A Critical Review of Industrial Fiber Hemp Anatomy, Agronomic Practices, and Valorization into Sustainable Bioproducts

Munmun Basak,[a] Mason Broadway,[a] James Lewis,[a] Heather Starkey,[a] Margaret Bloomquist,[b] Ilona Peszlen,[a] Jeanine Davis,[b] Lucian A. Lucia,[a,c] and Lokendra Pal,[a,*]

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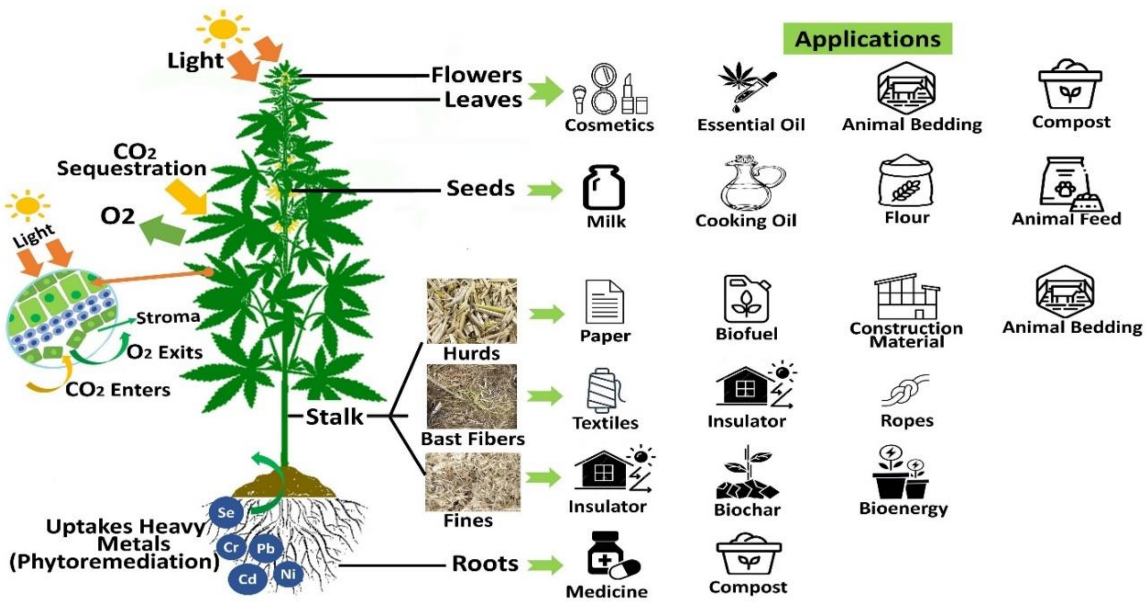
GRAPHICAL ABSTRACT



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The production of industrial hemp (*Cannabis sativa* L.) has expanded recently in the US. Limited agronomic knowledge and supply chain issues, however, stemming from a long-standing cultivation ban, pose a barrier to continued market expansion of hemp, which leads to the import of most hemp products. This review examines the most recent cultivation methods, fertilizer and nutrient requirements, soil management practices, environmental parameters, and post-harvest processing methods, particularly in the context of environmental benefits such as soil phytoremediation and CO_2 sequestration. Details of the valorization of hemp biomass into sustainable products, such as fibers, papers, packaging, textiles, biocomposites, biofuels, biochar, and bioplastics, along with current limitations and scope for improvements, are explored. Finally, an overall summary of the life cycle and techno-economic analysis aimed at optimizing their environmental performance and economic feasibility are discussed with a focus on intersection with the growing circular economy paradigm.

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Keywords: Industrial hemp; Agronomy; Post-harvesting methods; Sustainable fibers; Bioplastics; Biofuels

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INTRODUCTION

Industrial hemp is one of the earliest domesticated plant species for known human cultivation practices spanning millennia (Fike 2016). It is an anemophilous plant belonging to the Cannabaceae family (Farinon *et al.* 2020). Due to its close physical and chemical resemblance to its psychotropic variant, marijuana, hemp cultivation was prohibited in the US for over a century (Xu *et al.* 2022). *Cannabis* is often classified as either marijuana or industrial hemp based on the delta-9-tetrahydrocannabinol (THC) concentration threshold (Cherney and Small 2016). When the THC content is 0.3% or less, according to the US Food and Drug Administration (FDA), it is considered industrial hemp, whereas THC content above 0.3% is found in marijuana (Yano and Fu 2023). Hemp was produced from wild *Cannabis* plants that most likely originated in Central Asia more than 3,000 years ago (Adesina *et al.* 2020). Hemp was first thought to have arrived in North America in about 1606. It was grown for making clothes, sails, and ropes, but after World War II, hemp cultivation was banned in 1938 in North America (Cherney and Small 2016). Hemp has been grown in relatively limited quantities since World War II, due to the stigma associated with its sister plant, marijuana (Yano and Fu 2023). In the United Kingdom, Austria, Switzerland, and Germany, cultivars with extremely low concentrations of the psychoactive compound THC have been legal since 1990s. Hemp manufacturing was permitted in Australia and Canada in 1998 (United States Department of Agriculture 2000). The US Farm Bill of 2014 permitted the cultivation of industrial hemp in the US on a pilot scale for research purposes, though it was still considered a controlled substance (Cherney and Small 2016). The Farm Service Agency (FSA) of U.S. Department of Agriculture (USDA) reported that after the start of the pilot program, the number of planted acres increased to 146,780 acres by 2019 (Fig. 1).

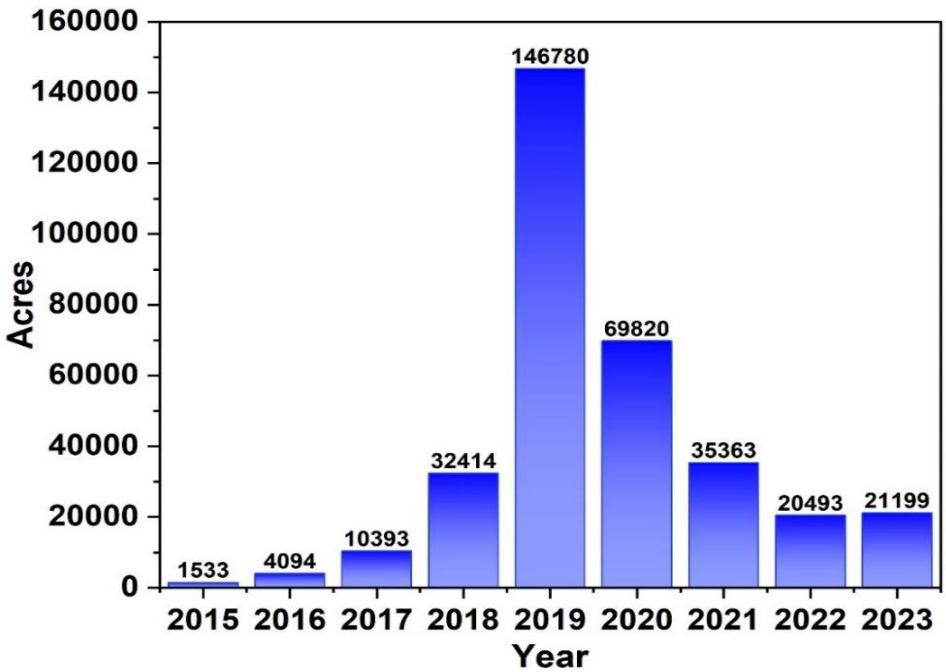

Fig. 1. Reported sum of planted acres of hemp, fiber, grain, and floral, from 2015-2023, source: USDA FSA

The US Farm Bill of 2018 defined hemp as a legal agricultural commodity and delisted hemp as a banned narcotic (Wylie *et al.* 2021). The legalization of the US Farm Bill in 2018 at the federal level led to a surge in planting in 2019. Many farmers anticipated high profits from hemp production, which resulted in oversupply. However, due to regulatory uncertainty, a surplus of hemp biomass and flower carried over from 2019, and a steady decline in wholesale pricing, U.S. farmers more recently have been planting less hemp than they did in 2019 (Caldwell *et al.* 2025). The lack of clear federal guidance on THC limits and complex state regulations made hemp farming risky. Many growers in 2019 were forced to destroy their plants after exceeding the legal THC limit of 0.3% (Stevens and Pahl 2021). Additionally, the COVID-19 pandemic disrupted supply chains, making it more difficult for farmers to process and sell hemp.

In the US, as of 2021, 49 states have legalized hemp production following the passage of the 2014 and 2018 Farm Bills, with the exception of Idaho (National Agricultural Statistics Service (NASS) 2022). Idaho became the 50th state to legalize industrial hemp and planted 680 acres for the first time in 2022 (National Agricultural

Statistics Service (NASS) 2023). Figure 2 illustrates the total industrial hemp grown across the US in open areas in 2023 based on the National Hemp Report 2024 (National Agricultural Statistics Service (NASS) 2024). The top five states based on planted acreage are: South Dakota (3,200), Montana (2,900), Oregon (2,300), California (2,100), and Missouri (1,750) (National Agricultural Statistics Service (NASS) 2024).

