternative or supplement to cotton and wood chips. Such positive effects on soil health are less frequently observed in traditional cotton cultivation or tree farming.

1.5. Multi-Dimensional Benefits of Hemp

1.5.1. Environmental Applications

Hemp is recognized as a multipurpose plant for its agronomic, environmental, industrial, and economic benefits. It contributes to soil health through its low input cultivation and its role as a high-yielding-cover crop. When used in crop rotation with other agricultural plants, hemp improves soil structure, enhances long-term productivity and organic matter, reduces erosion, decreases the need for synthetic agricultural chemicals, and increases biodiversity [43]. Hemp also suppresses weeds, requires minimal pesticide use, and improves soil conditions, making it a valuable energy crop [44], [45]. Additionally, hemp is used for land reclamation due to its high fiber yield and deep root system, which enhances soil structure and aids in contaminant removal, particularly heavy metals, making it a strong candidate for phytoremediation (**Figure 1.2**) [46]. As a carbon sink, hemp is highly efficient, with capable of absorbing up to −22 ton CO_2-eq per hectare per year [47].

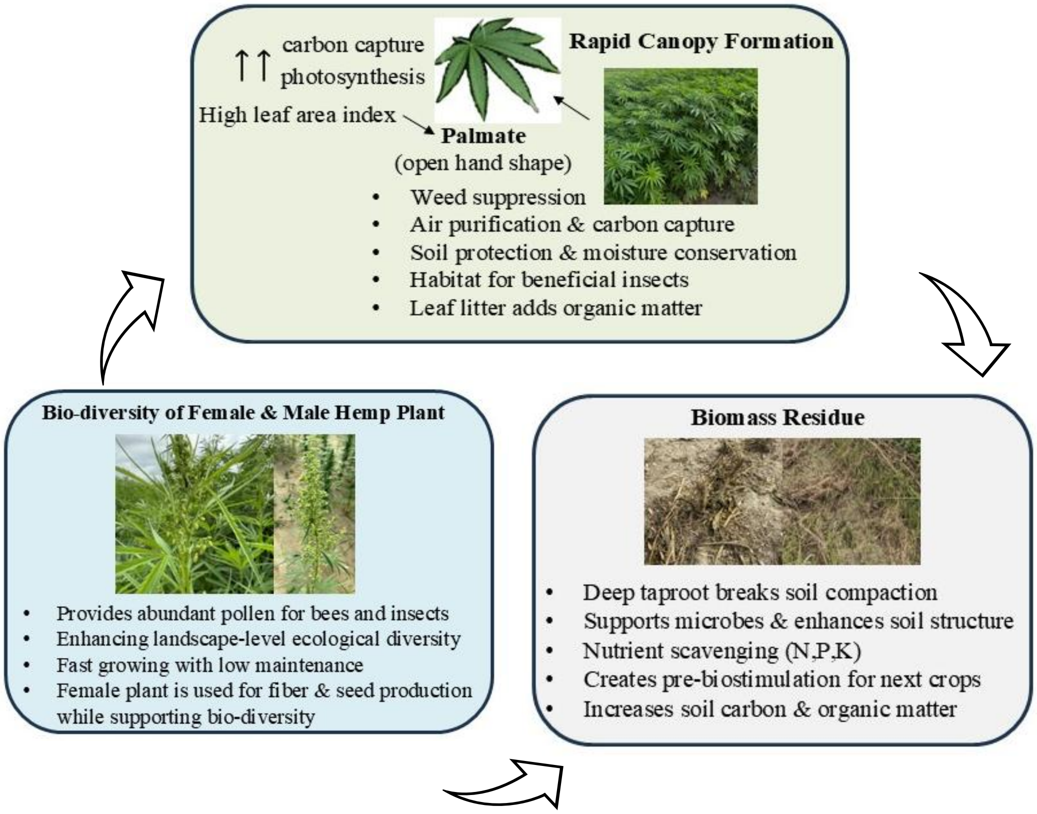

Figure 1.2: Environmental benefits of hemp as a cover crop, including rapid canopy formation, increased biodiversity, and the addition of biomass residues that enhance soil carbon and organic matter.

1.5.2. Textiles and Fashion

Hemp has gained significant attention in the textile industry as a sustainable alternative to cotton. Hemp fibers are stronger than natural fibers such as cotton, flax, and nettle, and their cultivation has a lower environmental impact [48]. To enhance textile applications, emphasis has been placed on optimizing bast fiber extraction and retting methods to soften fibers and improve drape, enabling cotton-like performance[49]. Hemp bast fiber is useful for its favorable properties needed for fabrics like thermal comfort, biodegradable, antimicrobial activity, UV-protection, making it suitable for clothing, bags, ropes, and home furnishings [50], [51]. Considering its lower environmental footprint and favorable LCA outcomes, hemp is an increasingly viable alternative for sustainable textiles.

1.5.3. Pulp and Paper Industry

Hemp hurd, the woody core of the hemp stalk, is emerging as a promising alternative feedstock in the production of pulp and paper, contains approximately 40–48% cellulose and only 21–24% lignin, compared to softwoods that contain about 40–45% cellulose and 26–34% lignin [52], [53]. Lower lignin content in hemp means reduced chemical and energy needed for the pulping and bleaching, reducing both environmental impacts and production costs [54].

Hemp also matures rapidly within 4–5 months, compared to 15–30 years for trees such as pine or spruce, reducing land use pressures [55]. In terms of yield, one acre of hemp can produce as much usable fiber annually as four acres of trees [26], [55]. Hemp pulp has a lower carbon footprint than wood pulp and hemp-based products are durable and strong to develop lightweight packaging products (**Figure 1.3**). From environmental and economic perspectives, hemp hurd offers a sustainable, circular alternative to forest-based resources in the paper sector.

Figure 1.3: Applications of hemp in the global market and its use in textile and paper industry [56], [57].

1.6. Sustainability

The increasing demand for raw materials, driven by rapid population growth and technological advancement, has placed significant pressure on global ecosystems and resource availability. As a result, attention has shifted toward alternative materials aligned with principles of sustainable development. Hemp (*Cannabis sativa L.*), a historically cultivated crop, is re-emerging as a potential solution due to its ecological, economic, and social benefits.

The concept of sustainability, while widely accepted, remains broad and open to varied interpretations. Originating from the United Nations World Commission on Environment and Development's 1987 report *Our Common Future*, sustainable development is defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). Within this framework, hemp offers a practical pathway toward sustainability because of its low environmental impact, strong capacity for carbon sequestration, rapid growth, and wide range of industrial applications. However, like sustainability itself, hemp's overall impact depends on policy, infrastructure, and socio-economic systems. Although often cited as a “sustainable” material, its scalability and global integration must be critically examined through comprehensive tools such as LCA and the United Nations Sustainable Development Goals (SDGs). Without systemic change, no single material including hemp can independently address the challenges of unsustainable development without systemic change [58].

1.7. “Triple Bottom Line” Approach to Sustainability

The “Triple Bottom Line” (TBL) approach to sustainability, introduced by John Elkington in 1994, emphasizes the interconnected performance of three key pillars: people (social)**,** planet (environmental)**,** and profit (economic). This framework encourages industries to evaluate success not solely by financial gains but also by their environmental and social impacts (**Figure 1.4**).

Within this context, hemp (*Cannabis sativa L.*) exemplifies a material that strongly supports the environmental pillar of the TBL model. Hemp cultivation requires significantly less water, pesticides, and synthetic fertilizers than traditional crops such as cotton, thereby reducing water pollution and soil degradation. Its fast growth cycle, high biomass yield, and biodegradability position hemp as a valuable renewable resource for industries seeking to minimize ecological footprints and transition to circular systems. In applications such as construction (e.g., hempcrete), textiles, and bioplastics, hemp-based products not only reduce dependency on fossil fuels and non-renewable materials but also contribute to a circular economy aligned with environmental sustainability objectives.

Figure 1.4: Triple bottom line and seventeen goals of sustainable development.

1.8. Introduction to Life Cycle Assessment (LCA) in Agriculture

Life Cycle Assessment (LCA) is a standardized methodological framework used to evaluate the environmental impacts associated with all stages of a product's life, from raw material extraction through production, use, and end-of-life disposal. In agriculture, LCA serves as a critical decision-support tool to identify environmental hotspots, improve resource efficiency, and guide sustainable farming practices.

Principles and ISO Standards

LCA is governed by international standards set by the International Organization for Standardization (ISO), specifically ISO 14040 and ISO 14044, which outline the principles, framework, requirements, and methodological guidelines to ensure consistency and transparency across studies [59]. According to ISO 14040, the LCA framework comprises four main phases (**Figure 1.5**):

1. **Goal and Scope Definition**: Defines the purpose of the study, the functional unit, system boundaries, and assumptions. For agricultural systems, boundaries may include stages such as land use, input production (fertilizers, seeds), field operations, and post-harvest activities.

2. **Life Cycle Inventory (LCI)**: Involves collecting quantitative data on inputs like water, energy, fertilizers, etc., and outputs like emissions, waste, etc. associated with the system. It provides the raw data necessary for impact assessment.
3. **Life Cycle Impact Assessment (LCIA)**: Translates inventory data into potential environmental impacts such as global warming potential (GWP), eutrophication, acidification, and land use. Characterization factors and models are used to quantify these impacts.
4. **Interpretation/ Improvement Analysis**: Evaluates results in relation to study goals, identifies key issues, assesses data quality, and provides conclusions and recommendations.

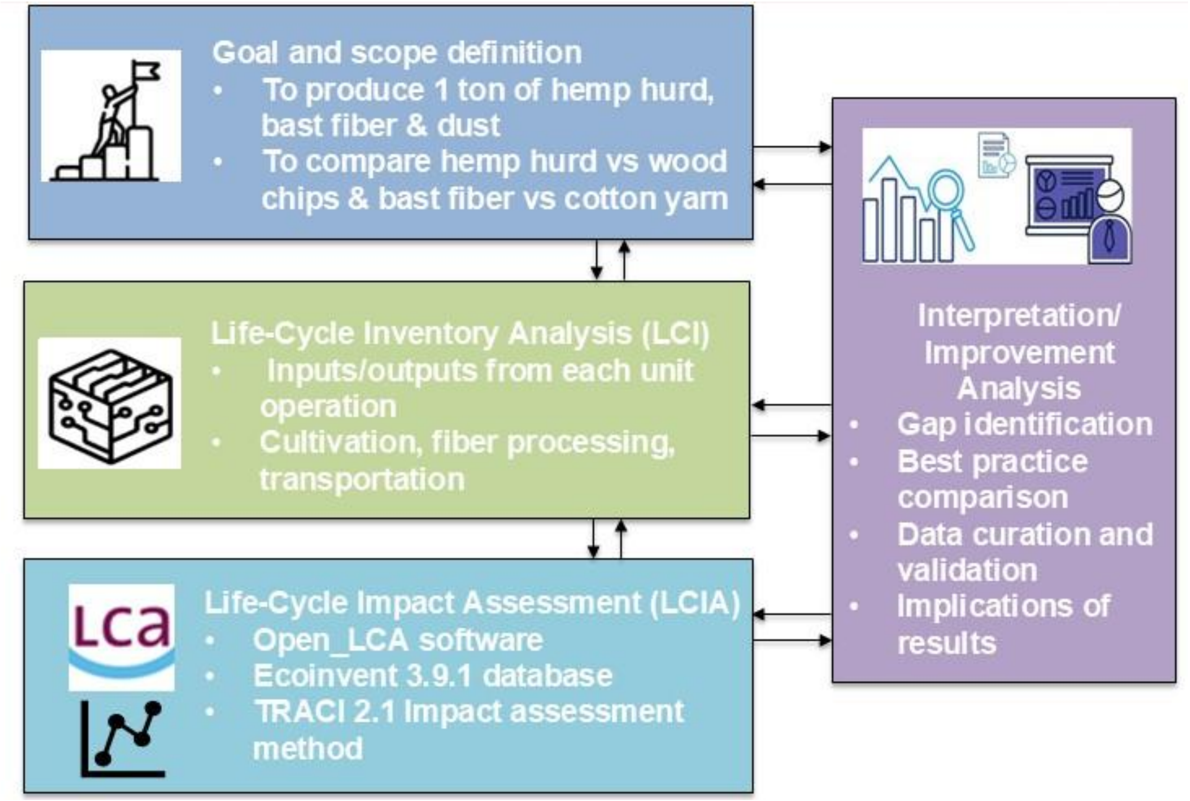

Figure 1.5: LCA framework (ISO 14040) showing goal and scope definition, LCI, LCIA, interpretation/ improvement analysis.

1.9. Environmental Impact Category

TRACI 2.1 impact assessment method quantifies emissions across ten different impact categories. Definition of each category, as outlined by the United States Environmental Protection Agency (EPA), are provided below.

Acidification: Acidification refers to the increase of acidic compounds in soil and water due to emissions like SO_2 and NO_x. This process lowers pH levels, harming ecosystems, damaging vegetation, impairing aquatic life, and corroding infrastructure. Major sources include power plants, vehicle emissions, and industrial processes.

Carcinogenic: Carcinogenic impacts measure the potential of chemical substances to increase cancer risk in humans. Exposure can occur through air, water, or food, with pollutants accumulating in tissues over time. This impact category indicates long-term human health risks.

Ecotoxicity: Ecotoxicity assesses the harmful effects of chemicals on terrestrial and aquatic organisms. It considers toxicity, persistence, and bioaccumulation of pollutants. Heavy metals, pesticides, and industrial effluents are common contributors.

Eutrophication: Eutrophication is nutrient enrichment, nitrogen and phosphorus in water bodies. Excessive nutrient loading leads to algal blooms, oxygen depletion, and ecosystem imbalance. Agricultural runoff and wastewater discharge are major drivers.

Fossil Fuel Depletion: This impact category measures the consumption of non-renewable fossil energy sources such as oil, coal and natural gas. Depletion affects energy security and increases environmental burdens from extraction. It is commonly expressed in MJ or kg of fuel equivalents.

Global Warming Potential: Global warming potential refers to the increase in average atmospheric temperatures due to greenhouse gas (GHG) emissions. Impacts include climate change effects such as sea-level rise, extreme weather, and ecosystem shifts. This category is typically expressed in CO_2-equivalents.

Non-carcinogenic: Noncarcinogenic impacts evaluate toxic effects that do not involve cancer, such as organ damage or developmental issues. Exposure can occur through inhalation, ingestion, or dermal contact. Heavy metals and solvents are common contributors.

Ozone Depletion: Ozone depletion measures the reduction of stratospheric ozone caused mainly by chlorofluorocarbons (CFCs) and halons. A depleted ozone layer increases harmful UV radiation reaching Earth's surface. Impacts are expressed in CFC-11 equivalents.

Respiratory Effects: This category evaluates pollutants that adversely affect the human respiratory system. Particulate matter, ozone, and NO_x are major contributors to respiratory irritation and disease. Associated impacts include asthma, reduced lung function, and respiratory infections.

Smog: Smog refers to ground-level ozone and fine particulate pollution formed when sunlight reacts with emissions. It impairs visibility and causes respiratory and cardiovascular issues. Major sources include vehicles, industry, and volatile organic compounds.

1.10. Life Cycle Analysis and Agronomy of Hemp

Within the LCA framework, hemp agronomy is analyzed by systematically examining each stage of cultivation to understand the environmental impacts from "cradle to farm gate." This includes assessing inputs such as seeds, fertilizers, water, energy, and machinery used in land preparation, planting, irrigation, pest management, and harvesting. Soil preparation methods like tillage affect fuel consumption and soil carbon release, while fertilizer application influences nutrient runoff and GWP. Water use, especially in drought-prone areas, is evaluated for its scarcity footprint. Pest and weed control practices are evaluated for their chemical inputs and potential effects on biodiversity and ecosystems.

Harvesting and post-harvest processes, including retting and fiber extraction, add to energy consumption and waste generation. By compiling data on these inputs and outputs, LCA quantifies cumulative environmental impacts such as global warming potential, eutrophication, and resource depletion linked to hemp cultivation. This comprehensive framework helps identify environmental hotspots, guiding improvements in agronomic practices, for example, adopting no-till methods to reduce soil disturbance emissions, using precision fertilization to minimize nutrient losses, and optimizing retting techniques to lower water pollution.

Thus, applying the LCA framework to hemp agronomy provides a holistic understanding of the crop's sustainability and supports informed decision-making to enhance environmental performance throughout the cultivation system. LCA is increasingly applied to hemp cultivation systems to evaluate their environmental performance across diverse applications, from textiles to bio-composites. Studies in Europe and North America have demonstrated that hemp generally has a lower environmental impact compared to conventional crops like cotton and corn, owing to its low agrochemical inputs, rapid growth, and high carbon sequestration potential [27], [60]. For example, an LCA conducted in Kentucky (USA) found that hemp fiber production had significantly lower GWP than traditional crops, especially under no-till and organic management practices. Similarly, studies in Canada have shown that hemp cultivation environmental impacts have some regulatory parameters like yield, field inputs, intensity of cultivation process, weather, soil condition, pH, soil type, water availability, soil nutrients, and micro-organisms.

1.11. Environmental Impacts of Hemp Cultivation

Hemp cultivation imposes lower environmental burdens compared to many conventional crops, primarily due to reduced chemical inputs, faster growth, and greater potential for carbon sequestration. For example, a comparative water-use study across fiber crops found that hemp requires about 38% less crop water, 60% lower total water footprint, 84% lower crop irrigation requirement, and 91% lower irrigated water footprint compared to cotton [61].

In terms of GWP and life cycle climate impacts, hemp used as a thermal insulator can result in net negative CO_2 eq emissions under certain allocation methods. One LCA study reported that producing one hectare of hemp biomass (15 ton) had a GWP of about −26.0 ton CO_2-eq when considering CO_2 uptake, with allocations of roughly −5.5 ton CO_2-eq allocated to technical fiber depending on the method of allocation [62]. Another study focused on hemp seed production in a Mediterranean environment comparing multiple hemp varieties, planting densities, and nitrogen fertilization rates, and found that environmental impacts (including the carbon footprint) rose with higher fertilizer inputs, while certain varieties and higher plant densities with moderate nitrogen application minimized the impacts [63]. In addition, an LCA comparing hemp with other energy crops (sugar beet, oilseed rape) in Ireland showed that hemp cultivation resulted in 3 ton CO_2-eq per hectare per year, which is moderate among bioenergy crops [64]. Collectively, these findings highlight that, when managed with optimized inputs and sustainable practices, hemp cultivation offers a promising low-impact alternative for fiber, food, and bio-based products within climate-smart agricultural systems.