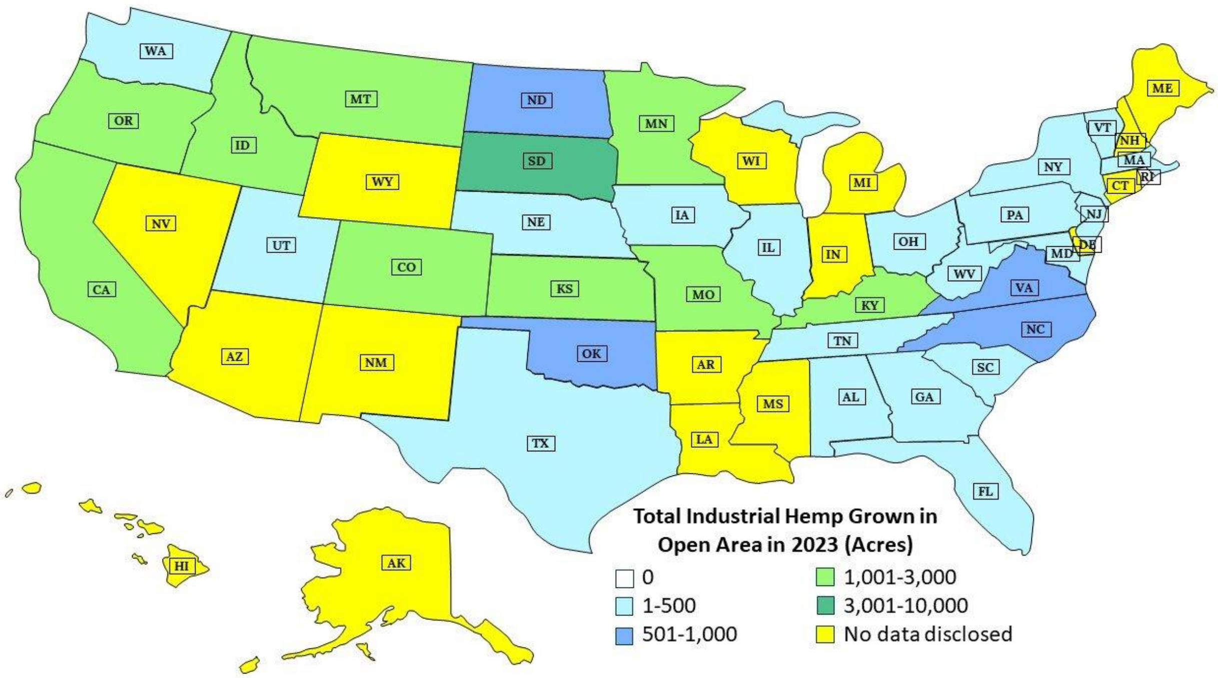

Fig. 2. Total industrial hemp cultivated (in acres) in the Open Area in 2023 according to National Hemp Report 2024.

Over 30 countries currently cultivate hemp and trade it as a cash crop (Adesina *et al.* 2020). Farmers who are interested in growing hemp in the US must obtain a license issued by the USDA, state, or tribe and pass the Federal Bureau of Investigation (FBI) criminal background check (Davis 2022). The cultivation and utilization of industrial hemp has experienced a remarkable resurgence in recent years because the practice promotes biodiversity, reduces chemical usage, conserves water, improves soil health, and contributes to climate change mitigation. Industrial hemp offers immense potential as a versatile and valuable crop with diverse applications ranging from textiles to construction materials to food, medicine, and bioenergy. More specifically, hemp can be used as a component in fiber composites (Shahzad 2012), biofuels (Zhao *et al.* 2020a), pulp and paper (Danielewicz and Surma-Ślusarska 2010), food source (Burton *et al.* 2022), insulators (Zampori *et al.* 2013), building materials (Jami *et al.* 2018), textiles (Zimniewska 2022), and as an adjuvant in cosmetics (Vogl *et al.* 2004).

Even with this huge range of applications, hemp comprises <1% of the total natural fiber used in the US due to the lack of processing infrastructure and agronomic guidelines as it competes against wood and related agro fibers (Aubin *et al.* 2015; Wenger *et al.* 2018). As regulations evolve and awareness grows, hemp can significantly contribute to sustainable agriculture and a low-carbon circular economy (Frazier *et al.* 2024), but it requires improved processing infrastructure, positive societal perception, favorable government incentives, and market opportunities to compete with other fiber sources.

Furthermore, successful cultivation of industrial hemp relies on understanding and implementing appropriate agronomic practices. This review aims to provide greater insight into the value of industrial fiber hemp by overviewing agronomic practices and possibilities for value-added bioproducts.

HEMP PLANT ANATOMY AND COMPOSITION

Industrial hemp is a herbaceous annual plant and is naturally dioecious, which means that it has both male and female reproductive organs, allowing it to self-pollinate. (Ehrensing 1998; Van der Werf 1994; Zheljazkov *et al.* 2023). Controlled selective breeding over time has developed monoecious cultivars. Monoecious varieties are used in dual-purpose hemp production and allow growers to produce both grain (seed used for food) and fiber. There are large differences between male and female plants physiologically. Male plants are highly desirable for fiber production because they can yield higher amounts of biomass (Schluttenhofer and Yuan 2017). Male plants mature on average two weeks sooner, and female plants survive three to five weeks longer than male plants until the grain is mature (Hall *et al.* 2012; Salentijn *et al.* 2019; Xu *et al.* 2022). Seed, used for grain, from monecious varieties are on average 25% lighter than dioecious varieties. Additionally, fiber yields from monoecious varieties are much lower than dioecious hemp. For these reasons, fiber hemp currently produced is nearly always dioecious (Ehrensing 1998; Williams and Mundell 2018).

A typical hemp plant is composed of stalks, flowers, leaves, roots, and seeds. The stalk consists of a hollow inner core of rigid woody material called hurd, which is surrounded by a layer of long fibers known as bast. Hemp's fibrous components are bast fibers and hurds. The hurd is engirdled by vascular cambium, along with an outer layer of cells made up of epidermal tissue, cortex, and phloem that forms the bark, within which the bast fibers are located (Snegireva *et al.* 2015). The vascular cambium is the tissue that is responsible for the radial development of the hurd (Ehrensing 1998; Jiang *et al.* 2018). A cross-section of a hemp stalk including xylem and phloem bundles is represented in Fig. 3.

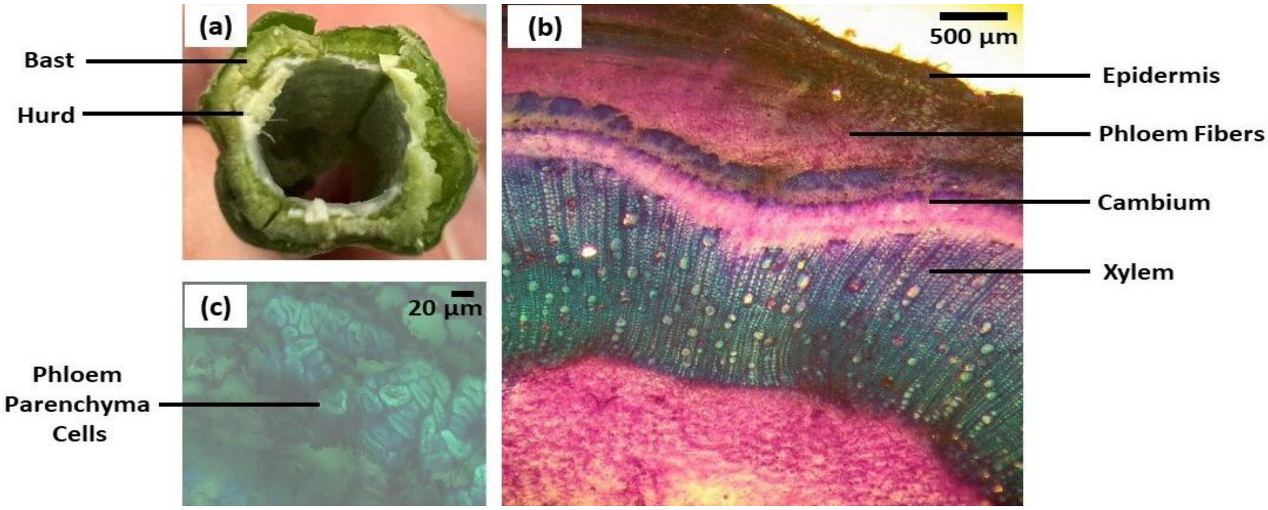

Fig. 3. (a) cross-section of hemp stalk, (b) cross-section of hemp stalk stained with Toluidine blue and observed through microscope at 4× magnification (c) phloem parenchyma cells observed at 10× magnification

Hemp ranges anywhere from 0.5 to 5 m in height, but on average grows to a height of 1 to 3.5 m with a diameter between 1 and 5.5 cm (Ramamoorthy *et al.* 2015; Zheljazkov *et al.* 2023). The variations in height and diameter mostly depend on sowing density, irrigation, and cultivar type (Burczyk *et al.* 2009). In lower sowing densities, hemp will branch out and increase its diameter and panicle density (Bhattarai, Jack Hall and Midmore 2014; Horne 2020). High planting densities cause plants to grow taller and more slenderer with smaller diameters (Burczyk *et al.* 2009). Hemp grown for grain and cannabinoids is almost always shorter compared to hemp grown for fiber. As plant height increases, the stem diameter decreases, causing the proportion of bast to hurd fibers to increase. If high-quality bast fiber is desired, then it is important to target maximum height and minimum diameter (Deng *et al.* 2019).