1.12. Research Contribution and Advancement Toward Sustainable Hemp Systems

This study addresses key gaps in hemp-related LCA by providing region-specific data from the U.S. and incorporating comprehensive co-product modeling. It offers actionable insights by linking environmental impacts with agronomic practices to guide sustainable cultivation. By integrating localized data with scalable methods, the study serves as a representative model that can be adapted for broader application across diverse hemp-growing regions in the US, supporting its role in a low-impact, high-value bioeconomy aligned with national sustainability goals.

1.12.1. Identified Gaps in Literature

Despite increasing global attention to the environmental benefits of hemp, significant gaps remain in the literature, particularly in U.S.-based LCA studies. A recent critical review of fiber hemp in the U.S. noted that while many studies cover cultivation practices such as soil requirements, nutrient management, climate, and pest control, very few provide full LCA outcomes using locally derived emission factors or actual agronomic data; many rely on generalized or secondary sources [65].

Additionally, many studies often underrepresent the complexity of hemp co-product systems. Hemp produces multiple valuable outputs (bast fiber, hurd, seeds, CBD oil), but few LCAs manage co-products effectively using robust allocation or system expansion methods. This often results in either over- or underestimation of environmental burdens. Furthermore, methodological limitations such as narrow system boundaries, reliance on secondary data, and inconsistent functional units hinder comparability across studies [66]. Most literature reviews do not consider the allocation factors of hemp co-products, which also affect the techno-economic analysis (TEA) of the hemp hurd, fiber, and seed. Moreover, while hemp is frequently compared to non-wood biomass such as flax, cotton, or straw, few studies examine its relationship to woody biomass systems.

1.12.2. Relevance and Contribution of the Current Study

This study directly addresses the gaps by conducting a region-specific LCA of hemp cultivation in the U.S. hemp cultivation using local agronomic data, updated emission factors, and realistic co-product handling. It contributes a cradle-to-industry-gate analysis, which evaluates energy use, GHG emissions, water consumption, and nutrient-related impacts.

A key contribution is the adoption of a multi-output modeling approach, enabling co-product allocation based on both mass and economic value. This is critical for accurately assessing hemp's diverse applications in textiles, building materials, and bioplastics. Moreover, by integrating field-level data and scenario analysis, the study enhances the practical relevance of LCA for decision-makers, policy developers, and farmers, bridging the gap between environmental modeling and real-world agronomic planning. In doing so, this research advances the scientific understanding of hemp’s environmental profile while also providing a methodological template for future LCA studies in underrepresented regions.

1.12.3. Advancing Environmental Sustainability through Life Cycle Thinking in Hemp Agronomy

By applying life cycle thinking to hemp agronomy, this study demonstrates how sustainable agricultural practices can be guided by environmental impact data. The integration of LCA results with agronomic variables (nitrogen inputs, fertilizer types, transportation, yield) allows for optimized cultivation strategies that reduce impacts while maximizing biomass yield and co-product value [67]. Additionally, hemp aligns with several United Nations Sustainable Development Goals (SDGs), notably SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land). Its low-input nature, carbon sequestration capacity, and multi-functional biomass make it a promising crop for countries pursuing net-zero targets and agricultural decarbonization [68].

This study contributes to the transition toward low-impact, high-value biomass systems by demonstrating how life cycle insights can directly inform agronomic planning, supporting both academic research and climate-smart agriculture in practice.

1.13. Purpose of the LCA Study on Hemp Cultivation

- To determine the environmental impacts of retted biomass, hemp hurd, bast fiber, and dust.
- To identify environmental hotspots by analyzing the most resource- and energy-intensive stages within the production chain.
- To assess the environmental performance of hemp hurd relative to conventional wood chips used in bio-based industries.
- To compare long hemp bast fiber with cotton fiber to highlight more sustainable alternatives in the textile sector.
- To use the North Carolina mountain region as a case study demonstrates regenerative agricultural practices where hemp acts as a soil-enriching cover crop under multiple scenarios.
- To conduct sensitivity analyses on fertilizer type, biomass yield, and transportation distances.
- To develop a comprehensive, representative framework for sustainable hemp farming at the national scale.

1.14. Hypothesis

- Environmental impacts for hemp hurd and dust will be lower than those of retted biomass and bast fiber.

- Compared with cotton, hemp bast fiber will exhibit a lower GWP, while hemp hurd will have higher GWP than wood chips.
- Mountain-region hemp systems using synthetic fertilizers will have higher environmental impacts.

CHAPTER 2

Methodology

2.1. LCA Methodology

2.1.1. Goal and scope definition

This LCA study evaluates the environmental impacts of industrial whole-hemp plant (retted biomass), and plant-derived products, such as hemp hurd, bast fiber, and dust, using both mass and economic allocation. The goal is to identify production hotspots under different scenarios and assess the environmental impacts of hemp cultivation, while benchmarking hemp hurd against wood chips for pulp and paper applications and bast fiber yarn against cotton yarn for the paper and textile industry. Sensitivity analysis was done to examine how changes in relevant inputs influence environmental outcomes. Agronomic data from the North Carolina Mountain Research Station (NCRS) were used as the baseline to inform sustainable, regenerative farming practices nationwide, with scenario analyses extended to other U.S. regions for broader applicability.

The functional unit (FU) for this study is one oven-dry metric ton (ODT) expressed as metric ton (MT) considering for each product in all scenarios, enabling consistent comparison across products and improving the interpretability of results. The functional unit provides a reference flow to which all inputs and outputs of the cultivation system are normalized [69].

To emphasize the analysis of the production phase, a “Cradle-to-gate” approach was developed, spanning from raw material acquisition to final product outputs. The system includes all unit operations and interactions with the surrounding environment, including emissions of air, water, and soil. The integrated LCA system approach consists of two main system boundaries. System boundary 1) Retted biomass production, including all agricultural practices. 2) Fiber processing, consisting of the conversion of retted biomass into hemp hurd, bast fiber and dust.

The system boundaries encompass all agricultural production unit operations, including soil management, fertilization, sowing, and harvesting (system boundary 1: retted biomass production), as well as the post-treatment of dew-retted biomass through decortication (system boundary 2). They also include baling and transportation of the bales to the pulp mill gate (**Figure 2.1**). In addition, the system boundary accounts for hemp seed production using conventional cultivation methods. Production data for hemp seeds were obtained from reference [31], and the seed production inventory data is included in Appendix A (Chapter 2), which details the traditional seed production process.

Diesel consumption for machinery used in each unit operation is included, along with both direct and indirect emissions. Emissions of NH_3, CO, CO_2, CH_4, particulate matter, and nitrate compounds are quantified following EPA methodology [70].

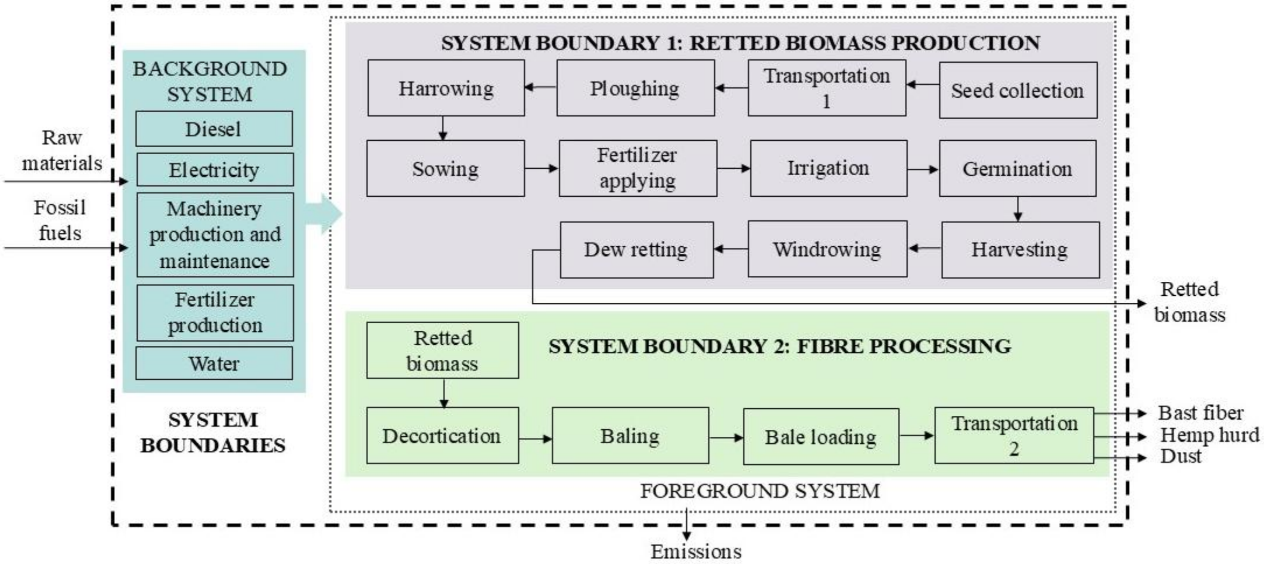

Figure 2.1: Schematic representation of system boundaries of retted biomass and the production of hemp hurd, bast fiber, and dust. System boundary 1 refers to retted biomass production and system boundary 2 refers to fiber processing (decortication).

2.1.2. Life Cycle Inventory

In this study, hemp cultivation began in late April with field preparation using conventional primary tillage. A 3–8-furrow plow was used on loam soil, which has a balanced composition of sand, silt, and clay, with an average working depth of approximately 15 cm. A rotary harrow with a 3 m working width was used for secondary harrowing. Fertilizer was applied during field preparation, with the remaining half applied after 3-4 weeks of field preparation, as optimal hemp growth necessitates adequate availability of the primary macronutrients nitrogen (N), phosphorus (P), and potassium (K) [71].

After field preparation, sowing was conducted with planting 65.56kg per hectare of hemp seed with a 95% germination rate. Rainwater provided irrigation during May, June, July, and August, totaling 5.04, 2.5, 11.62, and 3.88 inches, respectively, supporting an average growing degree day (GDD) of 588.71. Hemp grows in a wide range of soils but prefers humid environments with a rainfall of at least 25–30 inches per year. [72] Hemp is generally tolerant of pests and diseases and is self-weeding, requiring relatively low agricultural inputs compared with other fiber crops.[73] No pesticides and fungicides were used in this study.

The optimal harvesting period for hemp is around 90 days after planting. For this research, harvesting began in late July by cutting stems 6-8″ above the soil surface and leaving the biomass in the field for dew retting before further processing. Retting loosens the bond between the fibers and hurds through microbial action [74] Dew retting typically requires 1–2 weeks under warm and humid conditions but may extend to 4–5 weeks depending on prevailing atmospheric factors[75] From NCRS the yield of the retted biomass was 3.1 MT per hectare with 11.5% moisture content. The materials were windrowed or swathed before decortication for easy handling. After that retted biomass was decorticated to achieve the co-products as outputs. On field decortication was carried out. A decorticator was used to separate the bast fibers (outer layer) from the hemp hurd (inner woody core) [76]. Hemp hurd, bast fiber, and dust were collected, baled and transported to relevant industries by road transportation. The bulk density of lightly compressed hemp hurd, bast fiber, and dust was 120 kg/m^3. **Table 2.1** presents the inputs and outputs required to produce 1 MT of retted biomass, while **Table 2.2** presents the inputs and outputs needed to produce 1 MT of hemp hurd, 0.32 MT of bast fiber, and 0.15 MT of dust.

Table 2.1: Inputs and outputs to produce 1 MT of retted biomass.

Inputs/Outputs	Substance	Amount	Units
Inputs			
Planting (experimental data)	Seeds	26.73	kg
Field activities [26]	Diesel	7.87	kg
Fertilizer production [27],[77]	Ammonium nitrate, as N	31.89	kg
	Potassium chloride, as K_2O	28.37	kg
	Triple superphosphate, as P_2O_5	12.28	kg
Transportation [37]	Field site	6.51	t*km
Outputs	Retted biomass	1.00	t
Emissions from diesel and fertilizer production	Ammonia	0.453	kg
	Carbon black	8.74	g
	Carbon dioxide	24.87	kg
	Carbon monoxide	90.27	g
	Methane	0.684	G
	Nitrate compounds	1.04	Kg
	NMVOC, non-methane volatile organic compounds	27.86	G
	Particulate Matter, <2.5 µm	15.06	G
	Particulates, <10 µm	15.06	G
	phosphorus	0.03	Kg
	TSP	15.06	G

Table 2.2: Inputs and outputs to produce 1 MT of hemp hurd, 0.32 MT of bast fiber, and 0.15 MT of dust.

Inputs/Outputs	Substance	Amount	Units
Inputs			
	Retted biomass	1.47	T
Material handling	Baling	5.95	number (s)
	Bale loading	5.95	number (s)
Decortication [26]	Electricity	233	kWh
Transportation [38]	Field site	6.51	t*km
	Pulp mill gate	180	t*km
Outputs	Hemp hurd, bast fiber, dust	1.00, 0.32,0.15	T

2.1.3. Life Cycle Impact Assessment

The Open_LCA software was used for the cultivation process of the woody and non-wood biomass through the Ecoinvent 3.9.1 database, which is a widely used life cycle inventory (LCI) database that provides high-quality, transparent, and consistent data for LCA studies. The LCA framework ISO 14040,14044 methodology was followed for this work. The TRACI 2.1 impact assessment method was used developed by the Environmental Protection Agency (EPA). TRACI methodology translates inputs and outputs of the LCI into ten categories: ozone depletion potential, respiratory effects potential, global warming potential (GWP), carcinogenic potential, fossil fuel depletion potential, acidification potential, eutrophication potential, smog potential, ecotoxicity potential, and noncarcinogenic potential. The time horizon to measure the GWP is 100 years.

2.1.4. Allocation methods

Allocation was required because decortication of retted biomass yields three coproducts: (a) hemp hurd, (b) bast fiber, and (c) dust. As per ISO 14040, physical relationships should be prioritized for allocation; however, when this is not feasible, economic allocation is recommended.

In this study, the substantial disparity in market prices of hurd, bast and dust necessitated the use of both mass and economic allocation (**Table 2.3**).

Mass allocation: The yield of the retted biomass was 2.74 MT after cultivation of one hectare area with one rotation of plantation to harvest, 90 days. After decortication, the outputs were 1.86 MT of hemp hurd, 0.60 MT of bast fiber, and 0.27 MT of dust, respectively. The corresponding mass-based allocation factors for each coproduct are provided in Table 2.3. using the following equation:

Mass allocation % = Mass of one product/ Total mass of all products.

Economic allocation: Price assumption for all these three products depends on the purity of hemp hurd, bast fiber, and dust. In this study, the assumed US price for hemp hurd was \$90/ODT, bast fiber \$1400/ODT, and dust \$80/ODT. The corresponding economic-based allocation factors for each coproduct are provided in Table 2.3. using the following equation:

Economic allocation% = Value of one product/ Total value of all products

Table 2.3: Allocation factors for hemp hurd, bast fiber and dust.

Allocation Factors	Hemp hurd	Bast fiber	Dust
Mass	0.68	0.22	0.10
Economic	0.16363	0.8145	0.0218

2.2. Data Collection and Scenario Development

Different scenarios were developed from the baseline scenario, **Baseline NCRS (SF)**. The baseline scenario represents hemp cultivation system in North Carolina mountain region using synthetic fertilizer (SF) and the conventional mix grid electricity profile.

NCRS (Electricity): Electricity use is highest during the fiber processing stage. The baseline scenario models power from the regional grid using "market for electricity, high voltage – US, Southeast." The alternative scenario uses renewable electricity from a wood-chip combined heat and power (CHP) system modeled using "heat and power co-generation, wood chips, 6667 kW… US-SERC." This reflects the use of local forest residues in North Carolina and enables comparison between conventional grid electricity and biomass-based renewable power for fiber processing.

Fertilizer-Free Cultivation: In this scenario, all N, P, and K fertilizer inputs are removed to represent fertilizer-free hemp cultivation. A 25% reduction in biomass yield is assumed to reflect the expected productivity loss under nutrient-limited conditions. This scenario evaluates the sustainability trade-offs associated with eliminating synthetic fertilizers.

NCRS (OF) – **Organic Fertilizer Scenario**: The NRCS (OF) scenario modifies the baseline by replacing synthetic fertilizer with organic fertilizer, while maintaining the same mixed-grid electricity used in North Carolina mountain region.

Region Based Scenarios: Region-based scenarios were developed for three major U.S. geographic regions: mountain (western highlands), inland (midwestern plains), and coastal (eastern & southern coastal states), which are described as **mountain (SF) inland (SF) and coastal (SF)**. These scenarios, region-specific variations in biomass yield for oven-dry retted biomass based on the national average yield of 8.8 MT per hectare per year [79]. The study assumes three potential cultivation rotations per year but models only one rotation.

Yield assumptions for each region: 1) **Inland region (**5% above the national average) 3.08 MT per hectare, 2) **Coastal region** (10% below the national average) 2.64 MT per hectare, and 3) **Mountain region** (20% below the national average) 2.34 MT per hectare.

LCA was conducted for all three different regions using yield data, seeds requirements, and synthetic fertilizer use per hectare. In mountain regions, CaO is applied in addition to N, P, K fertilizers. Fertilizer application rates were collected from literature targeting inland states (Ohio and Oklahoma), mountain states (Colorado and Montana), and coastal states (New Jersey and North Carolina). In all regions, hemp cultivation is assumed to be rain-fed. Land area required to produce one metric ton of retted biomass include 0.32 hectare for inland, 0.38 hectare for mountain, and 0.43 hectare for coastal. **Table 2.4** presents inputs and outputs for regional hemp cultivation for 1 MT of retted biomass.

Table 2.4: Inputs and outputs for regional hemp cultivation for 1 MT of retted biomass.

Inputs/Outputs	Substance	Inland Region	Mountain Region	Coastal region	Units
Inputs					
Seeds [80], [81]	Planting	15.5	25	20	kg
Fertilizer production [82] , [83] [84] , [85]	Ammonium nitrate, as N	31.11	50.01	40.12	kg
	Potassium chloride, as K_2O	11.2	19.98	27.50	kg
	Triple superphosphate as P_2O_5	11.19	20.01	24.00	kg
	CaO	----	49.55	----	kg
Outputs	Retted biomass	1	1	1	t

The percentage of each product after decortication was assumed to remain the same as in the baseline scenario: 68% hemp hurd, 22% bast fiber, and 10% dust. The required amount of retted biomass for decortication, as well as the mixed-grid electricity used for fiber processing in all three regions, was assumed to be identical to the baseline scenario. For each region to produce 1MT of hemp hurd, 0.32 MT of bast fiber, and 0.10 MT of dust, a total of 1.47 MT of retted biomass is required. After decoration, bailed materials were transported to the pulp and paper mill gate. For transportation, a distance of 180 km was assumed, consistent with the baseline **NCRS (SF)** scenario.