Bast Fibers

Bast fibers are present in the bark obtained from the stalk, which is about one-third of the plant by weight. It is composed of 70% to 75% cellulose, 15% to 20% hemicellulose, 3% to 5% lignin, 0.8% pectin, 2% to 6% extractives, and 1% to 2% ash content (Manaia *et al.* 2019; Möller and Popescu 2009; Zheljazkov *et al.* 2023). The cellulose concentration of hemp bast fibers is higher at the center of the stalk than it is at the top and bottom, and lignin concentration decreases from the bottom to the top of the stalk, while concomitantly displaying higher hemicellulose content (Li *et al.* 2013). Hemp bast fibers are regarded as the strongest and longest natural fiber, and they are cheaper to manufacture, and last far longer than materials such as cotton (Cherney and Small 2016; Manaia *et al.* 2019; Rehman *et al.* 2021). Hemp bast fibers also demonstrate weather resistance, UV resistance, and antimicrobial properties (Lamberti and Sarkar 2017). Primary markets for bast fibers include textiles, construction, paper, and molded plastics in the automotive industry with a very large concentration in composite wood products (Kiruthika 2017; Zimniewska 2022). The cross-section of hemp bast fiber is uneven and changes along its length (Manaia *et al.* 2019). The cortex contains two separate bundles of hemp bast fibers that belong to phloem: primary bast fibers, which are about 50 mm long and 10 to 40 µm in diameter, and secondary bast fibers, which are ~ 2 mm long and 15 µm in diameter (Horne 2020). Primary bast fiber comprises 70 to 90% and secondary bast fiber comprises 10 to 30% of the bast fibers. The primary bast fibers are located under the epidermis and consist of large collenchyma cells, whereas secondary bast fibers are located near the cambium and consist of smaller collenchyma cells (Chernova *et al.* 2018; Horne 2020). Bast fiber composition can range from 14 to 48% of the plant's mass due to cultivar along with most fiber varieties having about 30% bast fiber content (Ehrensing 1998; Musio *et al.* 2018).

Hemp Hurds

Hemp hurds are the woody interior portions of the hemp stalk that have been broken down into pieces and separated from the bast fibers (Xu *et al.* 2022). Hurds are comprised of xylem tissue that is separated by the cambium tissues from the bast fiber layer. The vessel members, ray and paratracheal cells, and libriform fibers make up the xylem (Horne 2020). Hurds contain 18% to 27% hemicellulose and pectin, 21% to 28% lignin, and 40% to 48% cellulose, 2.2% extractives, and 1.4% ash content which makes it a viable option for use as a polymer reinforcement agent (Lawson *et al.* 2022; Momeni *et al.* 2021; Naithani *et al.* 2020; Stevulova *et al.* 2014). Although hemp hurds account for about two-thirds of the plant by weight (70 to 75% of the hemp stalk) which is a sustainable fiber source, yet often overlooked as a low-value residue byproduct (Momeni *et al.* 2021;

Muangmeesri *et al.* 2021; Pal and Lucia 2019). Hemp hurds have lower processing chemical demand compared to hardwoods and softwoods, which makes them a good contender for a sustainable lignocellulosic resource (Salem *et al.* 2021). The use of only water at high temperature and pressure has also proved to be effective for the defibrillation of hemp without the use of any harsh chemicals (Tyagi *et al.* 2021). Hurds have been used in recent years in animal bedding and animal feed (Agate *et al.* 2020; Andre *et al.* 2016; Pietruszka *et al.* 2019). Hemp-based construction materials have gained much potential due to having good thermal insulation and being carbon-negative (Ahmed *et al.* 2022; Jami *et al.* 2018; Walker *et al.* 2014).

Hemp Grains

The term “hemp grains” is commonly used to refer to the edible seeds that are harvested for human consumption or animal feed. This material contains around 5.6% minerals (calcium, magnesium, potassium, and phosphorus), 25% easily digestible protein, 28% total dietary fiber (TDF), and more than 30% oil (Callaway 2004; Oseyko *et al.* 2021; Teterycz *et al.* 2021). The primary minerals in hemp grains are calcium, magnesium, potassium, and phosphorus (Callaway 2004). Hemp grains are normally processed into oil with whole grains for food, making up a very small percentage of the market. Only approximately 10% of hemp grain oil is composed of saturated fatty acids, which are present as 0.2% behenic acid, 1.5% stearic acid, and 5% palmitic acid, all of which contribute to supporting human physiological processes (Xu *et al.* 2022). In general, hemp grown for grain is sown at lower densities and harvested at later dates with different equipment relative to hemp grown for fiber or dual-purpose varieties. In 2023, U.S. hemp grain production totaled 3.11 million pounds, a 28% increase from 2022, despite a 26% decrease in harvested area for hemp grain grown in the open to 3,986 acres. The average yield rose by 327 pounds to 779 pounds per acre. However, the total return dropped 36% ($2.31 million) from 2022 due to the dominance of Canadian hemp grain producers over the U.S. hemp market (Ahmadi *et al.* 2024; National Agricultural Statistics Service (NASS) 2024). Hemp grain yield depends on irrigation. The variety Felina 32 produced 2337 kg ha^{-1} grain with full irrigation which was 3.8 times higher than limited irrigation (Campbell *et al.* 2019).

Hemp Fines

Hemp fines are a by-product from the production process of hemp hurds and bast fibers and are made up of very small particles of hurds mixed with some very short bast fibers (Attard *et al.* 2018; Delhomme *et al.* 2020). During bast fiber separation, 15 to 33% of the hemp stalk’s mass becomes fines (Attard *et al.* 2018; Spierling *et al.* 2014). Hemp fines are often called hemp dust, which was not considered a valuable material and was landfilled and composted in the past. However, these are recently being used in the manufacturing of absorbents, plastics, biofuel, and biochar. While it has some lab-scale applications, industrial use is still rare. A few studies have been found in which biochar was made from hemp fines by hydrothermal carbonization to improve the fertility of the soil and to limit greenhouse gas emissions such as N_2O (Dicke *et al.* 2015). Hemp fines were extracted to produce high-value-added lipids and cannabidiol (CBD) (Attard *et al.* 2018). The material can absorb as much as 350% of its volume of water, and it also can balance the carbon/nitrogen ratio in sewage sludge (Gorchs and Lloveras 2003). Hemp fines with polylactic acid (PLA) were used to develop biocomposites with improved mechanical properties (Spierling *et al.* 2014). Hemp fines were also used to produce insulating materials such as hempcrete for acoustic barriers and thermal barriers for buildings (Delhomme *et al.* 2020).

Leaves and Inflorescences

Leaves allow identification of different varieties of the fiber hemp plant. Industrial hemp possesses compound palmate-shaped leaves with 5 to 7 leaflets (Anderson 2021). Hemp leaves contain higher amounts of phytochemicals, as they are chronologically arranged from root to top (Semwogerere *et al.* 2020). Hemp inflorescences are an arrangement of greenish-yellow flowers on the upper part of central stem with some leaves, which are the main product of medicinal cannabis (Spitzer-Rimon *et al.* 2019; Vogel 2017). The expansion of a symmetrical tubular bract or calyx in the flower serves as a female plant identification trait. The inflorescence of female plants is leafy, stocky, and unbranched, whereas the inflorescence of male plants is heavily branching and has few to no leaves (Van der Werf 1994). Hemp inflorescences contain many cannabinoids and secondary metabolites, such as THC, non-hallucinogenic CBD, monoterpenoids, and sesquiterpenoids (Bertoli *et al.* 2010). Hemp leaves and inflorescences are both employed as sources of phytochemicals for therapeutic applications due to numerous pharmacological properties, including antioxidant, anti-inflammatory, and hypoglycemic effects (Liu *et al.* 2022; Xu *et al.* 2022).