Mountain (OF), inland (OF), and coastal (OF)

The same region-based scenarios described earlier were extended to organic fertilizer conditions, where synthetic fertilizers were replaced with cattle-manure solids. To ensure proper management of organic fertilizer, it was assumed that manure would be sourced near the cultivation site, which also supports on-farm composting practices and reduces transportation impacts. Environmental impacts were calculated based on these scenarios for retted biomass and its coproducts after the fiber processing stage. Additional scenarios were also considered in which retted biomass was assumed to be cut by using a hammer mill instead of processed through decortication; this alternative product is referred to as chopped whole hemp stalk. The system boundary and LCI for these scenarios are explained in Appendix A- Chapter 2. Another scenario assumed that electricity was produced through dust utilization as a fuel and that this electricity was used for cutting retted biomass and for decortication, allowing for an assessment of the possible environmental impacts associated with these alternative scenarios. **Table 2.5** describes scenarios with three different parameters for hemp cultivation.

Table 2.5: Scenario descriptions with three different parameters for hemp cultivation.

Scenario	Fertilizer Type	Electricity	Region	Description
Baseline – NCRS (SF)	Synthetic	Grid electricity (mix)	NCRS	Baseline southeastern U.S. scenario using synthetic N,P,K fertilizers and conventional grid power for retted biomass cultivation and processing.
NCRS (Electricity)	Synthetic	Renewable CHP (woodchips)	NCRS	Same cultivation as baseline, but processing electricity is replaced with decentralized woodchip-based CHP to assess the GHG impact of renewable electricity.

Table 2.5 (continued)

Scenario	Fertilizer Type	Electricity	Region	Description
NCRS (WF)	None	Grid electricity (mix)	NCRS	Fertilizer-free cultivation; N,P,K inputs removed, resulting in a 25% yield reduction; examines sustainability trade-offs of no fertilizer use.
NCRS (OF)	Organic (cattle manure)	Grid electricity (mix)	NCRS	Synthetic fertilizers are replaced with locally sourced organic manure, which includes composting to enhance nutrient availability and reduce synthetic fertilizer emissions.
Inland (SF)	Synthetic	Grid electricity (mix)	Inland	Inland (midwestern plains) soils (pH 6–7, sandy loam) with lower fertilizer requirements; synthetic N,P,K fertilizers used; yield 5% above the national average.
Inland (OF)	Organic (cattle manure)	Grid electricity (mix)	Inland	Organic manure substitutes synthetic fertilizers in a low-input, fertile inland region; soil-building and nutrient cycling focus.
Coastal (SF)	Synthetic	Grid electricity (mix)	Coastal	Coastal marshy soils (pH 6.2–7) with higher nutrient requirements; synthetic fertilizers are applied; yields are 10% lower than the national average.
Coastal (OF)	Organic (cattle manure)	Grid electricity (mix)	Coastal	Organic manure replaces synthetic fertilizers in coastal soils; it examines the benefits of organic nutrient cycling under challenging coastal conditions.
Mountain (SF)	Synthetic	Grid electricity (mix)	Mountain	Mountainous acidic soils (pH 5.5–6.5) needing liming and micronutrients; the highest synthetic fertilizer demand; challenging growing conditions with assumed yield 20% lower than national average yield.
Mountain (OF)	Organic (cattle manure)	Grid electricity (mix)	Mountain	Organic manure used instead of synthetic fertilizers; improves soil acidity, microbial diversity, and assesses organic management feasibility in mountain regions.

2.3. Comparison of Hemp Hurd vs. Wood Chips and Hemp vs. Cotton Yarn

In this study, hemp hurd and bast fibers were evaluated as alternative raw materials for the paper and textile industries. Their mass allocated environmental impacts were assessed in comparison to those of conventional counterparts, including wood chips for paper production and cotton yarn for textiles, which served as the baseline scenarios.

2.3.1. Wood chips vs, hemp hurd production

For wood chips production, the Ecoinvent 3.9.1 database was used, where softwood pine is modeled as pulpwood production under "forestry management, under bark." The system boundary includes seed production and nursery propagation, followed by the transportation of logs to the chopping site. Electricity needed for wood chipping is included, as well as baling, bale loading, and transportation to the pulp mill gate (**Figure 2.2**). The functional unit is 1 MT of wood chips. Hemp hurd data was obtained directly from the NCRS dataset after the decortication stage, including transportation to the pulp mill gate.

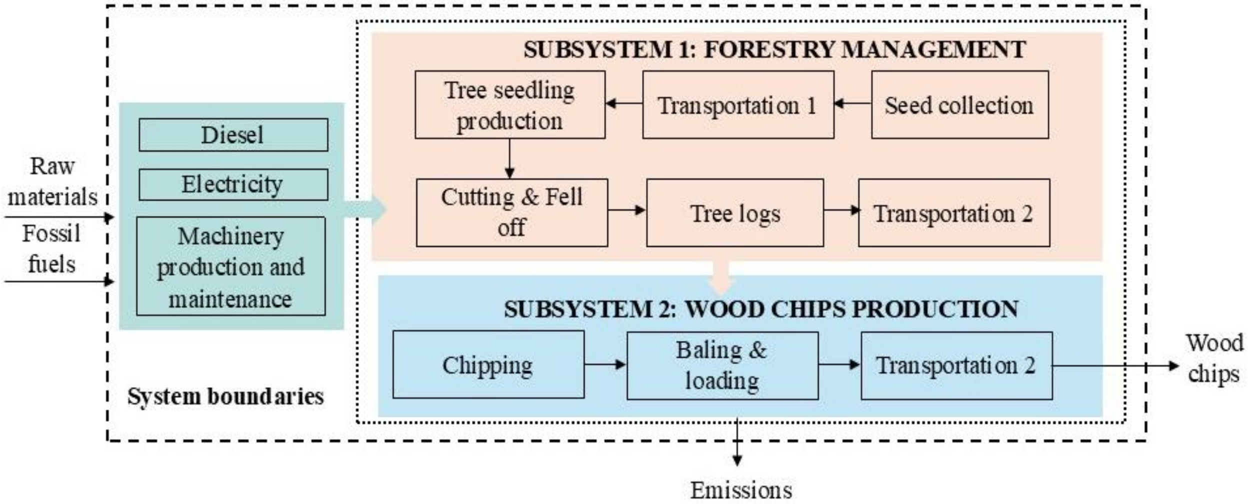

Figure 2.2: Schematic representation of system boundaries for wood chips production, where subsystem 1 is the forest management of pine softwood and subsystem 2 represents wood chipping.

2.3.2. Bast fiber yarn vs cotton yarn production

To produce bast fiber yarn, additional processing steps must be conducted beyond decortication. This analysis included the entire production chain from cultivation to fiber processing. For consistency and comparability, the environmental impacts of bast fiber and cotton yarn were assessed up to the ring-spinning stage, which encompasses ginning, cleaning, and carding operations (**Figure 2.3**).

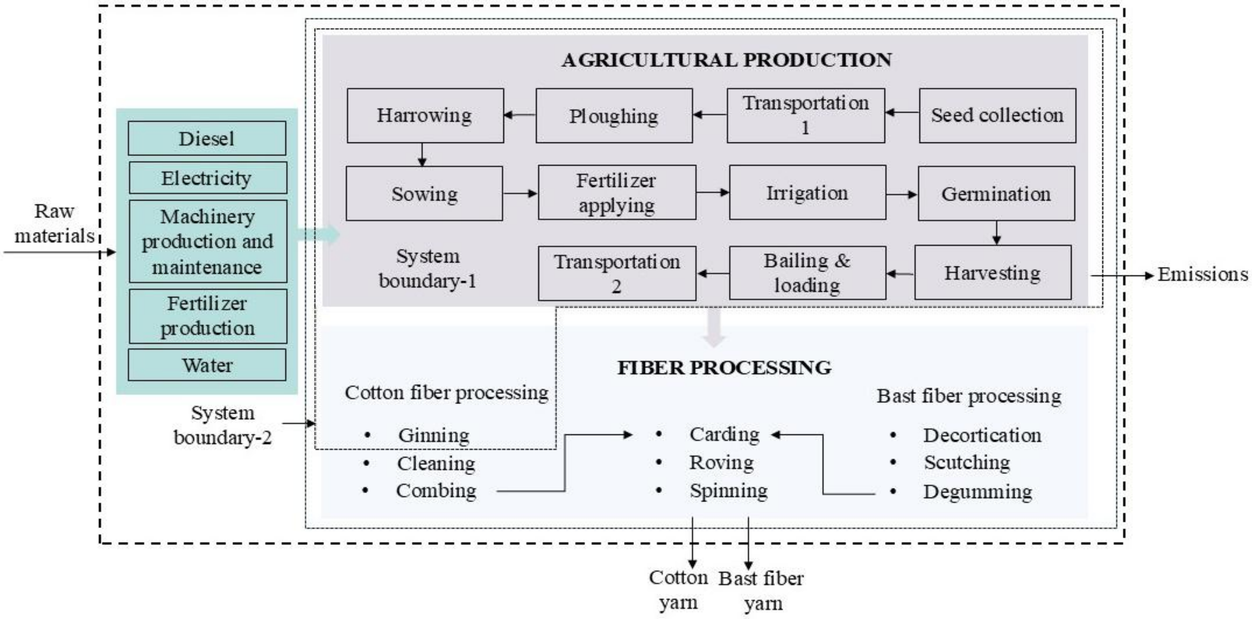

Figure 2.3: Schematic representation of process flow of hemp and cotton yarn cultivation and their processing. System boundary 1 represents the agricultural production of retted biomass, and system boundary 2 represents cotton lint production; fiber processing is common downstream stage for both output products.

Bast fiber yarn production

After decortication, bast fiber undergoes a series of subsequent fiber processing operations, including all the unit operations shown in **Figure 2.3**. This system boundary includes transportation to the scutching site, which is 50 km away [86]. To produce one metric ton of scutched bast fiber, 3 metric ton of decorticated bast fiber, and 336 kwh electricity are needed [30]. After scutching, it is assumed that degumming, carding, and spinning are conducted at the same site. Alkaline degumming is used following the previous studies [87] ,[88]. After the degumming process, it is assumed that both short and long fiber mix went for the carding operation (**Table 2.6**). Carding data was taken from this reference [89] The next stage is ring spinning, which was chosen as the yarn production method to produce 21 Ne (hanks/lb.) yarn (**Table 2.7**). Lubricating oil and electricity consumption data for ring spinning were sourced from [90]. The final output modeled is 1 MT of hemp bast fiber yarn. Transportation to the textile mill gate was also included, using value from the literature.

Table 2.6: Hemp bast fiber degumming inputs and outputs.

Substance	Amount	Units
Inputs		
Scutched Hemp fiber	1.3	Kg
Steam	15	MJ
Electricity from the grid	2.25	MJ
Hydrogen peroxide	0.07	Kg
Sodium hydroxide	0.2	Kg
Sodium carbonate	0.35	Kg
Tap water	50	L
Outputs		
Degummed hemp fiber	1	Kg
Wastewater (average)	50	L

Table 2.7: Hemp yarn ring spinning inputs and outputs.

Substance	Amount	Units
Inputs		
Carded fiber	1040	Kg
Transport to the industry site	180	t*km
Lubricant	53.3	Kg
Tap water	13300	L
Electricity from the grid	2900	MJ
Outputs		
Spinning yarn	1	T
Textile waste	40	Kg

Cotton Cultivation, Fiber Processing, and Yarn Production

Cotton cultivation is a long-cycle crop, typically lasting 5–7 months, beginning with land preparation mid to end of April in the southeast region of the U.S. Land preparation includes plowing, disking, and bed formation, followed by sowing once soil temperatures reach 18˚C to 20˚C for optimal germination [91], [92]. In this study, the sowing density was 10 kg per hectare. Seed germination relies primarily on rain-fed agriculture due to the region's high annual rainfall of 1,249 mm, with only 17% of cotton acreage requiring irrigation [93].

Farmers typically achieve yields of about 894 kg per hectare on Ulti sol soils, which are acidic and require high fertilizer use (223 kg per hectare per year) [94]. The production cycle for cotton is 170 days, after which harvesting is conducted using a spindle picker [95]. Total diesel consumption in the southeastern United States is 92.1L per hectare. After harvesting, raw cotton is transported for ginning, where cottonseed is separated from cotton lint. Electricity plays a major role during the ginning operation, separating roughly 380 kg of lint and 620 kg of cottonseed per ton of cotton processed [96]. Transportation from the field to the ginning site was assumed to be 50km. Cotton seed production data was obtained from Ecoinvent 3.9.1. database. **Table 2.8** shows the life cycle inventory for 1 MT of cotton lint cultivation.

Table 2.8: Life cycle inventory for 1 MT of cotton lint cultivation.

Substance	Quantity	Unit
Inputs		
Cotton seed	29.44	Kg
Transport	50	t*km
NPK fertilizer	305.73	Kg
Irrigation	8361.13	m^3
Baling	5	number (s)
Bale loading	5	number (s)
Outputs		
Cotton lint	1	T

After ginning, fibers undergo cleaning and combing. To produce 1 kg of cleaned, combed cotton fiber, the process requires 1.3 kg of cotton lint, 85 kWh of electricity, and 20 L of tap water. Outputs include 1 kg of cleaned fiber, 0.3 kg [97] of solid textile waste, and 20 L of wastewater, reflecting losses and residues generated during preparation [98], [99]. After fiber processing stage, cleaned cotton fibers processed to yarn production, starting with carding. Life cycle inventory for one kg of carded cotton fiber is taken from [100],[94] detailed are provided in Appendix 1 (Chapter 2). The next operation after carding is roving, which needs electricity, carded cotton fiber, and lubricating oil. Roved cotton fiber goes for final spinning operation. Life cycle inventory for one kg of roved cotton fiber performed according to the literature [101],[102], with full details inventory also provided in Appendix 1 (Chapter 2). Ring spinning was chosen as the yarn production method to produce 21 Ne (hanks/lb.) yarn. **Table 2.9** shows life cycle inventory for 1 MT of cotton yarn (ring spinning) [103], [104].

Table 2.9: Life cycle inventory for 1 MT of cotton yarn (ring spinning) [103], [104].

Substance	Quantity	Unit
Inputs		
Roved cotton fiber	1261.80	Kg
Transport	180	t*km
Electricity	2871	MJ
Outputs		
Cotton yarn	1	T
Waste textile, solid	261.80	Kg

2.4. CO_2 Uptake Estimation and Carbon Footprint Calculation

CO_2 uptake was estimated from biomass yield per hectare and carbon content of dry matter, assuming photosynthetic carbon fixation for 25 years of cultivation. The approaches for incorporating the climate benefits and impacts of biogenic carbon stored in sustainably cultivated biomass into LCA and introducing GWPbio factors applicable to both LCA studies and bioenergy systems. [105] In this study, CO_2 uptake estimation followed the GWP100 method based on mass allocation.

Total biomass yield from one hectare of land per year (assumed three rotations in one year) was 8.22 MT. The total biomass yield was 205.5 MT per hectare per 25 years, resulting in 139.74 MT per hectare per 25 years of hemp hurds according to mass allocation factor of 0.68. Similarly, bast fiber and dust yield would be 45.21 MT and 20.55 MT per hectare per 25 years based on mass allocation factors of 0.22 and 0.10. Biomass carbon content for industrial hemp was assumed to be 48% [106]. For comparison, wood chips yield was 174.3 m^3 per hectare per 25 years with a bulk density of 500 kg/m^3 [107], [108], translating in 87.2 MT per hectare per 25 years with 50% carbon content [109]. Cotton lint yields were 339.72 kg per hectare per year [96], totaling 8.75 MT per hectare per 25 years with a carbon content of 45% [110].

2.5. Sensitivity analysis

Four key drivers were evaluated to test the robustness of the cradle-to-gate GWP results: fertilizer management, transportation, economic allocation, and yield, using a structured scenario design.

Economic Allocation Sensitivity

For economic allocation, burdens for bast fiber, hemp hurd, and dust were apportioned by their bulk market prices (**Table 2.10**). Sensitivity was conducted using ±25% price variation for hemp hurd and dust. Price assumed for baseline scenario in the United States for hemp hurd \$90/ODT, bast fiber \$1400/ODT, and dust \$80/ODT. Two scenarios were considered for economic allocation sensitivity. (**Scenario-1**, 25% of hemp hurd and dust price increased, price for hemp hurd \$112.5/ODT, bast fiber \$1400/ODT, and dust \$80/ODT), (**Scenario-2**, 25% of the hemp hurd and dust price decreased, price for hemp hurd \$67.5/ODT, bast fiber \$1400/ODT, and dust \$60/ODT). Mass and economic allocation method followed the baseline scenario.

Table 2.10: Allocation factors to produce 1 MT of hemp hurd, 0.32 MT of bast fiber and 0.15 MT of dust.

Allocation Factors	Bast Fiber	Hemp Hurd	Dust
Baseline	0.8145	0.16363	0.0218
+ 25% price increase for hemp hurd and dust	0.7785	0.1954	0.0261
-25% price decrease for hemp hurd and dust	0.8541	0.1287	0.0172

Nitrogen Fertilizer Sensitivity

Nitrogen (N) fertilizer management sensitivity was conducted using ammonium nitrate (AN) as the reference N source. Literature reports 265.1 kg per hectare per year of urea–ammonium nitrate (UAN-30), containing 30% nitrogen, applied to industrial hemp, resulting in a retted biomass yield of 9 MT per hectare per year. Assuming three cropping rotations per year, this corresponds to an equivalent ammonium nitrate application rate of 75.3 kg per hectare in one rotation required to achieve the same biomass yield. This fertilizer application and resulting yield configuration was designated as Scenario 1. For Scenario 2, the retted biomass yield was maintained at 9 MT per hectare per year, but ammonium sulfate (AS) was used as the nitrogen source at a rate of 924 kg/ ha/year, reflecting the nitrogen equivalence of ammonium sulfate (21% N). For ammonium nitrate fertilizer use is 174.6 kg per hectare. Following decortication, the allocation of biomass into hemp hurd, bast fiber, and dust was assumed to be identical to that observed in the baseline scenario. These two scenarios thus provide a comparative framework to evaluate the impact of fertilizer type and nitrogen source on biomass yield and subsequent fractionation into industrial hemp components (**Table 2.11**).

Table 2.11: Sensitivity analysis of nitrogen fertilizer data to produce 1 MT of retted biomass.

Fertilizer (kg/ MT of retted biomass)		Baseline scenario	Scenario 1	Scenario 2
Retted biomass	Ammonium nitrate, as N [27], [77], [111]	31.89	25.24	58.2

Yield Sensitivity

Yield of retted biomass was varied by 25% of baseline scenario yield (2.74 MT per hectare) under two different yield scenarios based on data from a single crop rotation. The highest yield scenario was at 3.43 MT per hectare, while the lowest yield was 2.06 MT per hectare. After decortication, the allocation procedure is kept like the **baseline** scenario. Based on this sensitivity approach of yield, CO_2 sequestration also varied, affecting the net carbon footprint of hemp cultivation.

For± 25% yield (three rotations per year) of biomass was 10.29 and 6.18 MT per hectare of biomass. Over 25 years of one hectare land total biomass yield of 257.25 and 154.5 MT per hectare, resulting in 174.93 and 105.06 MT per hectare of hemp hurds according to mass allocation factor of 0.68. Similarly, bast fiber and dust yield was 56.60 and 33.99 MT per hectare and 25.73 and 15.45 MT per hectare based on mass allocation factors of 0.22 and 0.10.

Transportation Sensitivity

Transportation distance varies significantly due to geographic distribution of biomass. Sensitivity analysis was conducted according to [112], With minimum and maximum transportation distances of 50km to 500km within metropolitan regions.

CHAPTER 3

Results and Discussion

3.1. Environmental impacts of retted biomass and fiber processing

In system boundary 1 (retted biomass production), the generation of 1 MT of retted biomass results in 152 kg CO_2-eq of GWP. In system boundary 2 (fiber processing), the production of 1 MT of hemp hurd, 0.32 MT of bast fiber, and 0.15 MT of dust collectively generates 402 kg CO_2-eq. As shown in Figure 3.1A, the normalized environmental impacts indicate that retted biomass accounts for 37% of total GWP when compared against the three coproducts of the fiber-processing stage, which are normalized to 100%. The higher impacts observed in system boundary 2 arise from electricity consumption, material handling (baling and bale loading), and transportation, inputs that substantially contribute to the overall emissions intensity of the fiber-processing stage.

Figures 3.1B and 3.1C further demonstrate that ammonium nitrate is the dominant contributor to GWP during retted biomass and three coproducts development, accounting for 54.52% and 33.4% of the impacts, respectively. In contrast, the contribution of ammonium nitrate in the fiber-processing stage is markedly lower, as the environmental burden shifts toward energy-related inputs, primarily electricity (31.6%), material handling (12.3%), and transportation (4.9%) in Figure 3.1C. These findings indicate that both agricultural inputs and energy consumption are the key drivers of environmental impacts across the two system boundaries [113].

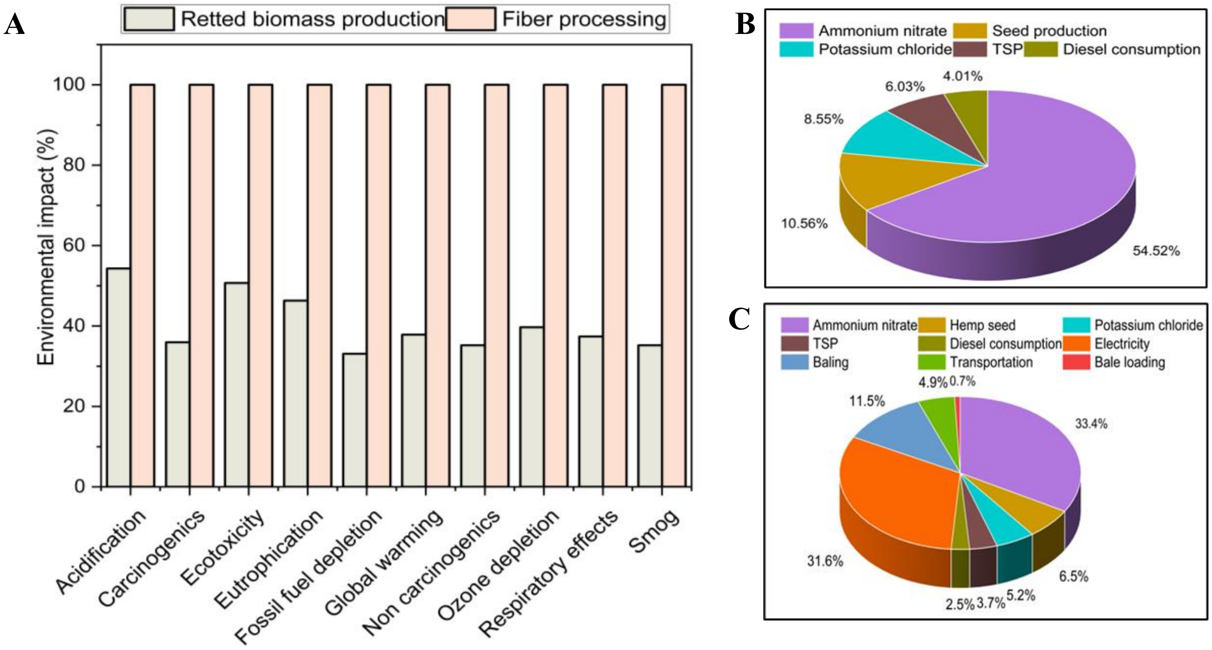

Figure 3.1: Environmental impacts of producing (A) 1 MT of retted biomass production and the fiber processing stage (production of 1 MT of hemp hurd, 0.32 MT of bast and 0.15 MT of dust). Relative contributions of (B) system boundary 1 (production of 1 MT of retted biomass), and (C) system boundary 2 (production of 1 MT of hemp hurd, 0.32 MT of bast fiber and 0.15 MT of dust).

3.2. Mass and economic allocation

Mass and economic allocation is conducted for the baseline scenario. The environmental impacts of hemp hurds, bast fiber and dust were assessed using both allocation approaches, as shown in Figure 3.2A and 3.2B, with particular emphasis on GWP. The total GWP of producing 1 MT of each coproduct was 402 kg-CO_2 eq, as illustrated in Figure 3.2A. Figure 3.2B shows the economically allocated GWP values per MT of 66 kg CO_2-eq, 1024 kg CO_2-eq, and 58 kg CO_2-eq for hemp hurd, bast fiber and dust, respectively. This demonstrates how economic allocation magnifies the perceived environmental burden of high-value bast fiber, relative to lower-value coproducts such as hemp hurd and dust. Under mass allocation, the environmental burden is distributed proportionally to the mass of each coproduct, yielding relatively similar GWP values for hemp hurd, bast fiber, and dust [114]. In contrast, economic allocation assigns a larger share of the burden to bast fiber because of its much higher market value, resulting in a significantly increased GWP for this high-value product [115].

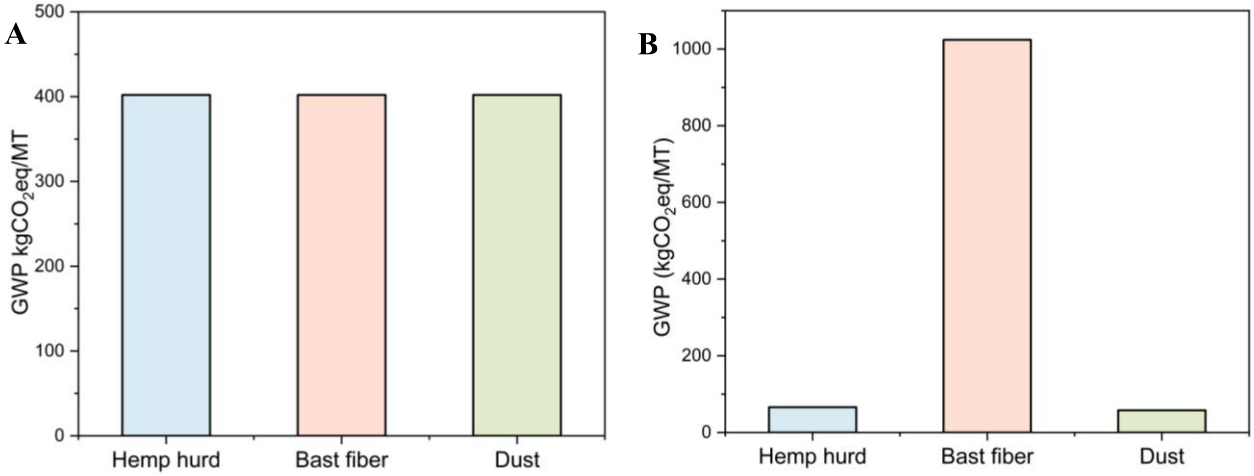

Figure 3.2: Global warming potential (GWP) of hemp hurd, bast fiber and dust based on (A) mass allocation and (B) economic allocation.

3.3. Scenario analysis

Different scenarios were considered in this study to illustrate how environmental impacts vary depending on fertilizer type, geographic region, and electricity source. In figure 3.3A shows the results of retted biomass production. The baseline scenario, NCRS (SF) results in 152 kgCO$_2$ eq per MT. The NCRS (WF) exhibits a substantially lower impact of 47 kg CO$_2$ eq per MT. For regional hemp cultivation, the inland (OF) has the lowest emissions at 115 kg CO$_2$eq per MT, whereas the mountain (SF) has the highest GWP of 583 kg CO$_2$ eq per MT. The higher impacts in the mountain region are attributable to greater fertilizer requirements and additional soil management needs due to relatively lower soil pH [116].

Under mass allocation (Figure 3.3B), all coproducts exhibit identical GWP values because the total environmental load is distributed by product mass. GWP values range from 247.8 kg CO_2-eq per MT in the fertilizer-free scenario to 800.9 kg CO_2-eq per MT in the Mountain (SF). This trend highlights that the use of synthetic fertilizers and region-specific conditions, especially in mountainous regions, greatly increases emissions, while organic or fertilizer-free systems significantly reduce them.

Synthetic fertilizers increase GWP because of their energy-intensive production and high N_2O emissions, and mountain regions amplify per- metric ton impacts due to lower yields and higher energy use [117]. Conversely, organic and fertilizer-free systems reduce both upstream and field-level emissions, leading to significantly lower GWP values for hemp hurd, bast fiber, and dust [118].

When economic allocation is applied (Figures 3.3C), the environmental burdens shift according to product value. Bast fiber, being the most valuable, shows the highest GWP (630.63–2038.49 kg CO_2-eq per MT, followed by hemp hurd (40.54–131.05 kg CO_2-eq per MT) and dust (36–116.39 kg CO_2-eq per MT). In the NCRS (OF) scenario, economic allocation shows significantly reduced GWP values of 43.14 kg CO_2-eq per MT for hemp hurd, 671.12 kg CO_2-eq per MT for bast fiber, and 38.32 kg CO_2-eq per MT for dust, representing approximately a 45–50 % reduction compared with synthetic fertilizer baseline. Across all allocation approaches, scenarios using organic fertilizer (OF) or renewable energy (e.g., wood chips, biomass energy systems), consistently demonstrate lower GWP values compared to the baseline (SF) and other site conditions, confirming that input management and cultivation practices play a decisive role in mitigating climate impacts in hemp production [119]. GWP for the scenario with retted biomass cutting (hammer milling) instead of decortication shows 215 kg CO_2-eq per MT, whereas mass-allocated baseline decortication scenario results in 402 kg CO_2-eq per MT. When electricity produced from dust utilization is used to power hemp decortication, the GWP decreases to 286 kg CO_2-eq per MT (mass allocation). Under economic allocation, this corresponds to 46 kg CO_2-eq per MT for hemp hurd, 730 kg CO_2-eq per MT for bast fiber, and 41 kg CO_2-eq per MT for dust (Appendix B, Chapter 3)

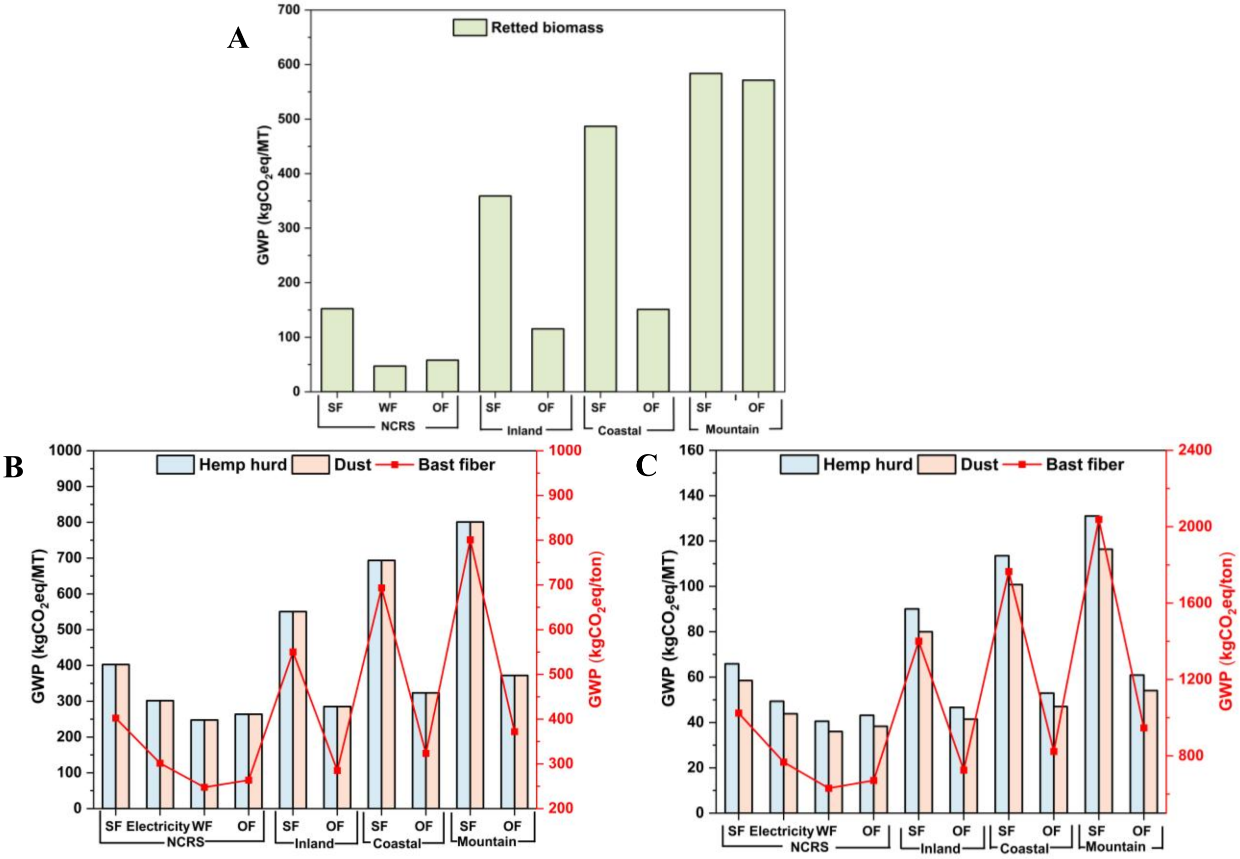

Figure 3.3: Global warming potential (A) for producing one ton of retted biomass, (B) for hemp hurd, bast fiber and dust based on mass allocation, and (C) for hemp hurd, bast fiber, and dust based on economic allocation across different scenarios. NCRS (SF) represents the baseline scenario.

3.4. Comparison of Hemp Hurd vs. Wood Chips and Hemp vs. Cotton Yarn

In Figure 3.4A, the results show that bast fiber yarn consistently exhibits lower environmental impacts than cotton yarn across all categories. This trend aligns with the quantified GWP data: cotton lint and cotton yarn generates 2,036 kg CO_2-eq per MT and 8,600 kg CO_2-eq per MT, respectively, whereas bast fiber after decortication and bast fiber after yarn production emit only 402 kg CO_2-eq per MT (mass allocated) and 5,200 kg CO_2-eq per MT, respectively. Thus, bast fiber yarn production results in approximately 40% lower GWP compared to cotton yarn. The higher impacts associated with cotton are mainly due to its resource-intensive agricultural practices, including large water, fertilizer, and pesticide inputs, as well as energy-demanding spinning processes [93]. In contrast, bast fibers such as hemp require fewer agrochemicals, lower irrigation, and contribute to carbon sequestration during growth.

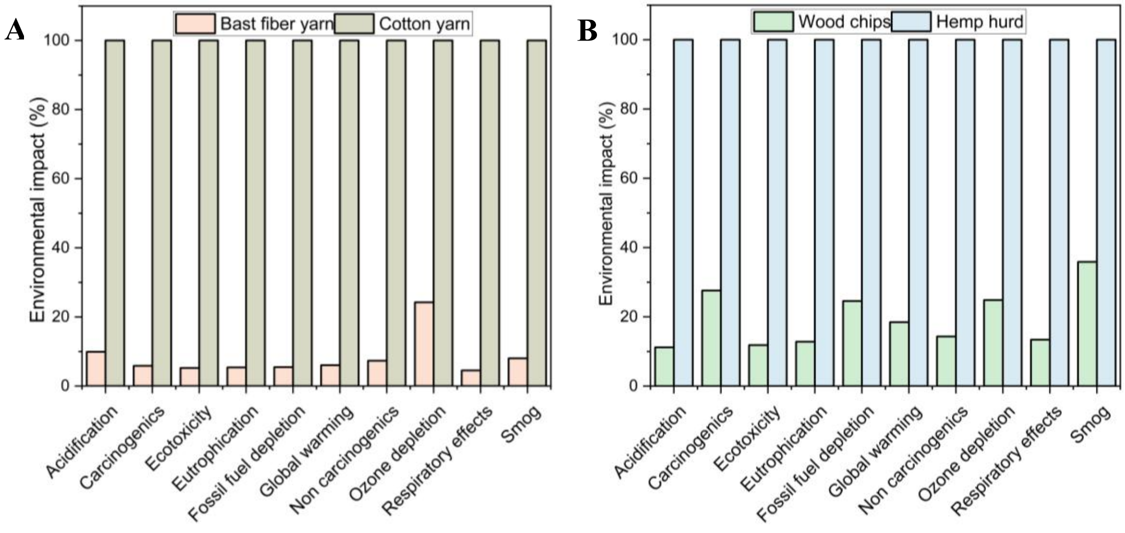

Figure 3.4: Environmental impact performance comparison for (A) hemp bast fiber yarn vs. cotton yarn and (B) wood chips vs. hemp hurd.