Hemp Roots

The industrial hemp plant has deep roots, 45 to 90 cm long, which helps in phytoremediation of heavy metals in the soil, such as chromium, iron, and cadmium (Placido and Lee 2022; Xu *et al.* 2022). Toxins may accumulate in the roots, leaves, and stalks of hemp plant when used for phytoremediation (Angelova *et al.* 2004). As a result, these parts are not used to make food or personal care products but may be used to make biofuel, paper, fabric, and construction materials (Placido and Lee 2022; Vandenhove and Van Hees 2005). Hemp root contains 0.13% to 0.24% triterpenoids, 0.06 to 0.09% sterols, and 0.001% to 0.004% cannabinoids (Jin *et al.* 2020). Hemp root also contains many secondary metabolites including stigmasta-3,5,22-triene, fucosterol, oleamide, glutinol, and β-amyrone (Kornpointner *et al.* 2021). Hemp root has received less attention than other plant parts, though it has been used to treat infections, fever, and pain (Ryz *et al.* 2017).

HEMP AGRONOMY

The yield of hemp bast fibers, hurds, and grains varies greatly depending on different agronomic conditions, such as seed selection, soil condition, pest control, nutrient management, time of harvest, and sowing density (Grabowska and Koziara 2006).

Soil Conditions

Hemp flourishes in agricultural soil with high fertility, abundant organic matter content, high cation exchange capacity, and high arability (Van der Werf 1991). The soil should be well drained, but still able to retain moisture. Hemp does not grow well on wet soils that have heavy clay content. Hemp is best adapted to well-drained soils with pH between 6 and 7.5, but it can also tolerate soil pH as low as 5.0 (Amaducci *et al.* 2015; Garstang *et al.* 2005).

Seeding and Spacing

Hemp seeds are defined as the reproductive structure that contains the embryo of a new plant. Fiber and grain hemp are grown from seed. Hemp seeds are small and grow poorly in sandy soils due to poor moisture retention and lack of a firm seedbed (Garstang *et al.* 2005).

Sandy loam soil is ideal for growing hemp (Amaducci *et al.* 2015). Seedbed preparation often starts with ploughing to break a hardpan layer (Amaducci *et al.* 2015). Seeding into a highly compacted soil can result in a L-shaped root which negatively affects water and nutrient uptake (Adesina *et al.* 2020; Amaducci *et al.* 2015). During seedbed preparation, fertilizers are applied and a seed drill (Fig. 5) is used to space the fiber or grain hemp seeds evenly at the appropriate depth, no more than 3 cm, and cover them with soil (Amaducci *et al.* 2015). Cherney and Small (2016) recommended row spacing ranges from 7 to 17 cm, but sometimes for fiber hemp 20 to 40 cm row spacing is used (Liu *et al.* 2017; Zheljazkov *et al.* 2023).

Sowing Density and Seed Type

Sowing density is one of the largest factors to consider depending on the type of hemp that will be grown. Generally, excessive sowing densities will decrease bast fiber content and quality, overall biomass yield, grain yield, panicle yield, stalk height and diameter, and partially, cellulose content (Burczyk *et al.* 2009). However, the reduction of sowing densities can also lead to undesirable qualities depending on the application for which the hemp is being grown. Few applications will benefit from a seed density of more than 60 to 80 kg/ha (Burczyk *et al.* 2009; Iványi and Izsáki 2009). Hemp sown at 60 to 80 kg/ha is most efficiently used in textile applications (Burczyk *et al.* 2009). The lowest sowing densities typically used are between 10 and 20 kg/ha, and this hemp is grown for grain and cannabinoid yield (Burczyk *et al.* 2009). Unless the hemp is intended for textile applications, going above 30 kg/ha can decrease stem height, diameter, grain, and biomass yield. Good yields of stem, grain, and inflorescence combined were generated by 120 plants per m^2 with 0.5 m interrow spacing (Krüger *et al.* 2022; Zheljazkov *et al.* 2023). The effect of average sowing density on fresh biomass, final dry weight, and bast fiber yield has been summarized in Table 1 for different industrial hemp strains.

Table 1. Effect of Average Sowing Density on Fresh Biomass, Final Dry Weight, and Bast Fiber Yield for Different Industrial Hemp Strains

Strains	Sowing density (per m^2)	Fresh Biomass (t/ha)	Retted dry stem weight (t/ha)	Bast fiber yield (t/ha)	References
Futura 75	81	48.5	18.6	4.6	(Tsaliki *et al.* 2021)
Fedora 17	123	43.5	12	2.4	(Tsaliki *et al.* 2021)
Bialobrzeski	142	50.5	16.6	4.3	(Tsaliki *et al.* 2021)
Felina 32	102	50.0	15	3.5	(Tsaliki *et al.* 2021)
Santhica 27	116	35.0	14	3.8	(Tsaliki *et al.* 2021)
Tygra	101	40.0	11	3.1	(Tsaliki *et al.* 2021)
Yunma 1	33 to 37	-	-	2.2	(Deng *et al.* 2019)
Narlısaray	150 to 200	20.4	9.4	2.6	(Yazici 2023)
Marina	120 to 240	31.6 to 55.1	9.5 to 16.9	3.8 to 6.0	(Bajić *et al.* 2022)

Both seed cultivar and seed type have a significant impact on the yield of bast fibers, hurds, oils, and grains. Typical regular seeds of dioecious hemp have been chosen over monoecious strains for fiber production for many years. These seeds reveal themselves as male or female after a few weeks of growth. One of the most important factors to consider is that only female plants produce grain; therefore, the production of grain from a dioecious variety needs to be pollinated by male flowers. To optimize output as a grain crop, it is best to have a predominantly female population with a few male plants for pollination, or to have a monoecious variety (Schluttenhofer and Yuan 2017). Conversely, when hemp is cultivated to produce fiber, male plants are mostly desired without flowering, which promotes taller height with less branching (Johnson 2019).

Fertilization and Nutrients

Key macronutrients for growing hemp are nitrogen, potassium, and phosphorus (Wylie *et al.* 2021). Soil nutrient levels and applied amounts determine crop intake. Measuring residual soil nutrients before fertilization prevents under or over-exposure. Nutrient content can be directly measured from leaf tissue samples after about the 10^{th} week of growth (Iványi and Izsáki 2009). Nitrogen is the most influential nutrient on hemp plant growth and is often the only nutrient added prior to sowing and during cultivation. A daily nitrogen intake of 3 to 4 kg/ha occurred throughout the first month, accounting for 79% of the total nitrogen uptake (Ivonyi *et al.* 1997). Dual-purpose cultivars can benefit from nitrogen fertilization at rates of up to 200 kg/ha, which can increase biomass yields, grain yields, plant height, and stem diameter (Aubin *et al.* 2016; Zheljazkov *et al.* 2023). However, applying nitrogen beyond 150 kg/ha can have no effect or may decrease fiber yield and quality simultaneously (Aubin *et al.* 2015; Grabowska and Koziara 2006). There are mixed conclusions about the effects of potassium and phosphorus (Aubin *et al.* 2015; Cherrett *et al.* 2005). Phosphorus has some effect on plant height, tensile strength and elasticity of bast fibers but does not affect grain, stem, or biomass yield (Adesina *et al.* 2020; Finnan and Burke 2013; Vera *et al.* 2006). P_2O_5 fertilization should not exceed 22.4 kg/ha of phosphorus, because if this level is exceeded, the hemp seed mortality rate increases significantly (Williams *et al.* 2019; Zheljazkov *et al.* 2023). Fiber, grain, and dual-purpose hemp require a high amount of potassium; around 336 kg/ha (Zheljazkov *et al.* 2023). The quality and yield of bast fiber are affected more by potassium than phosphorus (Adesina *et al.* 2020; Cockson *et al.* 2019; Merfield 1999). Potassium uptake also increases with maturity of plant and the highest uptake occurs at the development stage of bast fibers which causes significant increases in cellulose and hemicellulose content (Adesina *et al.* 2020; Aubin *et al.* 2015). The recommended amount of potassium fertilizer for hemp plants is around 175 kg/ha (Adesina *et al.* 2020). On the other hand, cotton requires 50 to 412 kg/ha (Shah *et al.* 2022) and 110 to 250 kg/ha (Kommineni *et al.* 2024) of nitrogen and potassium fertilizer, respectively. Another fiber-generating crop, ramie, requires 525 kg/ha, 140 kg/ha, and 525 kg/ha of nitrogen, phosphorus, and potassium fertilizer, respectively, for maximum yield (An *et al.* 2024), which are higher relative to hemp.

Some other secondary macronutrients and micronutrients, such as magnesium, and calcium have slight effects on hemp plant growth but no direct effect on grain and bast fiber yield except for boron and copper (Adesina *et al.* 2020; Cockson *et al.* 2019). The most common symptoms of different nutritional deficiencies are listed in Table 2 and Fig. 4.