Figure 3.4B compares the environmental impacts of hemp hurd and wood chips across several categories, showing wood chips have lower impacts in all categories, particularly for GWP, where wood chips emit 74 kg CO_2-eq per MT, compared with 402 kg CO_2-eq per MT (mass allocated) for hemp hurd In contrast, hemp hurd has an equivalent GWP (66 kg CO_2-eq per MT) when impacts are allocated based on economic value for industrial hemp production.

3.4.1. Contributions to environmental impact categories (Cotton vs. hemp bast fiber yarn)

Acidification potential (AP)

The acidification potential for cotton and bast fiber yarn is 193 and 19 kg SO_2-eq per MT respectively. For cotton yarn, the largest contribution comes from the yarn production stage (46.82%), where ring spinning is the most energy intensive step. Fiber processing contributes an additional 41.5% (Figure 3.5A), with combing being the highest contributor due to significant material waste generated during the process [93].

For hemp bast fiber yarn, the highest contribution arises from the fiber-processing stage (62%; Figure 3.5B), primarily due to degumming of scutched bast fiber. Steam use during degumming contributes 38%, with the remaining contribution coming from scutching and decortication [120]. During bast fiber spinning, the contribution is relatively low due to less bast fiber waste generation. Overall, bast fiber yarn demonstrates substantially lower acidification potential compared with cotton yarn.

Ecotoxicity

Ecotoxicity values for cotton yarn and bast fiber yarn are 604622 and 31676 CTUe per MT, respectively. In cotton cultivation, irrigation (32%), fiber processing (38%), and yarn production (26%) are the largest contributors to ecotoxicity. In contrast, for hemp bast fiber yarn, fiber processing (52%) and fertilizer (26%) contribute the highest to ecotoxicity.

Hemp cultivation in the southeastern United States is largely rain-fed, resulting in lower ecotoxicity compared with cotton, which requires considerable irrigation. Additionally, hemp's fertilizer-related ecotoxicity stems mainly from emissions of N_2O, CO_2, and NH_3 due to nutrient leaching. Cotton's higher ecotoxicity is driven by intensive irrigation, agrochemical use, and processing requirements, as illustrated in Figures 3.5 A and B.

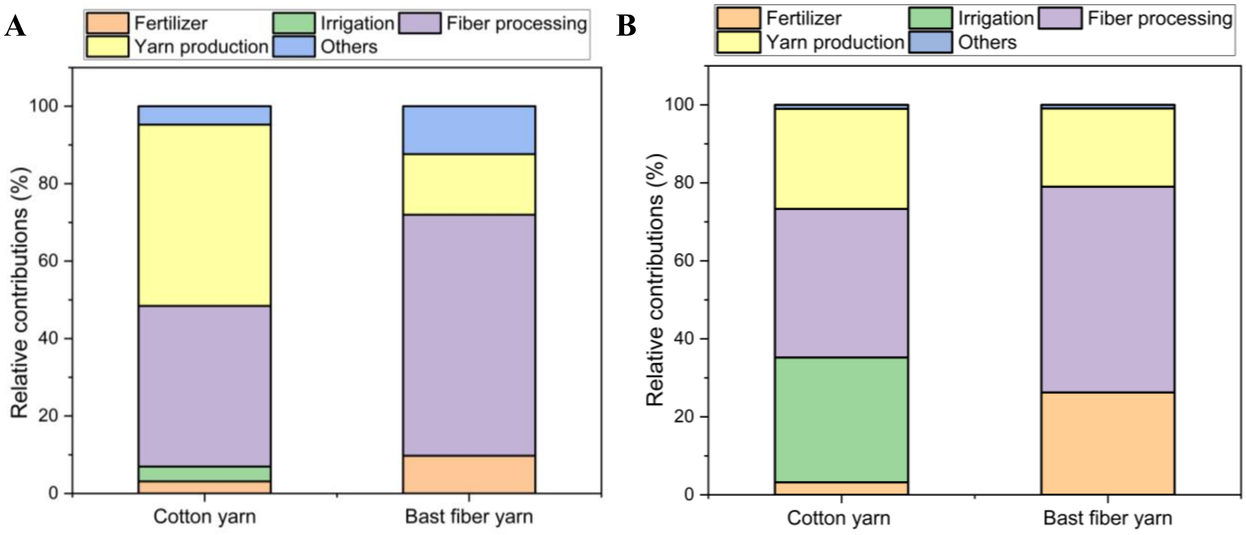

Figure 3.5: Relative contribution of cotton yarn vs. bast fiber yarn for (A) acidification potential and (B) ecotoxicity. Fiber processing refers to the ginning, cleaning, combing (for cotton) and decortication, scutching, degumming (for bast fiber). Yarn production refers to carding, roving and spinning. Others refer to material handling and transportation of raw materials to mill gates.

Fossil fuel depletion (FFD)

The fossil fuel depletion (FFD) for cotton and bast fiber yarn are 136,485 and 31,676 MJ surplus per MT, respectively. In Figure 3.6A, the cotton-fiber processing stage contributes 50%, while yarn production stage contributes 45% due to the use of non-renewable energy sources (natural gas and crude oil) in machinery production. In Figure 3.6B, bast fiber has the highest contribution in the fiber-processing stage (64%), due to the energy-intensive nature of scutching, degumming and decortication. Yarn production contributes 25%, significantly lower than that of cotton. Overall, bast fiber yearn is a substantially less energy-intensive alternative to cotton yarn.

Global warming potential (GWP)

The Global warming potential (GWP) associated with cotton and bast fiber yarn production is 86,678 and 5,232 kgCO_2 eq per MT. In Figure 3.6B cotton fiber yarn production shows 50% of total GWP for fiber processing and 44% of total GWP for yarn production. For bast fiber yarn in Figure 3.6B, 68% of total GWP arises from degumming, scutching, and decortication due to electricity generation (coal-based), as well as heat and steam usage and emissions associated with chemical production for degumming (CO, CO_2, etc.). Yarn spinning and roving contributes only 21% of total GWP, much lower than the cotton yarn production stage.

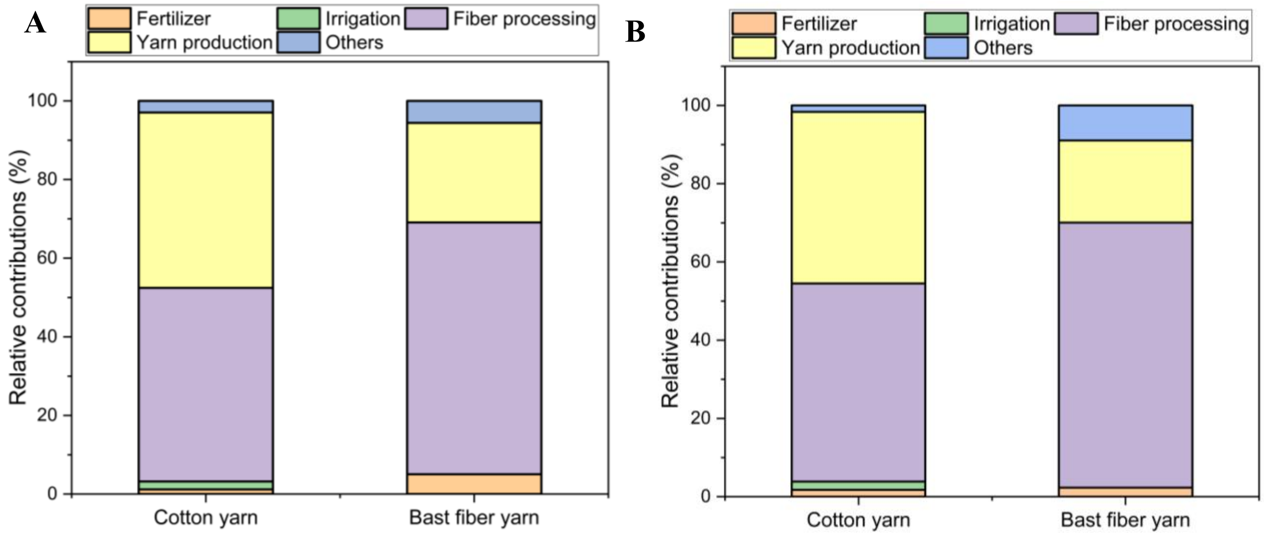

Figure 3.6: Relative contribution of cotton yarn vs. bast fiber yarn for (A) fossil fuel depletion and (B) GWP. Fiber processing refers to the ginning, cleaning, combing (for cotton) and decortication, scutching, degumming (for bast fiber). Yarn production refers to carding, roving and spinning of fiber. Others refer to material handling and transportation of raw materials to mill gates.

3.4.2. Contributions of environmental impact categories (Wood chips vs. hemp hurd)

Acidification potential (AP)

The acidification (AP) values for hemp hurd and wood chips were 2.72 and 0.30 kg SO_2-eq per MT, respectively. In hemp cultivation, field activities account for 72% of total AP, comprising 46% of direct emissions, mainly ammonia volatilization and nitrogen-related soil emissions, and 26% indirect emissions from the upstream production of nitrogen fertilizers and energy use. Material handling and chipping contribute 10% and 8%, respectively. In contrast, for wood chips, field activities contribute 30%, material handling 26%, and chipping 17.44% (Figure 3.7A). These differences arise from sulfur dioxide (SO_2) emissions from combustion of sulfur-containing fossil fuels, ammonia emissions associated with fertilizer use and production, and nitrogen oxides (NO_x) generated from fuel combustion [121].

Eutrophication potential (EP)

The eutrophication (EP) values for hemp hurd and wood chips were 1.5 and 0.20 kg N-eq per MT, respectively. For hemp hurd, field activities show 63% of total EP followed by chipping (25%) and material handling (6%) (Figure 3.7B). These impacts are primarily due to fertilizer application and upstream fertilizer production, including nitrate (NO_3^-) leaching, nitrogen emissions, and phosphate releases. These impacts are primarily due to fertilizer application and upstream fertilizer production, including nitrate (NO_3^-) leaching, nitrogen emissions, and phosphate releases [121]. For wood chips, the largest contribution also comes from field activities (68% of total EP), followed by chipping (7%), and material handling (6%). In forestry operations, eutrophication impacts arise from harvesting activities such as forest floor disturbance, root removal, soil compaction, and the accumulation of slash, branches, and leaves on site, which increase nutrient runoff and aquatic eutrophication potential [122]

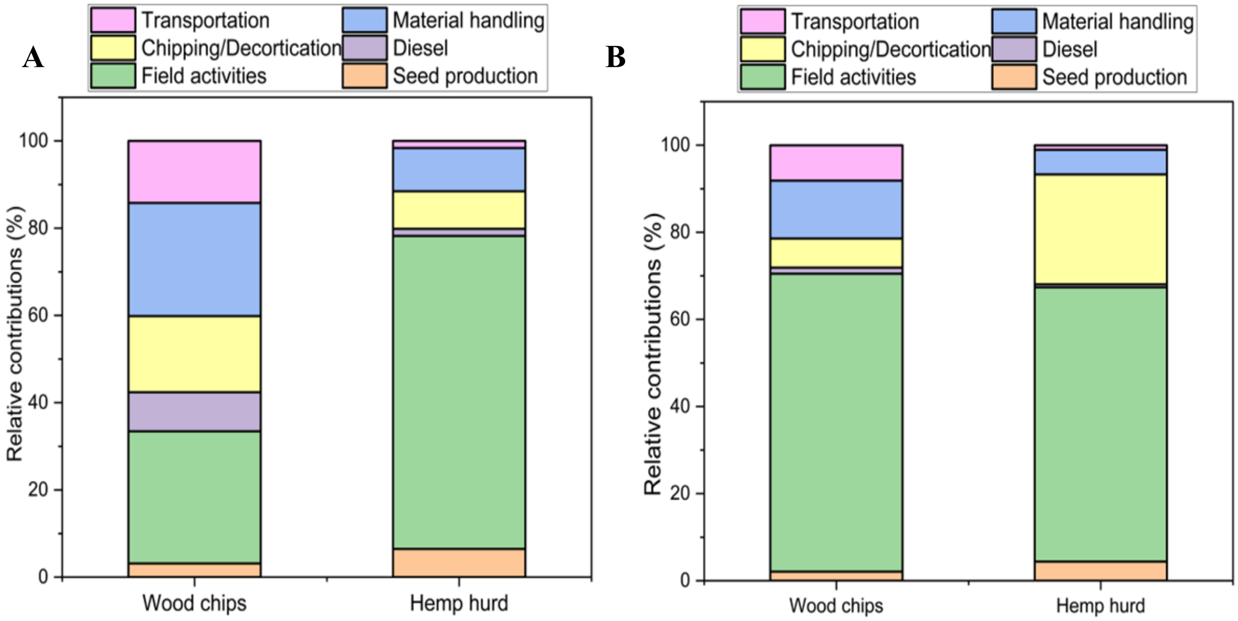

Figure 3.7: Relative contributions to (A) acidification, and (B) eutrophication for wood chips and hemp-hurd scenarios. “Field activities” refer to agricultural production (fertilizer) for hemp hurd and harvesting, sawing, forwarding for wood chips. Material handling refers to baling, bale loading, and skidding. Transport refers to transportation of tree logs, seeds and seedlings, and bales to the pulp mill.

Fossil fuel depletion (FED)

The fossil fuel depletion (FFD) values for hemp hurd and wood chips were 613 and 150 MJ surplus per MT, respectively, indicating a substantially higher fossil energy burden for the hemp-based system. In hemp hurd production, field activities represent the largest share of FFD (27%), primarily driven using crude oil and natural gas for fertilizer manufacture and agricultural operations [27]. Conversely, the wood-chip system is dominated by downstream energy requirements: transportation (26%), material handling (22%), and chipping (24%) contribute most of the fossil fuel use (Figure 3.8A), due to the substantial mass and size of whole tree logs that require intensive handling and processing [123].

For hemp hurd, contributions from transportation (6.3%), material handling (18%), and decortication (27%) reflect the fossil energy embodied in machinery production and the mechanical processing steps required for fiber separation [124].

Global warming potential (GWP)

Hemp hurd has substantially higher GWP during field-activity stage compared with wood chips, contributing 47% of total GWP (38% indirect and 9% direct emissions), whereas forestry-based wood chips contribute only 26%. This difference is driven primarily by using ammonium-nitrate fertilizer in hemp cultivation, which accounts for 30% of hemp's field-activity emissions. Dominant fertilizer-related GWP mechanisms include N_2O and CO_2 emissions from soil nitrogen application, as well as emissions from nitric acid production and fossil-fuel-based electricity used in fertilizer manufacture [121].

Downstream operations further differentiate the systems: wood chips show markedly higher emissions from transportation (24%), material handling (18%), and diesel consumption (4%), reflecting the greater mass, length, and logistics burden associated with whole tree logs. Processing emissions also differ, hemp decortication accounts for 28% of total GWP, slightly higher than 24% for wood chipping operations. This difference arises from mass allocation, which favors the hurd fraction, while the entire debarked log mass is allocated to wood chips during chipping operations.

Collectively, these results underscore that agricultural inputs dominate hemp's GWP, whereas transport and mechanical handling dominate the GWP of wood chips.

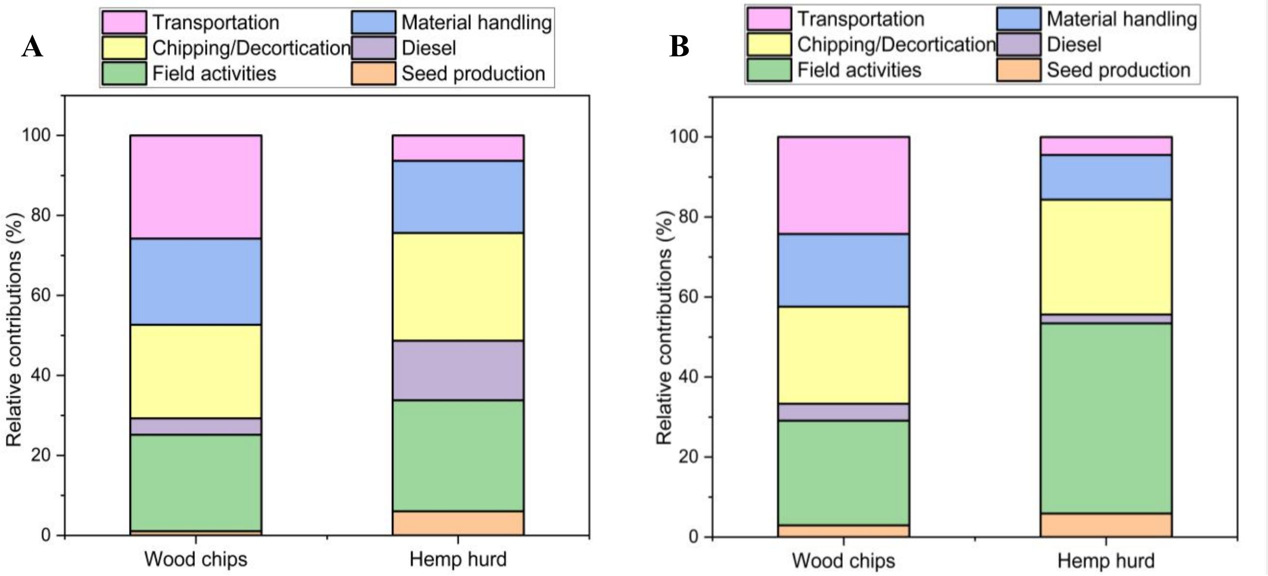

Figure 3.8: Relative contributions to (A) Fossil fuel emissions, (B) Global warming potential for wood chips and hemp hurd scenarios. “Field activities” refers to agricultural production (fertilizer) for hemp hurd and harvesting, sawing, and forwarding for wood chips. Material handling refers to baling, bale loading, and skidding. Transport refers to movement of tree logs, seeds and seedlings, and bales to pulp mill.

3.5. CO_2 Uptake Estimation, GWP, and Net Carbon Footprint

Despite the higher GWP of hemp relative to conventional materials, its long-term carbon mitigation potential remains greater for both paper and textile applications. As shown in Figure 3.9, hemp hurd achieves higher net carbon sequestration (−189.86 MT CO_2-eq per hectare per 25 years) compared with wood chips (-153 MT CO_2 eq per hectare per 25 years), due to rapid biomass accumulation, high photosynthetic efficiency, and shorter cultivation cycles that offset its higher fossil energy requirements [125]. Similarly, bast fiber surpasses cotton lint, attaining net carbon sequestration of −61 MT CO_2-eq per hectare per 25 years, whereas cotton lint results in net emissions of 36.64 MT CO_2-eq per hectare per 25 years. This advantage is driven by hemp’s higher yields, lower fossil-input intensity, and more efficient carbon uptake. Hemp dust also shows a lower net carbon footprint of −28 MT CO_2-eq per hectare per 25 years.

Table 3.1: CO_2 uptake estimation, GWP, and net carbon footprint (MT CO_2 eq per hectare over 25 years) for the baseline NCRS (SF) scenario.

	CO_2 sequestration	**GWP**	**Net carbon footprint**
Retted biomass	−361.68	31.24	−330.44
Hemp hurd	−245.94	56.08	−189.86
Wood chips	−159.86	5.89	−153.97
Decorticated bast fiber	−79.56	18.09	−61.47
Cotton lint	−14.44	50.9	36.46
Dust	−36.17	8.14	−28.03

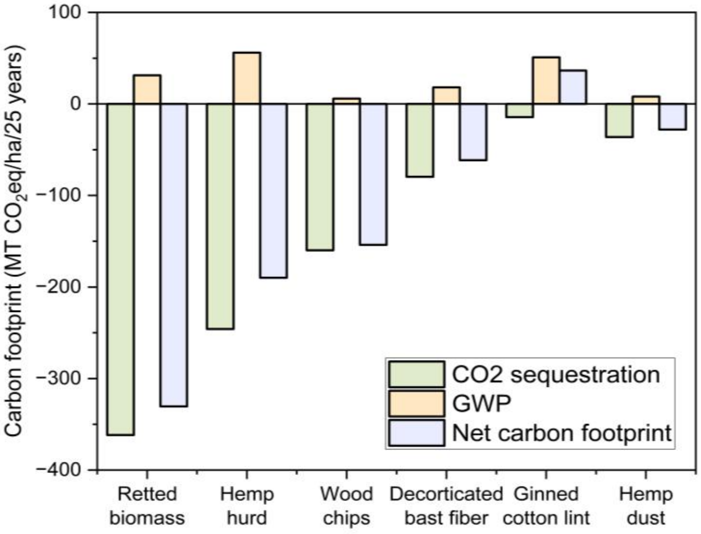

Figure 3.9: Comparative analysis of CO_2 uptake, fossil emissions, and net carbon footprint for hemp hurd, wood chips, bast fiber, cotton fiber and dust, expressed in MT CO_2-eq per hectare over 25 years.

3.6. Sensitivity Analysis

3.6.1. Sensitivity analysis based on economic allocation

In the baseline scenario, bast fiber receives 81% of the total environmental burden due to its dominant economic value, resulting in the highest GWP (1024 kg CO_2-eq per MT), whereas hemp hurd and dust shows 66 kg CO_2-eq per MT and 58 kg CO_2-eq per MT, respectively. When the relative prices of hemp hurd and dust increase by 25%, their allocation factors rise (to 0.195 for hemp hurd and 0.026 for dust), shifting a portion of the burden away from bast fiber. As a result, the attributed GWP of bast fibers decreases slightly, while the GWP of hemp hurd and dust increases to 76 kg CO_2-eq per MT and 67 kg CO_2-eq per MT, respectively. Conversely, when the prices decrease by 25%, bast fiber allocation factor increases to 0.854, concentrating more of the process emissions on the bast fiber. Under this scenario, the GWP of hemp hurd and dust decreases to 59 kg CO_2-eq per MT and 53 kg CO_2-eq per MT, respectively (Figure 3.10).

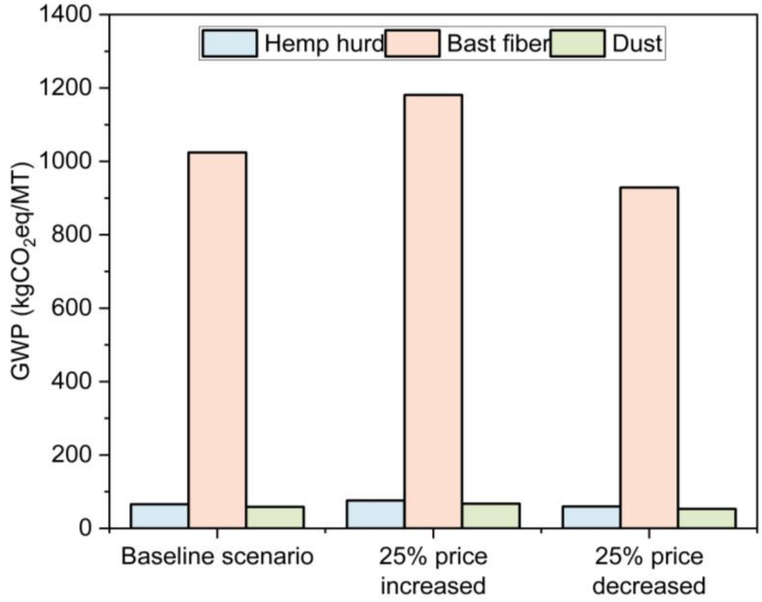

Figure 3.10: Sensitivity analysis based on economic allocation for one dry ton of hemp hurd, bast fiber and dust.

3.6.2. Sensitivity analysis based on nitrogen fertilizer

Ammonium nitrate fertilizer is the primary hotspot in hemp cultivation. In retted biomass cultivation (Figure 3.11A), the baseline scenario emits 150 kg CO_2 eq per MT of retted biomass. When the nitrogen fertilizer application increases to 174.6 kg per hectare scenario 1, GWP increased to 220 kg CO_2-eq per MT. In scenario 2, when ammonium nitrate is reduced to 75.3 kg per hectare, GWP decreased to 135 kg CO_2-eq per MT. In Figure 3.11B, scenario 2 shows 80 % of the GWP of scenario 1 while the baseline scenario shows 90% of scenario 1's GWP, illustrating the strong influence of nitrogen fertilizer rate on emissions intensity.

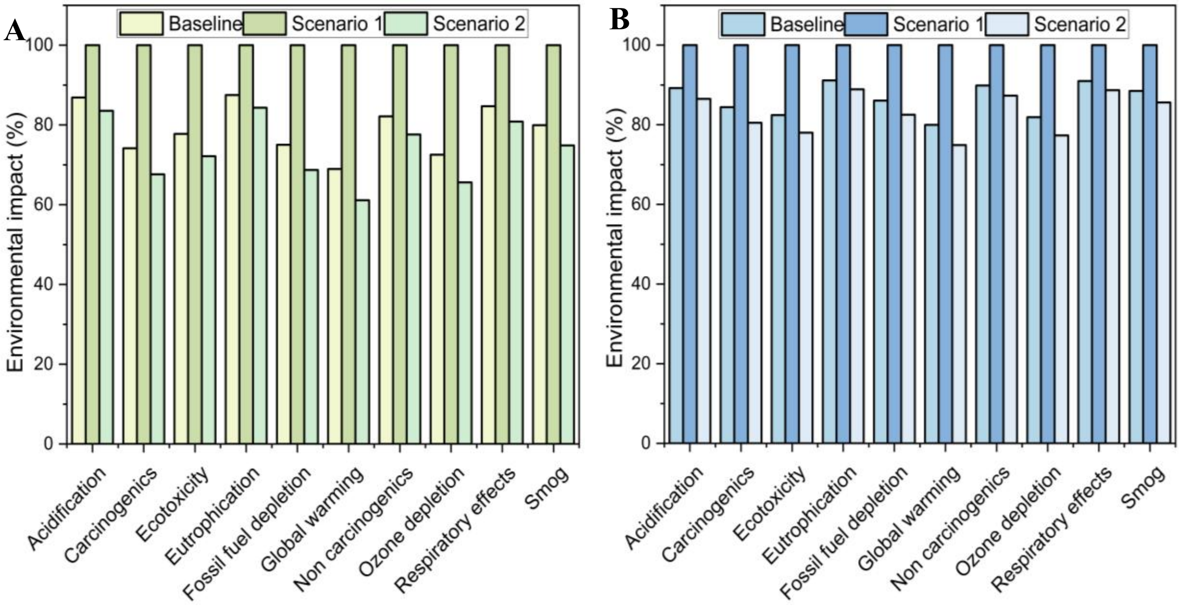

Figure 3.11: Sensitivity analysis based on the nitrogen fertilizer input intensity for (A) 1 MT of retted biomass and (B) 1 MT of hemp hurd, 0.32 MT of bast fiber and 0.15 MT of dust (fiber processing stage).

In Figure 3.12A, the baseline scenario results in 402 kg CO_2-eq per MT for all the outputs according to mass allocation. Scenario 2 reduces this impact to 377 kg CO_2-eq per MT, whereas scenario 1 increases it to 503 kg CO_2-eq per MT (scenario 1). GWP emissions for the baseline scenario are 66 kg CO_2-eq per MT for hemp hurd, 1024 kg CO_2-eq per MT for bast fiber and 58 kg CO_2-eq per MT for dust. For bast fiber specifically, GWP varies from 1280 kg CO_2-eq per MT (scenario 1) to 959 kg CO_2-eq per MT (scenario 2). This trend clearly demonstrates that increasing fertilizer application rates exacerbate environmental burdens across all categories. Reducing fertilization inputs (scenario 2), lowers impacts by ~5% and increasing fertilizer input (scenario 1) increases the environmental impacts by ~10%, emphasizing fertilizer intensity as a primary driver of system-wide emissions.

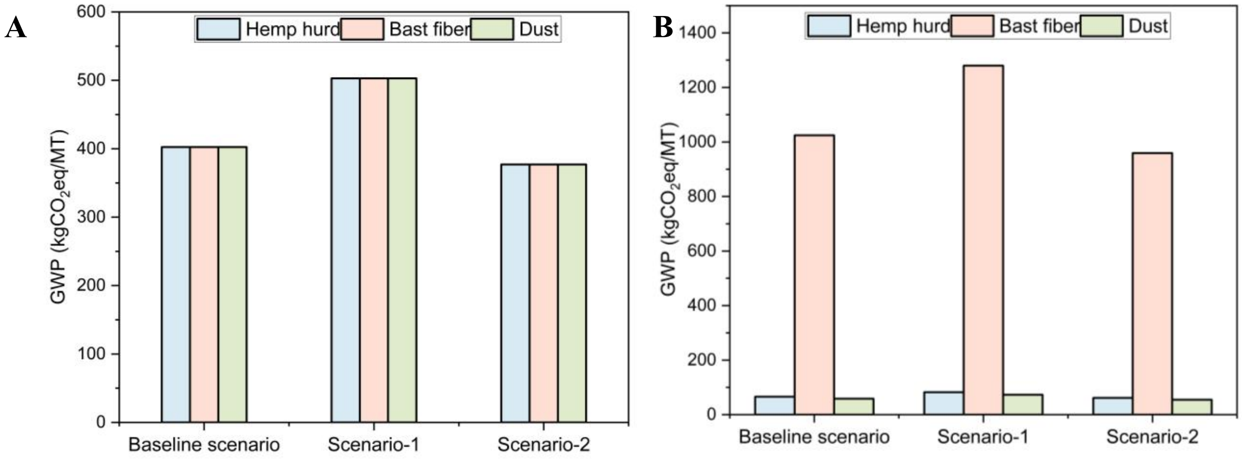

Figure 3.12: Sensitivity analysis based on the nitrogen fertilizer input intensity for (A) mass allocation and (B) economic allocation.

3.6.3. Sensitivity analysis based on yield

The comparison of environmental impacts across three yield-based scenarios: baseline yield, a 25% increase and a 25% decrease, reveals that increasing crop yield significantly reduces environmental burdens per unit of production while decreasing yield substantially increases them Higher yield demonstrates the lowest impacts, while reduced yields result in the highest GWP [126]. In Figure 3.13A, the yield of retted biomass shows significant impact on environmental impacts compared with baseline. When yield is increased by 25% GWP decreases from 150 kg CO_2-eq per MT to 126 kg CO_2-eq per MT. Conversely, when yield decreases by 25%, GWP rises to 194 kg CO_2-eq per MT. In Figure 3.13B, representing the fiber processing stage, increasing yield reduces GWP from 402 kg CO_2-eq per MT to 365 kg CO_2-eq per MT, while a 25 % decrease in yield elevates GWP to 464 kg CO_2- eq per MT. These changes occur because increasing yield reduces the relative burden of field-input operations, making the system less energy-intensive and lowering impacts from agricultural practices[127].

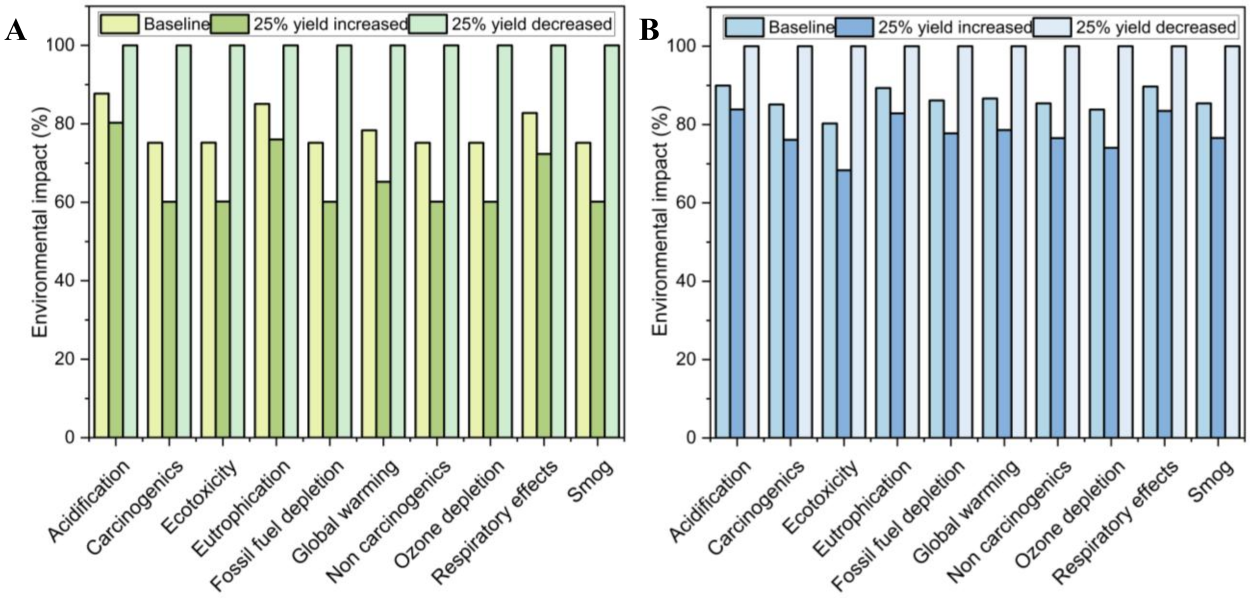

Figure 3.13: Sensitivity analysis based on yield assumption for (A) 1 MT of retted biomass and (B) 1 MT of hemp hurd, 0.32 MT of bast fiber and 0.15 MT of dust (fiber processing stage).

As shown in Figure 3.14A, GWP decreases to 365 kg CO_2-eq per MT when yield is increased by 25%, likely due to more efficient fuel and nutrient use per kilogram of crop produced. The baseline scenario falls between the high- and low-yield cases, but its relative closeness to the lower-impact scenario suggests inefficiencies in current practices, such as suboptimal input use or limited adoption of precision agriculture [128]. When yield decreases by 25%, mass-allocated GWP increases by 15.36% across all outputs. Under economic allocation (Figure 3.11B), reduced yield similarly increases emissions for all coproducts: hemp hurd rises from 66 to 76 kg CO_2-eq per MT, bast fiber from 1024 to 1181 kg CO_2-eq per MT, and dust from 58 to 67 kg CO_2-eq per MT. These results demonstrate that lower productivity substantially amplifies environmental burdens, while higher yields dilute impacts per functional unit, reinforcing yield as a critical determinant of system-emissions

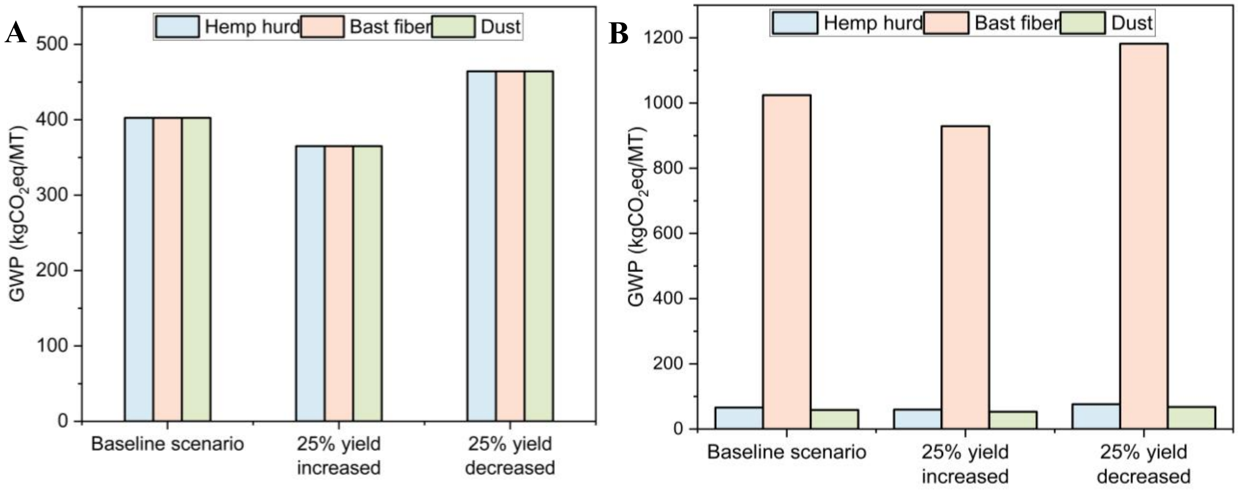

Figure 3.14: Sensitivity analysis based on yield for one dry ton of hemp hurd, bast fiber and dust under (A) mass allocation and (B) economic allocation.

In Figure 3.15 (A), CO_2 sequestration, GWP and net carbon footprint are analyzed based on assumption of a 25% increase in yield from baseline scenario. CO_2 sequestration also increases from −361 to −484 MT CO_2-eq per hectare per 25 years for retted biomass; from −245 to −307 MT CO_2-eq per hectare per 25 years for hemp hurd; and from −79 to −99 MT CO_2-eq per hectare per 25 years for bast fiber. These changes subsequently reduce the net carbon footprint, making hemp hurd a more sustainable biomass source than wood chips. For bast fiber, the comparison with cotton lint is especially notable: cotton lint shows a positive net carbon balance, whereas bast fiber maintains a negative one, indicating that bast fiber is a more sustainable raw-material alternative for the textile industry.