Table 2. Nutritional Deficiencies Symptoms in Hemp Plants at Advanced Stages

Nutrient	Deficiency Symptoms	References
Nitrogen	Paleness, stunting, and yellowing of the lower leaves, decreased yield of bast fiber	(Kaur *et al.* 2023)
Phosphorus	Impaired growth, reddening of leaves, and lower immunity to diseases	(Adesina *et al.* 2020)
Potassium	Yellowing of the leaf that extends inward toward the midrib with the progress of symptoms	(Cockson *et al.* 2019)
Copper	Breakdown of the hemp stem	(Adesina *et al.* 2020)
Magnesium	Yellowing or graying white spots on the lower older leaves	(Adesina *et al.* 2020)
Sulfur	Yellowing of foliage, pale yellow around midrib	(Cockson *et al.* 2019)
Calcium	Yellowing, irregular geometries, and orientations, and stunted growth of leaves	(Cockson *et al.* 2019)

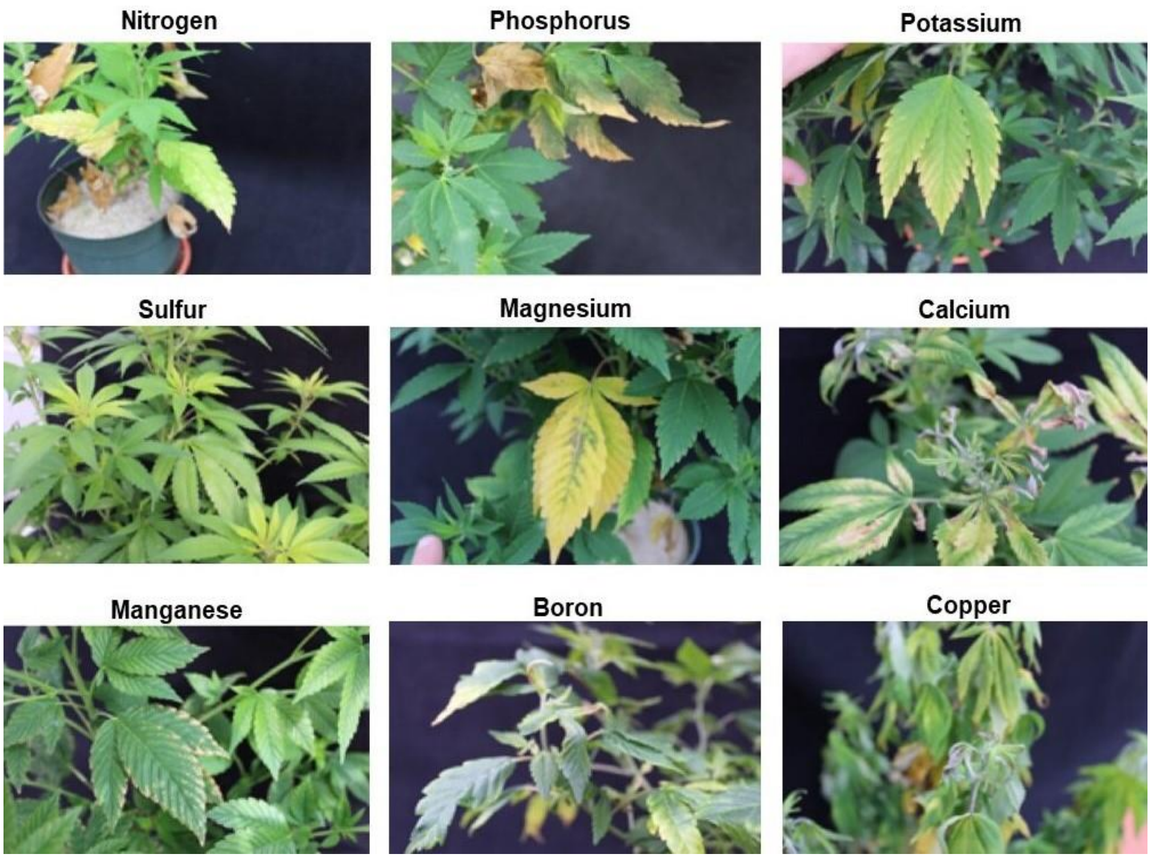

Fig. 4. An inspection of the visual cues for common symptoms of advanced stage nutritional deficiencies in hemp plants. Reproduced from (Cockson *et al.* 2019), under the terms of the CC-BY Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses /by/4.0/).

Climatic Conditions

For germination and early development, hemp has certain needs with respect to temperature and moisture profiles. Late spring is the best time to plant seeds (Van der Werf 1991). Spring soil temperatures should be ~ 10 °C if rapid establishment of hemp plants is desired and optimal vegetative growth is to be achieved. When seeded in warm soils (>10 °C) with adequate soil moisture, most hemp varieties will sprout in 3 to 7 days (McGue *et al.* 2021). An air temperature range of 13 to 25°C is considered optimal temperature conditions, although the hemp plant can survive in warmer and colder temperatures (Averink 2015; Bouloc *et al.* 2013). If hemp is being grown for grain, then a much warmer climate and longer growing seasons are required. Being a short-day plant that matures more quickly as the days become shorter in the fall, early plantings yield higher amounts of fiber. Later plantings may lessen stem length and mass for grain and fiber production (Averink 2015). The plant requires rain, especially during seed germination and until it becomes well-rooted, because fiber and grain hemp are not irrigated generally (Kraenzel *et al.* 1998). But the plants grown in US Southwestern summer undergo heat stress, which means that watering is needed to keep the roots cool (McGue *et al.* 2021). According to past research, industrial hemp has a lower water footprint than wood or cotton. Hemp uses approximately 2,719 liters of water per kg of mass, whereas cotton uses approximately 10,000 liters of water per kg (Averink 2015). Abaca and ramie plants require rainfall of 2000 to 3000 mm/year (Bande *et al.* 2013) and 1500 to 3000 mm/year (Roy and Lutfar 2012), respectively. However, the primary need for rainfall for effective outdoor hemp growth in a temperate area is around 700 mm annually, which is lower (Vogel 2017). Hemp will only begin to mature when the length of the day is less than 12 hours. Another important factor to consider is that hemp is sensitive to the photoperiod, meaning that it grows and flowers according to photoperiod or daily hours of sunlight received rather than physiological maturity (Amaducci *et al.* 2008).

Weed, Insects, Diseases and Pests

Prior to extensive domestication, hemp exhibited natural mechanisms to deter insects and diseases, primarily through the production of bioactive compounds such as CBDs and terpenes, beneficial structural characteristics, and symbiotic relationships with endophytic fungi. The extract of hemp, containing cannabinoids (*e.g.*, essential oil and terpenes), can significantly repel insects and pests. Evidence of antimicrobial activity was demonstrated in autohydrolyzed hemp pulp containing hemp extract, which reduced the growth of *E. coli* by 99.7% (Tyagi *et al.* 2022). Industrial hemp extract also showed insecticidal activity against *Plodia interpunctella* and can act as a potential sunflower grain protectant (Prvulović *et al.* 2023). Hemp essential oil was found to be toxic to aphids, flies, larvae, *etc.*, and is recommended for use in Integrated Pest Management (IPM) and organic agriculture (Benelli *et al.* 2018). Hemp leaf extract containing CBD has demonstrated larvicidal properties against mosquito larvae, including strains resistant to conventional insecticides (Martínez Rodríguez *et al.* 2024). The dense foliage and rapid growth of hemp enable it to outcompete weeds, reducing the need for herbicides. These traits also contribute to its resilience against various pests and diseases, minimizing the necessity for chemical interventions. However, no evidence of inhibiting insects or diseases directly by the hemp plant itself was found in the literature before domestication.

Like any other crop, hemp plants are also susceptible to insects, diseases, and weeds. Table 3 represents the common diseases caused by pathogens and their symptoms that affect hemp plants.