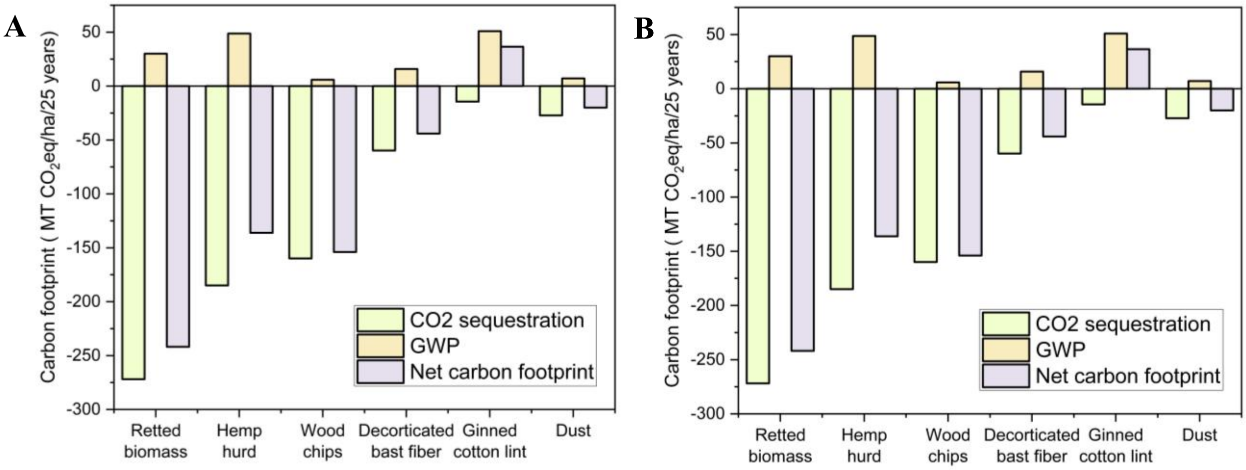

Figure 3.15: CO_2 sequestration sensitivity analysis based on yield for dry tons of hemp hurd, bast fiber and dust per hectare over 25 years under (A) 25% yield increase and (B) 25% yield decrease.

Table 3.2: CO_2 uptake estimation, GWP, and net carbon footprint expressed (MT CO_2 eq per hectare per 25 years) assuming a 25% yield increase from baseline scenario NCRS (SF).

	CO_2 sequestration	**GWP**	**Net carbon footprint**
Retted biomass	−484.44	32.63	−451.81
Hemp hurd	−307.88	63.85	−244.03
Wood chips	−159.86	5.89	−153.97
Decorticated bast fiber	−99.62	20.66	−78.96
Cotton lint	−14.44	50.9	36.46
dust	−45.28	9.39	−35.89

When the yield is decreased by 25% from the baseline scenario CO_2 sequestration, and GWP both decreases, but the net carbon footprint increases from the baseline. Compared with wood chips, hemp hurd shows a slightly higher net carbon footprint under the reduced yield scenario, demonstrating that biomass yield strongly influences environmental outcomes.

Table 3.3: CO_2 uptake estimation, GWP, and net carbon footprint expressed (MT CO_2 eq per hectare per 25 years) assuming a 25% yield decrease NCRS (SF).

	CO_2 sequestration	**GWP**	**Net carbon footprint**
Retted biomass	−271.92	30.03	−241.89
Hemp hurd	−184.91	48.75	−136.16
Wood chips	−159.86	5.89	−153.97
Decorticated bast fiber	−59.82	15.77	−44.05
Cotton lint	−14.44	50.9	36.46
dust	−27.19	7.17	−20.02

3.6.4. Sensitivity analysis based on transportation

The sensitivity analysis from Figures 3.16A and 3.16B reveals that transportation distance exerts a significant influence on impact categories directly associated with energy consumption and emissions. GWP increases from approximately 389.44 kg CO_2-eq per MT (scenario 2) at 50 km to 414.51 kg CO_2-eq per MT (scenario 1) at 500 km in Figure 3.16A.

Under economic allocation, environmental impacts rise by 3% with increasing transportation distance. Figure 3.16B shows that hemp hurd has a GWP of 63.72 kg CO_2-eq per MT at 50 km transportation distance (scenario 1). For bast fiber, GWP ranges from 1055.06 kg CO_2-eq per MT at 500 km to 991.25 kg CO_2-eq per MT at 50 km, while dust ranges from 60.24 kg CO_2-eq per MT to 56.59 kg CO_2-eq per MT across the same distance range. These increases occur due to the additional crude oil and natural gas required to produce the diesel consumed by transportation vehicles [129]

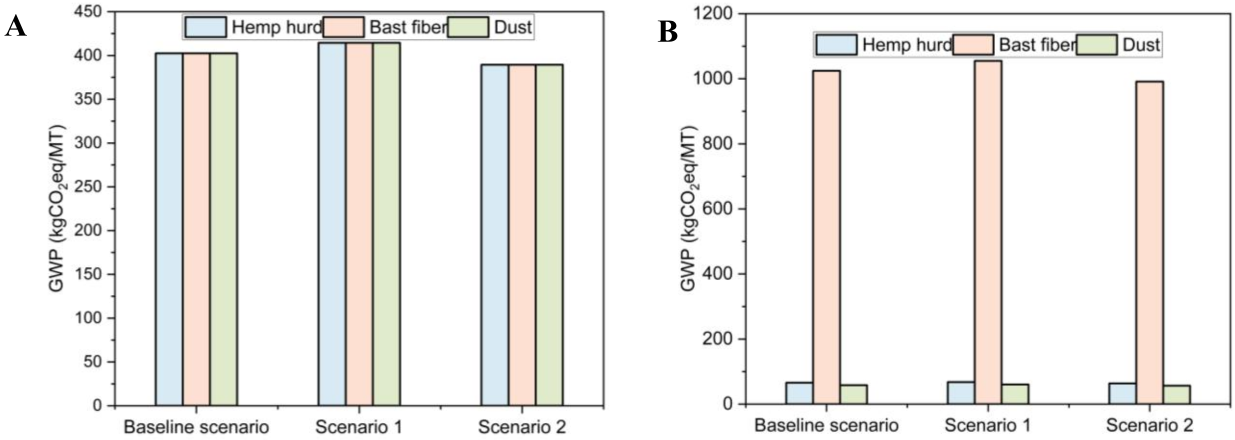

Figure 3.16: Sensitivity analysis based on road transportation for (A) mass allocation and (B) economic allocation.

CHAPTER 4

Conclusions and Future Scope

4.1. Conclusions

The combined results of the LCA and sensitivity analyses reveal that allocation method, cultivation practices, fertilizer use, transportation distance, yield variation, and market allocation are critical determinants of GWP and overall environmental sustainability for retted biomass and hemp-based products. For retted biomass, the baseline scenario shows a GWP of 152 kg CO_2-eq per MT. In the baseline NCRS (SF) scenario, under mass allocation, the total GWP for producing 1 MT of hemp hurd, 0.32 MT of bast fiber, and o.15 MT of dust is 402 kg CO_2-eq, distributed evenly across coproducts. When economic allocation is applied, the GWP increases substantially for the high-value bast fiber (1024 kg CO_2-eq per MT), while the burdens assigned to hemp hurd (66 kg CO_2-eq per MT) and dust (58 kg CO_2-eq per MT) are much lower, demonstrating that market value strongly influences environmental burden distribution. The largest emission sources for the fiber-processing stage include ammonium nitrate fertilizer (30%) and electricity use (28%), followed by baling (10.5%) and hemp seed production (5%), indicating that fertilizer production and energy-intensive processing dominate overall impacts.

For retted biomass, the NCRS (SF) scenario results in 152 kg CO_2-eq per MT, with the lowest impact in the NCRS (WF) scenario (47 kg CO_2-eq per MT) and the highest in the Mountain (SF) scenario (583 kg CO_2-eq per MT). For fiber-processing outputs under different cultivation scenarios, GWP ranges from 247.8 kg CO_2-eq per MT under fertilizer-free conditions to 800.9 kg CO_2-eq per MT when synthetic fertilizers are used in mountain regions, confirming that synthetic fertilizers substantially elevate emissions through energy-intensive production and N_2O release. In contrast, organic and fertilizer-free systems achieved 45–50% reductions in GWP. Under different allocation approaches, bast fiber shows GWP values between 630.63–2038.49 kg CO_2-eq per MT, hemp hurd between 40.54–131.05 kg CO_2-eq per MT, and dust between 36–116.39 kg CO_2-eq per MT, illustrating the combined impact of coproduct value and management practice. In the organic-fertilizer (OF) scenario, emissions fall to 43.14 kg CO_2-eq per MT (hemp hurd), 671.12 kg CO_2-eq per MT (bast fiber), and 38.32 kg CO_2-eq per MT (dust), reinforcing that input optimization improves environmental performance.

Retted biomass shows a net carbon footprint of –330 MT CO_2-eq per hectare per 25 years. Hemp demonstrates clear environmental advantages over conventional materials such as cotton and wood chips, supported by substantial net carbon sequestration of –189 MT CO_2-eq per hectare per 25 years for hemp hurd and –61 MT CO_2-eq per hectare per 25 years for bast fiber. These findings are consistent with GWP data showing that cotton lint and cotton yarn emit 2036 kg CO_2-eq per MT and 8600 kg CO_2-eq per MT, respectively, whereas bast fiber after decortication and bast fiber yarn emit only 402 kg CO_2-eq per MT and 5200 kg CO_2-eq per MT. Bast fiber yarn production thus has approximately 40% lower GWP than cotton yarn, highlighting hemp as a more sustainable textile alternative.

Sensitivity analysis confirmed that changes in market value can significantly alter perceived sustainability performance, even though total system emissions remain constant. Economic allocation shows that bast fiber receives about 81% of the total burden due to its dominant economic value. When prices for hemp hurd and dust increase by 25%, their allocation factors rise to 0.195 and 0.026, slightly reducing bast fiber's share. When prices decrease by 25%, bast fiber allocation factor increases to 0.854, increasing its apparent environmental load. This demonstrates how market changes can reshape perceived sustainability profiles despite unchanged underlying emissions.

Fertilizer intensity is another major driver. Ammonium nitrate was identified as the primary hotspot. In the baseline scenario, for retted biomass, GWP increases from 150 kg CO_2-eq per MT to 220 kg CO_2-eq per MT with higher N-fertilizer application and decreases to 135 kg CO_2-eq per MT with reduced application. For coproducts, total GWP is 402 kg CO_2-eq per MT, with fertilizer-sensitivity scenarios ranging from 377 to 503 kg CO_2-eq per MT under mass allocation. Under economic allocation, bast fiber's GWP ranges from 959 to 1280 kg CO_2-eq per MT, indicating that fertilizer intensity can increase impacts by up to 10.4%, while reduced inputs lower emissions by about 5%.

Yield-based sensitivity results revealed that increasing yield by 25% reduces the GWP of retted biomass from 150 to 126 kg CO_2-eq per MT, while decreasing yield by 25% increases it to 194 kg CO_2-eq per MT. For hemp hurd, bast fiber and dust, mass allocated GWP increases by 15.36% under decreased yield. Under economic allocation, decreased yield increases GWP from 66 to 76 kg CO_2-eq per MT (hemp hurd), 1024 to 1182 kg CO_2-eq per MT (bast fiber), and 58 to 67 kg CO_2-eq per MT (dust), showing that higher yields dilute fixed environmental burdens and reduce per-unit impacts.

Transportation also exerts a measurable influence: increasing distance from 50 km to 500 km raises GWP from 389 to 414 kg CO_2-eq per MT, a 3% increase. Under economic allocation, emissions vary from 63–66 kg CO_2-eq per MT for hemp hurd, 991–1055 kg CO_2-eq per MT for bast fiber, and 56–60 kg CO_2-eq per MT for dust, confirming that optimizing transport logistics can meaningfully reduce impacts.

Overall, these results demonstrate that fertilizer management, yield improvement, transport optimization, and transparent allocation are pivotal for minimizing emissions and enhancing the sustainability of hemp production. Transitioning to organic or fertilizer-free systems, adopting renewable electricity, and selecting market-stabilized allocation methods can reduce GWP by nearly half while maintaining productivity. Hemp's strong carbon-sequestration capacity and superior performance relative to cotton and wood establish it as a climate-positive, low-impact, and economically viable material for bio-based and textile industries, supporting long-term sustainability goals.

4.2. Future scope

4.2.1. Development Of Low-Input Hemp Cultivation System

Since fertilizer use, particularly ammonium nitrate, is a major contributor to GWP, future work could focus on evaluating organic or bio-based fertilizers, precision nutrient management strategies, or intercropping systems that reduce emissions while maintaining fiber yield. Biochar, a carbon-rich material produced via pyrolysis of organic biomass under limited oxygen, improves soil aeration, water retention, and nutrient-holding capacity, while also acting as a long-term carbon sink, thereby contributing to climate change mitigation.

Biofertilizers, which contain live or dormant microorganisms such as nitrogen-fixing bacteria (*Rhizobium*, *Azotobacter*), phosphate-solubilizing bacteria (*Bacillus*, *Pseudomonas*), and mycorrhizal fungi, also enhance plant growth by improving nutrient availability, soil structure, and root development. Unlike synthetic fertilizers that often cause nitrate leaching and GHG emissions, biofertilizers and biochar can reduce dependency on chemical inputs and restore soil biological activity.

Hemp dust can be converted into biochar and reapplied as a soil amendment, creating a circular bioeconomy loop within hemp cultivation. Additionally, hemp dust may be used in hempcrete production, adding value to a traditionally low-value byproduct.

4.2.2. Lifecycle Impact of Blended Fibers and Composites

With growing interest in sustainable materials, blended fibers and bio-composites, such as hemp-cotton yarns or hemp-wood fiber panels, are gaining traction in both textile and construction industries. These hybrid materials combine favorable properties across feedstocks, such as hemp's tensile strength and cotton's softness, or hemp hurds' low density with wood's structural rigidity. However, while these blends offer functional advantages, their environmental implications remain understudied. Future research can undertake comprehensive lifecycle assessments (LCA) to evaluate trade-offs in carbon footprint, energy demand, water use, and end-of-life scenarios. Blends may dilute the environmental benefits of hemp if they incorporate high-impact components (e.g., conventionally grown cotton or fossil-based binders), or they may enhance overall sustainability if they displace more carbon-intensive inputs.

Key challenges such as processing compatibility, recyclability, and durability should be factored into impact models. As blended materials continue to enter commercial markets, developing standardized LCA methodologies for multi-material systems will be essential to support design decisions and guide sustainable product development.

4.2.3. End-of-Life Scenarios and Circularity

Most LCAs of hemp-based materials focus on cradle-to-gate or cradle-to-use boundaries, often excluding the critical end-of-life (EoL) phase. Future studies could incorporate EoL pathways such as composting, anaerobic digestion, recycling, incineration with energy recovery, or reuse in secondary applications (e.g., soil amendments, insulation filler). Evaluating these pathways through LCA will help quantify the full environmental benefits of hemp-based products, including biodegradability, carbon sequestration potential, and compatibility with circular economy models.

Integrating EoL performance into material design will also support eco-design practices and regulatory compliance, especially as environmental product declarations (EPDs) and circularity metrics gain prominence in green building standards and textile certifications.

4.2.4. Optimization of Processing Energy Mix

While hemp cultivation typically has a low environmental impact, post-harvest processes such as retting, decortication, drying, and fiber refinement can contribute significantly due to their reliance on electricity and thermal energy, often sourced from nonrenewable sources. Future studies could investigate energy-efficient technologies such as microwave retting, solar-assisted drying, and low-energy fiber extraction methods. Additionally, integrating renewable energy sources (solar, biomass, biogas, or on-site energy recovery from hemp residues) can be considered to further reduce global warming potential (GWP) and improve the overall sustainability of hemp-based products. Such optimization efforts will be critical for meeting carbon-neutrality targets and advancing climate-smart bioproducts.

4.2.5. Comparison Across Regions and Climates

Environmental impacts of hemp systems vary depending on regional conditions, including climate, soil type, farming practices, and energy grid composition. Conducting comparative LCAs across diverse ago-climatic zones can identify region-specific hotspots and guide tailored strategies for sustainable production. For instance, the benefits of hemp cultivation in a region with a renewable-heavy energy grid and low irrigation demand may differ significantly from those in areas with intensive fossil-based electricity and water stressed regions. Such comparisons are vital for establishing contextual benchmarks, supporting geographically relevant policy decisions, and informing international standardization efforts within the emerging hemp-based bioeconomy.

4.2.6. Techno-Economic and Policy Analysis

While environmental assessments provide critical insights, the commercial viability of hemp-based materials must also be evaluated through techno-economic analysis (TEA). Future research could assess the cost-effectiveness of hemp production systems, considering factors such as input costs, processing technology investments, product pricing, and supply chain logistics. Additionally, the role of policy mechanisms, such as carbon credits, renewable material incentives, green procurement standards, and farm subsidies, could be examined to understand their influence on scaling adoption. Integrating LCA with TEA and policy modeling can enable holistic assessments that align environmental benefits with economic feasibility and regulatory pathways, facilitating a transition toward sustainable material systems at scale.

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Appendices

Appendix A-Chapter 2

2.1. Life cycle inventory for hemp seed production

Hemp seed production data was taken from [29] where it explained the process of hemp seed production in conventional method.

Table S2.1: Inputs and outputs to produce one dry ton of hemp seed.

Parameter	Unit operation	Amount	Units
Input			
Fertilizer production	Ammonium nitrate	48.00	kg
	Triple superphosphate	63.00	kg
Field Activities	Ploughing	1.00	ha
	Harrowing	1.00	ha
	Sowing	1.00	ha
	Fertilizer applying	1.00	ha
	Harvesting	1.00	ha
Transportation	Field site	245	t*km
Outputs	Hemp seed	1.00	t

Table S2.2: Provider used to produce one dry ton of hemp seed.