Table 3. The Most Common Diseases of Hemp Caused by Pathogens and their Symptoms

Pathogens	Common Name of Disease	Symptoms	Associated Damage	References
Alfamovirus	Alfalfa Mosaic Virus	Yellow blotches on foliage, curling and discoloration of leaves	Mottling, plant death	(Murray *et al.* 2022)
Beet curly top virus (Vector: Beet leafhoppers)	Curly top disease	Yellowing of leaves, curling of plant and leaf edges	Stunted growth, yield loss up to 100%	(Giladi et al. 2020; Hu et al. 2021)
Botrytis cinerea	Gray mold	Dying and formation of gray mycelium in flower	Bud rot, reduced yield	(Murray *et al.* 2022)
Fusarium oxysporum	Fusarium wilt	Chlorotic leaf tips	Wilting of plant and death	(Punja 2021)
Fusarium solani	Fusarium crown rot	Rotting of root and crown discoloration		
Golovinomyces chicoracearum, G. ambrosiae	Powdery mildew	Powdery white spot on leaves, buds and stems	Reduced photosynthesis, leaf drop, stunted growth	(Thiessen *et al.* 2020)
Sclerotinia sclerotiorum	Stem cankers	Brown lesion on stems	Wilting of plant and death	(Murray *et al.* 2022)

Hemp is also a host for many insects, such as hemp russet mite, hemp aphid, hemp flea beetle, grasshoppers, crickets, hemp leafroller, and armyworms, as well as predatory birds that attack hemp plants and cause yield losses (Britt and Kuhar 2020; Pejić *et al.* 2020). Due to limited approved insecticides, fungicides, and pesticides, it is suggested to employ pathogen-resistant cultivars that are less susceptible to diseases and to follow IPM techniques involving biological methods to determine the appropriate timing of seeding, use of beneficial insects, and rotation with non-host crops (Ajayi and Samuel-Foo 2021; Kostuik and Williams 2019; Zheljazkov *et al.* 2023). Several weeds may also significantly hinder the growth of hemp, such as bindweed, pigweed, Johnson grass, and quack grass (Fike 2016; Fortenbery and Bennett 2001). As a response to crop protection, the Environmental Protection Agency (EPA) has approved only one herbicide, ethalfluralin, registered under the trade name Sonalan® HFP herbicide for fiber hemp (McVane *et al.* 2024). Crop rotation, appropriate tillage, and dense plantation can shade out the majority of weedy growth (Kaiser *et al.* 2015; Zheljazkov *et al.* 2023).

Harvest Seasons

During the pre-harvest period, hemp growers need to report the total THC at least 15 days prior to harvesting, depending on state or federal requirements, to ensure that the total THC is lower than the threshold of 0.3% as determined by laboratory testing (McGue *et al.* 2021). The relevant Department of Agriculture will advise the producer on proper disposal techniques if the harvested material exceeds the threshold. To avoid excessive total THC, early harvest is recommended. Hemp is harvested in late summer to early autumn depending on the type of hemp grown. Vegetative periods for hemp growth are typically 60 to 150 days, but the period can vary depending on the cultivars (Strzelczyk *et al.* 2022). These periods are much shorter than other crops that produce raw materials for some of the same products, such as cotton and wood (Garstang *et al.* 2005).

Typically, hemp is harvested at three different stages in its growing cycle; at the beginning of the inflorescence, during full bloom, and after grain maturity (Burczyk *et al.* 2009). As the plant develops, parts of the plant mature and flower, thus yielding more grain and cannabinoids. Conversely, the stalk becomes more lignified, decreasing the processability and strength compared to if harvested earlier in the growing season (Musio *et al.* 2018). If high quality bast fiber is desired, then the plant should be harvested before grain and cannabinoids begin to develop (Burczyk *et al.* 2009). If the maximum yield of bast fiber, cellulose, and overall biomass is desired then hemp should be harvested at full bloom. When the male plants have finished blooming, dioecious hemp grown for bast fiber are normally harvested (Fike 2016). The best period to harvest for bast fiber is before grains are completely mature, typically 70 to 90 days after sowing. Beyond this time, bast fiber will become too coarse for textiles (Fortenbery and Bennett 2004). When growing for high grain or cannabinoid yields, hemp should be harvested at full maturity or when 70% of the grains are ripe. Waiting longer than this will cause losses due to reduced moisture and nutrient concentrations (Garstang *et al.* 2005). Research shows that hemp farmed for energy can provide yields of 9.9 t DM/ha in the spring and 14.4 t DM/ha in the fall (Prade *et al.* 2011).

Harvest Method

Depending on the volume of production, height of the plant, the intended purpose for the crop, and the resources on hand, several techniques are used for industrial hemp harvesting. Manual harvesting is carried out on small-scale fields using traditional tools including sickles or specialized hemp harvest knives. Mechanical harvesting is very common for large-scale fields (Kaiser *et al.* 2015).

Six fundamental procedures are involved in the harvesting of industrial hemp, such as chemical defoliation, cutting, retting, baling, loading, and transport (Fortenbery and Bennett 2004). The process of applying chemical agents to prevent or hasten the natural loss of hemp plant leaves is known as chemical defoliation. It is frequently used to make harvesting easier, especially in crops intended for grain or fiber production (Bengtsson 2009).

The chemical defoliation process is only used in Eastern Europe and is not popular in US. In US, hemp stem is typically cut with sickle bar mowers or forage harvesters; however, neither of these machines is specifically designed for harvesting hemp (Ehrensing 1998; Kaiser et al. 2015; Williams and Mundell 2018). A common seed drill equipment and sickle bar mower for harvesting industrial hemp is represented in Fig. 5.

The most popular technique for harvesting uses standard hay-making machinery (Zheljazkov *et al.* 2023). For high-quality bast fiber applications, stalks are cut into 1 m sections and aligned parallel, leaving a continuous layer of stalks on the ground before being retted or being sent to processing. Grain and dual-purpose varieties are harvested similarly to other grain crops, for which axial flow combine harvesters initially cut the hemp and separate the grain from the stalks (Merfield 1999). It is important to run combines and augers at lower speeds than normal to avoid unnecessary losses to the quality and yield of grain. The stalks from grain varieties are often left to rot in the field after harvest because the return of this low-quality lignified fiber is often not worth the labor.

Fig. 5. (a) Seed drill equipment for spacing the seeds and (b) sickle bar mower for harvesting industrial hemp plants

POST-HARVEST HANDLING AND PROCESSING

Retting

Retting (Fig. 6a) is a microbial process that breaks down the chemical bonds between bast fiber bundles and hurds. By degrading lignin or pectin; retting enables the separation of hurds from the bast fibers (Ehrensing 1998; Fortenbery and Bennett 2001; Zimniewska 2022). There are various ways to carry out the retting, and among them, dew retting and water retting are the most common (United States Department of Agriculture 2000; Zimniewska 2022). After harvesting, hemp stalks are usually left in the field for dew retting to enhance processability (Fig. 6a) (Williams and Mundell 2018). Field or dew retting takes 1 to 2 weeks in warm humid weather, but it usually takes around 4 to 5 weeks depending on atmospheric conditions (Ehrensing 1998). The yield of bast fiber content derived from unretted stems is slightly higher, ~ 6.5%, compared to retted hemp stems (Musio *et al.* 2018).

Water retting, which immerses hemp stalks in large basins of water, is faster than field retting, taking only 5 to 10 days (Franck 2005; Zimniewska 2022). However, this method has a large environmental impact due to the large water use and increased Biological Oxygen Demand (BOD) (Musio *et al.* 2018). The water retting used to extract the long bast fibers is distinguished by their high quality, such as fineness, mechanical characteristics, and spinnability, making them superb for textile applications.

Natural field and water retting have been replicated in an anthropogenic process in which enzymes act as bacteria to speed up the microbial degradation of the stems, which is called enzymatic retting (Horne 2020; Lee *et al.* 2020). The main drawback of this process is the high initial cost of the enzymes (Horne 2020). Chemical retting involves the use of sodium hydroxide, sodium sulfite, sodium carbonate, and sometimes with ethylenediaminetetraacetic acid (Horne 2020). It is cost-efficient and ensures high yield and high quality of bast fibers (Kostic *et al.* 2008). Physical retting, such as steam explosion, is carried out using hot steam and pressure to remove lignin, pectin, wax, and other non-cellulosic materials (Sauvageon *et al.* 2018). Stand retting, a modified form of field retting, involves spraying herbicide before harvest to initiate degradation and mitigate crop losses due to inadequate retting (Garstang *et al.* 2005). Over-retting can result in bast fiber deterioration and decreased fiber strength, while under-retting may produce weak bast fibers and poor bast fiber separation. To obtain the best fiber quality, the retting process must be carefully controlled, which includes maintaining temperature, moisture content, and microbiological activity before being sent to fiber separation facilities (Williams and Mundell 2018).

Decortication

After retting, the windrowed or swathed hemp stalks undergo decortication. The term windrowed or swathed refers to crops that are cut and laid in rows in the field for retting before decortication. Figure 6b shows the process of separating the bast fibers from the hurds of the hemp stalk, which is called decortication. It can be performed on unretted stems as well, but the scutched (freed fibers from woody parts by beating) and hackled fiber yield is much lower in that case (Musio *et al.* 2018). It becomes easier for retted hemp due to the reduction of non-cellulosic content (Musio *et al.* 2018). Decorticated hemp had the lowest shive content if it had undergone dew retting before decortication (Musio *et al.* 2018). This processing technique works best if high-quality bast fibers are desired and the stands are to be harvested at technical maturity or before grain production begins (Ehrensing 1998).