Parameter	Unit operation	Provider
Fertilizer production	Ammonium nitrate	market for ammonium nitrate | ammonium nitrate | Cutoff, U - RoW
	Triple superphosphate	market for triple superphosphate | triple superphosphate | Cutoff, U - RoW
Field Activities	Ploughing	market for tillage, ploughing | tillage, ploughing | Cutoff, U - GLO
	Harrowing	market for tillage, harrowing, by rotary harrow | tillage, harrowing, by rotary harrow | Cutoff, U - GLO
	Sowing	market for tillage, ploughing | tillage, ploughing | Cutoff, U - GLO
	Fertilizer applying	market for fertilizing, by broadcaster | fertilizing, by broadcaster | Cutoff, U - GLO
	Harvesting	market for combine harvesting | combine harvesting | Cutoff, U - GLO
Transportation	Field site	market for transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, U - RoW

Table S2.3: Provider used to produce one dry ton of retted biomass for each unit operation.

Parameter	Unit operation	Provider
Seeds	Planting	Hemp seed
Fertilizer production	Ammonium nitrate, as N	market for ammonium nitrate | ammonium nitrate | Cutoff, U - RoW
	Potassium chloride as, K_2O	market for potassium chloride | potassium chloride | Cutoff, U - RoW
	Triple superphosphate as P_2O_5	market for triple superphosphate | triple superphosphate | Cutoff, U - RoW
Energy	Diesel	market for diesel | diesel | Cutoff, U - RoW

Table S2.4: Provider used to produce one dry ton of hemp hurd, 0.32 dry tons of bast fiber and 0.15 dry tons of dust.

Parameter	Unit operation	Provider
Retted biomass	Decortication	Hemp Stalk
	bale loading	market for bale loading | bale loading | Cutoff, U - GLO
	baling	market for baling | baling | Cutoff, U - GLO
Electricity	Decortication	market for electricity, high voltage | electricity, high voltage | Cutoff, U - US-SERC
Transportation	Pulp mill site	market for transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, U - RoW

Table S2.5: Change of provider considering the use of organic fertilizer as cattle manure (solid).

Parameter	Unit operation	Provider
Fertilizer production Experimental data	Organic nitrogen fertilizer as N	nutrient supply from cattle manure, solid| organic nitrogen fertilizer, as N | Cutoff, U-GLO
	Organic phosphorus fertilizer as P_2O_5	nutrient supply from cattle manure, solid| organic phosphorus fertilizer, as P2O5 | Cutoff, U - GLO

Table S2.5 (continued).

	Organic potassium fertilizer as K_2O	nutrient supply from cattle manure, solid| organic potassium fertilizer, as K2O | Cutoff, U - GLO

2.3. System boundary for chopped stem (Retted biomass cutting scenario)

After cultivation of retted biomass, it can be used directly to the pulping industries without decortication. For this case, retted biomass is chopped using a hammer mill instead of decortication without any loss of raw materials which reflects the whole material utilization also reduced the burden on energy consumption.

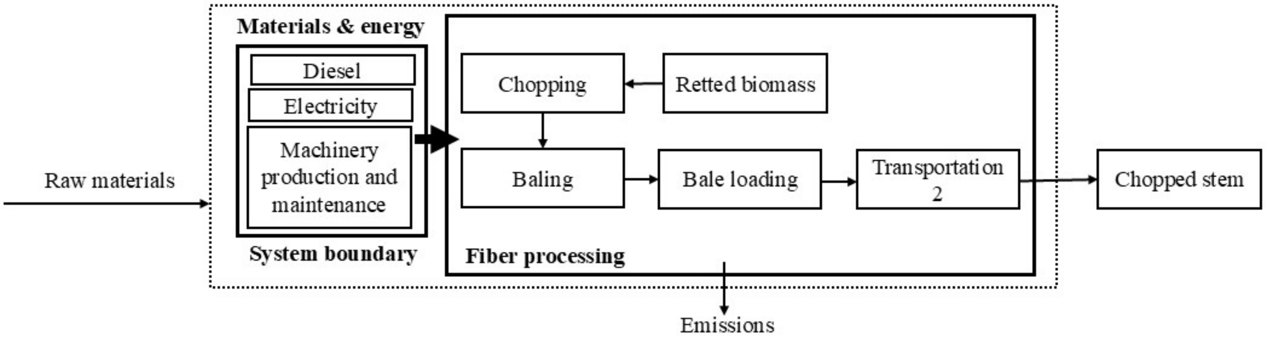

Figure S2.1: System boundary for chopped hemp stem.

Table S2.6: Inputs and outputs of chopping to produce one dry ton of chopped hemp stem.

Parameter	Unit operation	Amount	Units
Inputs	Retted biomass	1.00	t
	Baling	5.95	number (s)
	Bale loading	5.95	ha
Energy	Chopping	65.97	kWh
Transportation [38]	Field site	6.51	t*km
	Industry site	180	t*km
Outputs	Chopped stem	1.00	t

Appendix B-Chapter 3

3.1. Environmental impacts

Table S3.1: Environmental impacts for one ton of retted biomass

Impact category	Reference unit	Result
Acidification	kg SO2 eq	1.48
Carcinogenic	CTUh	9.72E-06
Ecotoxicity	CTUe	2474.58
Eutrophication	kg N eq	0.69
Fossil fuel depletion	MJ surplus	203.09
Global warming	kg CO2 eq	152.32
Non carcinogenic	CTUh	4.35E-05
Ozone depletion	kg CFC-11 eq	2.06E-06
Respiratory effects	kg PM2.5 eq	0.13
Smog	kg O3 eq	7.49

Table S3.2: Environmental impacts for one ton of hemp hurd, 0.32 ton of hemp hurd and 0.15 ton of dust.

Impact category	Reference unit	Result
Acidification	kg SO2 eq	2.718866
Carcinogenic	CTUh	2.7E-05
Ecotoxicity	CTUe	4881.316
Eutrophication	kg N eq	1.501871
Fossil fuel depletion	MJ surplus	613.4116
Global warming	kg CO2 eq	402.4783
Non carcinogenic	CTUh	0.000124
Ozone depletion	kg CFC-11 eq	5.2E-06
Respiratory effects	kg PM2.5 eq	0.352844
Smog	kg O3 eq	21.28794

3.2. Comparison of wood chips vs hemp hurd

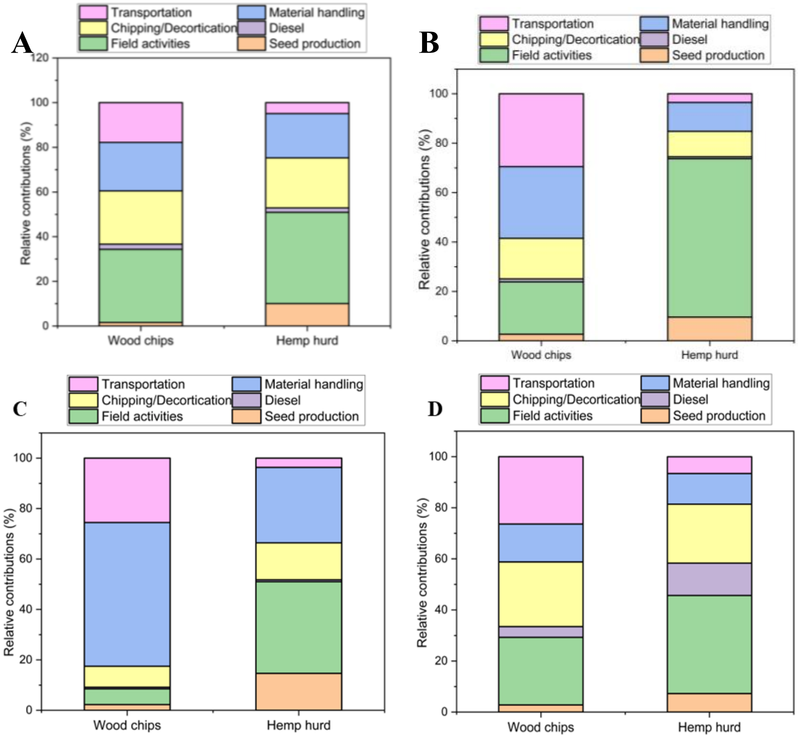

Figure S3.1: Relative contributions of wood chips vs hemp hurd (A) carcinogenic, (B) ecotoxicity, (C) non-carcinogenic, (D) ozone- depletion.

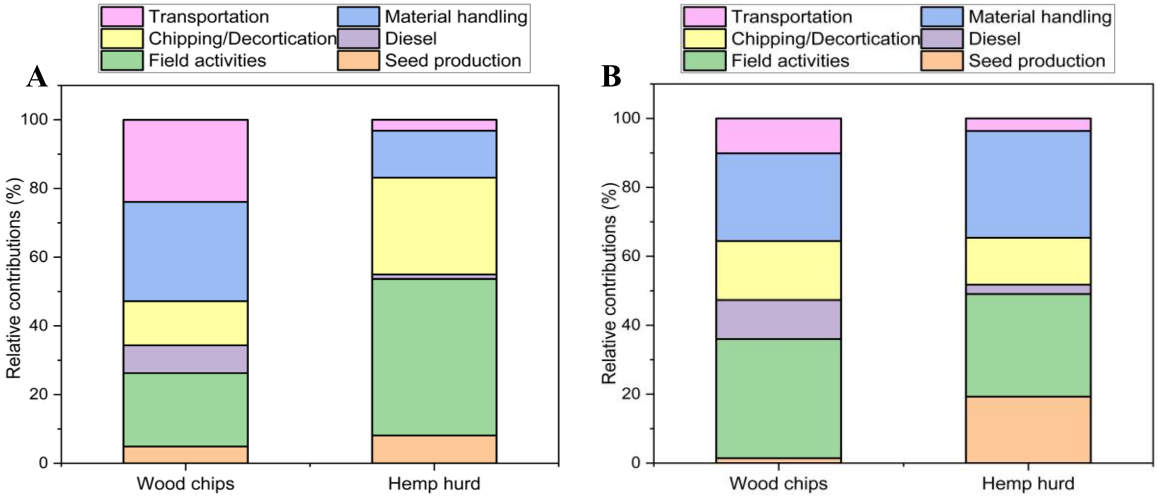

Figure S3.2. Relative contributions of wood chips vs hemp hurd (A) respiratory effects and (B) smog.

3.3. Calculation of mass and economic allocation

Scenario-1, 25% of hemp hurd and dust price increased

The prices for all three products depend on the condition of hemp hurd and bast fiber, purity of the dust. Price for hemp hurd in the USA for hemp hurd \$112.5/ dry ton, bast fiber \$1400/ dry ton, and dust \$80/ dry ton. The allocation factors to produce 1 ton of hemp hurd, 0.32 ton of bast fiber, and 0.15 ton of dust are given below, respectively.

Allocation factor for hemp hurd = (112.5*1)/ ((112.5*1) +(1400*0.32) +(100*0.15))

= 112.5/(112.5+448+15) =112.5/575.5 =0.1954

Allocation factor for bast fiber = (1400*0.32)/((112.5*1) +(1400*0.32) +(100*0.15))

= 448/(112.5+448+15) =448/575.5 =0.7785

Allocation factor for dust = (100*0.15)/((112.5*1) +(1400*0.32) +(100*0.15))

= 15/575.5 = 0.0261

Scenario-2, 25% of hemp hurd and dust price decreased:

The prices for all these three products depend on the condition of hemp hurd and bast fiber, purity of dust. Price for hemp hurd in the USA for hemp hurd \$67.5/ dry ton, bast fiber \$1400/ dry ton and dust \$60/ dry ton. The allocation factors to produce 1 ton of hemp hurd, bast fiber and dust were given below respectively,

Allocation factor for hemp hurd = (67.5*1)/ ((67.5*1) +(1400*0.32) +(60*0.15))

= 67.5/(67.5+448+9) =67.5/524.5 =0.1287

Allocation factor for bast fiber = (1400*0.32)/((67.5*1) +(1400*0.32) +(60*0.15))

= 448/(67.5+448+9) =448/524.5 =0.8541

Allocation factor for dust = (60*0.15)/((67.5*1) +(1400*0.32) +(60*0.15))

= 9/524.5 =0.0172

Table S3.3: Allocation factors for hemp bast fiber, hemp hurd, and dust based on mass and economic allocation.

Allocation Factors	Bast Fiber	Hemp Hurd	Dust
Baseline	0.8145	0.16363	0.0218
+ 25% price increase for hemp hurd and dust	0.7785	0.1954	0.0261
-25% price decrease for hemp hurd and dust	0.8541	0.1287	0.0172

Environmental impact calculation (Scenario-1)

Environmental impact to produce 1 ton of hemp hurd, 0.32 ton of bast fiber, and 0.15 ton of dust, 402.48 kgCO$_2$ eq.

Environmental impact after doing economic allocation:

hemp hurd= (0.1954*402.48) kgCO$_2$ eq. =78.64 kgCO$_2$ eq.

Bast fiber=(0.7785*402.48) kgCO$_2$ eq. =313.33 kgCO$_2$ eq.

Dust=(0.0261*402.48) kgCO$_2$ eq. =10.50 kgCO$_2$ eq.

Total environmental impacts= (78.64+313.33+10.50) kgCO$_2$ eq. = 402.47 kgCO$_2$ eq.

Calculation of environmental impact for 1 ton of each product,

1 ton of hemp hurd= (78.64/1)=78.64 kgCO$_2$ eq.

1 ton of bast fiber= (313.33/0.32)=979.16 kgCO$_2$ eq.

1 ton of dust= (10.50/0.15)=70 kgCO$_2$ eq.

Environmental impact calculation (Scenario-2)

Environmental impact to produce 1 ton of hemp hurd, 0.32 ton of bast fiber and 0.15 ton of dust 402.48 kgCO$_2$ eq.

Environmental impact after economic allocation:

Hemp hurd= (0.1287*402.48) kgCO$_2$ eq. =51.80 kgCO$_2$ eq.

Bast fiber=(0.8541*402.48) kgCO_2 eq. =343.76 kgCO_2 eq.

Dust=(0.0172*402.48) kgCO_2 eq. =6.92 kgCO_2 eq.

Total environmental impacts= (51.80+343.76+6.92) kgCO_2 eq. = 402.48 kgCO_2 eq.

Calculation of environmental impact for 1 ton of each product,

1 ton of hemp hurd= (51.80/1)=51.80 kgCO_2 eq.

1 ton of bast fiber= (343.76/0.32)=1074.25 kgCO_2 eq.

1 ton of dust= (6.92/0.15)=46.13 kgCO_2 eq.

Table S3.4: Life cycle inventory for one kg of carded cotton fiber [100].

Substance	Quantity	Unit
Inputs		
Electricity	75	kwh
Lubricating oil	0.75	kg
Tap water	20	l
Cleaned cotton fiber	1.15	kg
Outputs		
Carded cotton fiber	1	kg
Waste textile, solid	0.15	kg

Table S3.5: Life cycle inventory for one kg of roved cotton fiber.

Substance	Quantity	Unit
Inputs		
Electricity	50	kwh
Lubricating oil	0.5	kg
Tap water	15	kg
Carded cotton fiber	1	kg
Output		
Roved cotton fiber	1	kg

3.4. Scenario analysis for retted biomass cutting.

Figure 3.3 shows that GWP decreases from about 402 kg CO_2 eq/t in NCRS(SF) to 250 kg CO_2 eq/t in both NCRS (without fertilizer) and NCRS (chopped stem), reaching the lowest value of around 150 kg CO_2 eq/t in NCRS (chopped stem + without fertilizer). The high GWP in NCRS(SF) is mainly due to the use of synthetic fertilizer and unprocessed straw, which generate significaSnt CO_2, CH_4, and N_2O emissions during production and decomposition. Removing fertilizer reduces N_2O emissions from the soil, while chopping the straw improves aeration, leading to more efficient decomposition and lower methane emissions. When both practices are combined, chopped stem without fertilizer, the overall greenhouse gas emissions are minimized, making it the most climate-friendly and sustainable management approach.

Another scenario is considered where electricity is produced from hemp dust and that electricity is used in decortication and in cutting of whole hemp stalk. GWP after using produced electricity for hemp hurd, bast fiber and dust is 286.93 kgCO_2-eq per ton as of mass allocation and 46.95 kgCO_2-eq for hemp hurd, 730.31 kgCO_2-eq of bast fiber 41.70 kgCO_2-eq of dust after doing economic allocation. For whole chopped hemp stalk GWP will be 215.33 kgCO_2-eq.

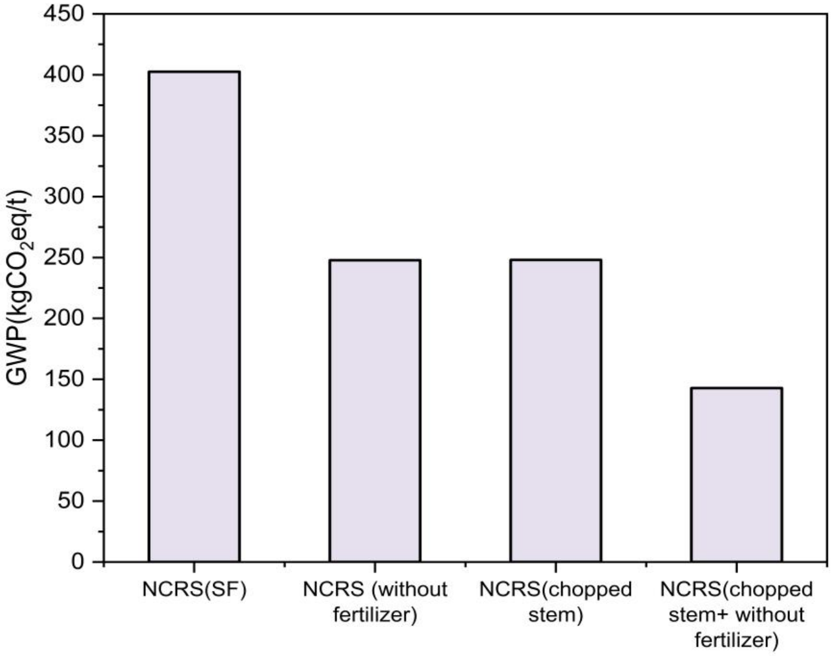

Figure S3.3. Global warming potential for chopped hemp stem (retted biomass cutting scenario).

3.5. Electricity production from hemp dust

The average heating value for hemp dust is 18.44 MJ/kg (dry mass). The amount of dust after decortication is 0.32 tons to get 1 dry ton of hemp hurd. The electricity produced (5.12*0.32) kWh. So, 768.3 kWh can be produced from 0.32 tons of dust. The efficiency is about 33%. So, 256.3 kWh electricity can be produced from 0.32 tons of hemp dust which is further used in electricity needed for decortication of retted biomass. To produce one dry ton of hemp hurd electricity needed for decortication is 233 kWh. This can still have some surplus energy while reducing the environmental burond.