Decortication is either done on site at the farm or the raw material can be baled and sent to a processing facility. However, if material is baled, it must be dried below 15% to 18% moisture; otherwise, rotting can occur during transportation and storage (Garstang *et al.* 2005; Kaiser *et al.* 2015). It is almost always more cost-effective to undergo this process on the growing site. This eliminates the cost for drying, baling, and transportation to the decorticating facility as well as lost profit gained by the decortication facility. Decortication yield varies greatly depending on its intended purpose, with anywhere from 18% to 33% of mass turned into dust. Hammer mills are often used to decorticate unretted stalks at high speed when low purity fibers are targeted as it generates a lot of dust and fines (Chen *et al.* 2004).

There exist some other processing methods, especially for bast fiber separation, which varies based on their end use, such as breaking, shaking, screening, scutching, and hackling (Pejić *et al.* 2020). Breaking is a step of bast fiber separation in which hurds are broken down by cylindrical rollers, which partially separates the bast fibers (Ehrensing 1998; Pejić *et al.* 2020). Vibratory screening machines are used to separate hemp bast fibers from small hurds and fine particles as they move across a vibrating mesh deck with pre-determined perforations. As the deck vibrates, hurds and fine particles fall through the perforations, either as a desired end product or as byproducts for alternative uses. With mainly bast fibers left, there are a variety of ways that hemp bast fibers can be processed. Regardless of the process used, the bast fibers must undergo both scutching and hackling. Scutching removes impurities from the hemp such as grains and woody stems. Hackling combs the hemp bast fibers to make them softer and more uniform, preparing them for spinning into textile materials (Musio *et al.* 2018). Hemp bast fibers can be cottonized and spun at cotton mills or, if not, at flax mills. Historically, cotton mills, with slight modifications, have been preferred because they can produce much higher volumes of fibers than flax (Miller 1991).

Transportation Importance

Transportation (Fig. 6c) is a very important cost factor in industrial hemp production due to the bulky and low-density nature of hemp biomass. Transportation cost and return efficiency are substantially lower for hurds than bast fiber (Bouloc *et al.* 2013). During grain harvesting, the combine harvester cuts, threshes, and cleans the grains automatically. The leftover shortened biomass is field dried and baled for transportation and storage. Transportation costs can also be affected by the type of bales formed. Square bales, for example, are more efficient geometrically. Square bales are typically cut at short lengths and are tied with elastic string because natural fiber string cannot withstand square baling pressure.

However, biomass for pulp and paper processing or into high-strength particle boards must be plastic-free and round baled. These shortened fibers of grain production byproducts could significantly benefit the paper and board industry with better storage infrastructure and supply chain dynamics (Ehrensing 1998). In hurd applications where long bast fiber yield is not a concern, hemp is more apt to be baled immediately after harvest in a non-parallel orientation before being sent to a processing or storage facility. Since fibers are baled and the stems do not maintain a parallel orientation, the long bast fiber yield is much lower for baled hemp than for parallel-aligned and processed hemp.

Storage

Storage (Fig. 6d) is critical for both grain and stalks after harvest and must be closely monitored to avoid losses in quality, especially for extended storage times. Grain for food has very high standards for moisture and quality to be acceptable for processing. Sweating, evaporation, and condensation can lead to rejection, significant quality loss, and reduce hemp grain profitability while failing to aerate grains 3 to 4 hours post-harvest due to oxidation. Grains should be dried and stored at ~ 9% moisture in well-aerated silos and not collected from harvest until they reach below 12% moisture content.

Full-floor aeration or rocket systems in hopper bins are effective for drying and cooling hemp grains through aeration (Brook *et al.* 2016). Low heat is maintained at less than 35 °C to avoid toasting of the grain and to ensure grain and grain oil quality is not compromised (Brook *et al.* 2016). Sun drying is practiced by farmers but is not recommended for commercial-scale production *(Moon et al*. 2020; Parihar *et al.* 2014). Hemp is typically stored between 7% and 9% moisture and closely monitored. Moisture content must be lower than 15% to prevent microbial breakdown in storage (Ehrensing 1998). Figure 6 represents a typical scenario of industrial hemp post-harvest handling and processing operations such as field retting, decortication, transportation, and storage.

Fig. 6. A representation of industrial hemp post-harvest handling and processing operations (a) field retting, (b) decortication, (c) transportation, and (d) storage

HEMP BIOPRODUCTS- SUSTAINABLE FIBERS, PACKAGING, AND BIOPLASTICS

Due to renewable, biodegradable, and recyclable qualities, hemp is considered the second-largest farmed bast fiber after jute, which is a suitable feedstock for the manufacture of fibers, biocomposites, packaging, and bioplastics (Dayo *et al.* 2017).

Bast Fibers

Hemp bast fibers are well known for being breathable, long-lasting, and sustainable, which makes them well suited for textiles. However, hemp's coarse, stiff bast fibers and poor spinnability necessitate blending with cotton to overcome spinning difficulties caused by pectin and lignin. A 50:50 hemp-cotton blended textile material has a better crease recovery angle, higher tensile resilience, toughness, higher surface friction, shear, and bending rigidity compared to 100% cotton (Ahirwar and Behera 2022). The first American flag and the earliest denim trousers designed by Levi Strauss were the oldest known woven items made of hemp (Crini *et al.* 2020). The addition of natural fibers such as hemp to a polymer matrix enhances the strength properties, reduces the environmental impact, and potentially decreases production costs (Joshi *et al.* 2012). A list of several biocomposites developed using hemp bast fibers including processing techniques, and applications are listed in Table 4.

An obstacle associated with hemp biocomposites is that process temperatures cannot exceed 230 °C; otherwise, the bast fibers would experience thermal degradation. This means they are suitable for polypropylene and polyethylene plastics, but not for polyamides, polyesters, or polycarbonates, which require temperatures above 250 °C (Shahzad 2012).

Hemp Hurd Fibers

The hemp hurds biomass can be converted into pulp fibers by traditional chemical and mechanical pulping processes. For example, kraft, carbonate, and soda processes have been successfully used to isolate hemp hurds fibers (Naithani *et al.* 2020; Tyagi *et al.* 2021; Gaynor *et al.* 2024). The yield of carbonate hemp pulps was slightly lower than that of carbonate eucalyptus and bamboo but nearly the same as carbonate hardwood and softwood pulps. However, the yield of mild kraft hemp pulp was comparable to eucalyptus and higher than other kraft pulps (Salem *et al.* 2020).

Furthermore, hydrothermal pulping, a chemical-free process, has shown promising results in extracting fibers from hemp hurds (Naithani *et al.* 2020; Tyagi *et al.* 2021). Organosolv pulping, using an ethanol-water mixture, has also been effective for fiber extraction (Muangmeesri *et al.* 2021). Additionally, alkaline pretreatment followed by pulping has been employed in recent studies to increase the yield of cellulosic fibers (Gaynor *et al.* 2024).

Table 4. Processing Method and Application of Hemp-based Biocomposites

Matrix	Processing Method	Application	Reference
Hemp bast fiber-polylactic acid (PLA)	Hot pressing	Textile reinforcement	(Salmins *et al.* 2023)
Hemp bast fiber-polybenzoxazine	Compression molding	Used as high-performance composites	(Dayo *et al.* 2018)
Hemp bast fiber-glass fiber-epoxy	Hand lay-up technique	Automotive industry	(Murugu Nachippan *et al.* 2021)
Hemp bast fiber-glass fiber	Compression molding	Light-weight structural applications	(Mahmud *et al.* 2023)
Hemp bast fiber-polypropylene/polyester	Needle punching and heat pressing	Nonwoven fabrics	(Stelea *et al.* 2022)
Hemp bast fiber-dicyanate ester of bisphenol-A/bisphenol-A based benzox-azine resins	Compression molding	Indoor and outdoor application	(Zegaoui *et al.* 2019)
Hemp bast fiber- recycled high density polyethylene	Hydro-entanglement process and compression molding process	Secondary structural applications	(Angulo *et al.* 2021)
Hemp bast fiber-epoxy	Vacuum assisted resin transfer molding	Automotives, constructions, and internal finishes	(Väisänen *et al.* 2018)
Hemp bast fiber-polypropylene /poly[styrene-b-(ethylene-co-butylene)-b-styrene) (SEBS)	Extrusion and injection molding	Electric vehicles	(Panaitescu *et al.* 2020)
Hemp bast fiber-colemanite	Chemical impregnation and hot pressing	Friction material, automotive applications	(Karakaş *et al.* 2024)

Hemp bast fiber-vinyl ester	Compression molding	Structural and non-structural applications	(Thirukumaran *et al.* 2024)
Hemp bast fiber-poly(ethylene succinate)	Melt mixing	Active packaging	(Zamboulis *et al.* 2023)

Several modifications, such as carboxymethylation (Yao *et al.* 2022), acetylation (Basak *et al.* 2024), have been used to enhance the functional properties of hemp hurd fibers. Enzymatic treatment using pectinase (Li *et al.* 2017) and cellulase (Li *et al.* 2021) has improved the mechanical properties of composite materials made from hemp hurds, wood, and polypropylene. Further, recyclable hemp hurd fiber-reinforced PLA composites have been developed for 3D printing, exhibiting high stiffness, tensile strength, and good thermal stability (Beg *et al.* 2024).

Sustainable Packaging

The short fiber length of hemp hurds provides a distinct advantage to produce nanocellulose biopolymers in terms of energy consumption (Agate *et al.* 2020). Hemp whole stalk fibers and hurd fibers were used to produce molded packaging (Lo *et al.* 2024; Yimlamai *et al.* 2023), food packaging (Barbash *et al.* 2022), tissue and towels (Naithani *et al.* 2020), and barrier coatings and films (Tyagi *et al.* 2021). Paper produced with 2% hemp-derived nanocellulose showed an improvement in breaking length by 42% due to an increased number of fiber-fiber bonds, making it suitable for premium-grade food packaging (Barbash *et al.* 2022). The antimicrobial activity of hemp packaging products also gained a lot of attention, since hemp contains biologically active compounds, such as alkaloids, saponins, and flavones responsible for bacterial growth inhibition (Tyagi *et al.* 2022). Edible-coated packaging of gelatin with hempseed oil on golden apples, cheese, and pork reported antibacterial activity against *Penicillium expansum*, *Saccharomyces cerevisiae*, *Staphylococcus aureus*, and *Escherichia coli* pathogens (Mihaly Cozmuta *et al.* 2015). Edible coating of hempseed protein with carrageenan for food preservation lowers the moisture vapor transmission rate of food (Noor *et al.* 2022). The use of hemp in active packaging films with shikonin, starch, and anthocyanin also indicates the freshness of foods such as shrimp, grape, clam, and salmon, respectively by color change with pH change (An *et al.* 2023; Dash *et al.* 2024; Zhu *et al.* 2023).

Bioplastics

Petroleum-based plastics introduce a variety of environmental issues, including human health issues, GHGs, and marine contamination. Therefore, bioplastics are gaining popularity as an alternative to traditional plastics (Atiwesh *et al.* 2021). The most common bioplastic synthesized from hemp is poly-3-hydroxybutyrate P(3HB) from *Ralstonia eutropha* fermentation and enzymatic hydrolysis of hemp hurds (Khattab and Dahman 2019). P(3HB) is strong, hydrophobic, biodegradable, biocompatible, non-toxic, and has thermoplastic properties similar to polypropylene (PP) (Moliterni *et al.* 2022). It has many comparable properties to petroleum-based plastics such as high strength and melting temperature; however, it is a brittle material in large part due to the crystallization of the polymer when at room temperature (Avella *et al.* 2000). P(3HB) has found a profitable use in medical implants to repair the peripheral nerve and soft tissue defects. Different grades of bioplastics are made from hemp which is 2.5 × stronger and 5 × stiffer than PP (Karche and Singh 2019). Another bioplastic made from hemp is reinforced wheat gluten plastics which is 2 × stronger than the control wheat gluten plastics (Wretfors *et al.* 2009).

HEMP BIOFUELS AND ENERGY MATERIALS

Industrial hemp can be used as solid fuel and converted into liquid and gaseous fuel. A cleaner alternative to wood fuel, solid hemp fuels, such as biochar, pellets, and briquettes, because it has lower toxic emissions and reduces wood consumption (Parvez *et al.* 2021). After extracting valuable components such as grains, flowers, and bast fibers from hemp stalks, the remaining hemp hurds are often considered low-value. However, processing them into bioproducts, biofuels, biochar, and energy materials can valorize the whole hemp plant, creating additional revenue streams (Das *et al.* 2017; Ji *et al.* 2021). Mechanical grinding to finely ground hemp followed by anaerobic digestion for biogas production yields 15% higher methane (Ji *et al.* 2021). The produced biogas can be burnt to produce electricity or used as vehicle fuel. Recently, biohydrogen has become more popular as a green fuel due to a number of benefits (Almarsdottir *et al.* 2010), including a high energy yield, which is nearly three times greater than that of fossil fuels (Kapdan and Kargi 2006), and minimal impact combustion products (Das and Veziroğlu 2001). It has several uses, ranging from transportation to power. *Clostridium thermobutyricum*-like novel thermophilic bacterial strain AK14 has been used in the production of biohydrogen from hemp (Almarsdottir *et al.* 2010).

Pyrolysis, fermentation, anaerobic digestion, and transesterification are the most common methods to produce liquid fuels, such as biodiesel and bioethanol (Parvez *et al.* 2021; Zhao *et al.* 2020b). The yield of bioethanol has been found to vary with different pretreatment methods such as 67.4 to 74.7% for liquid hot water pretreatment, 67.2 to 89.6% for acid pretreatment, and 95.8 to 96.7% for alkali pretreatment, which are almost similar to other crops (Das *et al.* 2017; Zhao *et al.* 2020b). Past studies describe the conversion of hemp biomass into biochar. Hemp hurd, which is the main byproduct of bast fiber generation, has been pyrolyzed and gasified with fir sawdust to produce biochar (Puglia *et al.* 2023). The char yield depends on pyrolysis temperature, residence time, pH, carbon, hydrogen, and ash content (Lehmann and Joseph 2009; Puglia *et al.* 2023). The obtained hemp biochar showed compatibility with seed germination when mixed with soil as a soil amendment (Puglia *et al.* 2023). It boosts soil carbon (C) and nitrogen (N) levels because of its high C/N ratio which is around 25 mg N g^{-1} C (Luxhøi *et al.* 2006), and enhances microbial metabolic activities.

Biochar's porous structure (pore size > 50 nm) provides a habitat for microorganisms, protecting them from predation by larger arthropods. Additionally, the high water-holding capacity and high adsorption capacity of biochar help immobilize pollutants in soil, reducing migration and toxicity, which further benefits soil microorganisms (Huang *et al.* 2023). Hemp residue and biochar have both been reported to increase the soil enzymatic (*e.g.*, phosphodiesterase, arylsulfatase, acid phosphatase, β-glucosaminidase, and β-glucosidase) activities by 1 to 2 fold compared to hardwood biochar (Atoloye *et al.* 2022). Hemp biochar carbonized at 400 to 600 °C and 800 to 1000 °C showed potential for solid biofuel and electronics applications, respectively (Marrot *et al.* 2022). In the bioenergy production process, hemp biochar blended with coal can result in a 10% reduction in CO_2 emissions (Parvez *et al.* 2021). Hemp can generate 13 t/ha biochar per year, which helps carbon sequestration and reduces GHGs (Adesina *et al.* 2020).

CONSTRUCTION MATERIALS

The building sector consumes 40% of the global energy, mainly for heating and cooling, and consumes 32% of global energy demand and is responsible for 30% energy related CO_2 emissions (Abdellatef and Kavgic 2020; Ahmed *et al.* 2022; Ingrao *et al.* 2015). In the US, 29% of the total greenhouse gases, and over 40% of the global CO_2 is emitted by the building sector (Lee and Chong 2016). Therefore, scientists seek more eco-friendly, carbon-negative materials to replace carbon-positive materials in construction and the building sector (Ahmed *et al.* 2022). Hempcrete is an alternative concrete used as a building material that has a negative carbon footprint (Pochwała *et al.* 2020). It is a biocomposite, made up of hemp hurd fibers, lime, and water (Collet and Pretot 2014). The notable use of hempcrete began in the early 1980s (Dartois *et al.* 2017). Due to its superior thermal insulation capabilities, hempcrete insulates against both heat and cold. It is used in floor, roof, and wall insulation materials because of its lightweight, breathability, fire-resistance, and acoustic properties, helping regulate indoor temperature and reducing the need for additional heating or cooling (Antonov *et al.* 2017; Delhomme *et al.* 2020; Ingrao *et al.* 2015). The Adnams Warehousing and Distribution Centre in Suffolk is the UK's largest application of lime/hemp for wall construction, which achieved significant thermal performance savings. The use of hemp fiber reduces the heat transfer through walls and decreases the U-value to 0.18 W/m^2K (Muhit *et al.* 2024). Hemp bast fiber incorporation in asphalt for road construction also increases mechanical performance such as fatigue resistance and tensile strength while reducing rutting and cracking (Muhit *et al.* 2024).

ENVIRONMENTAL BENEFITS- LIFE CYCLE ASSESSMENT (LCA) AND TECHNO-ECONOMIC ANALYSIS (TEA)

Industrial hemp, a fast-growing plant, acts as a carbon sink, absorbing up to 22 t CO_2/ha, which is more than any other crop (Adesina *et al.* 2020). Hemp absorbs and stores carbon in stem, roots, and leaves *via* photosynthesis and bio-sequestration. Therefore, hemp-based products have a low or negative carbon footprint (Pochwała *et al.* 2020). Decomposing or incinerating biomass in the field releases CO_2 back into the atmosphere. For hemp to achieve a truly negative carbon footprint, its biomass must be processed or stored in ways that prevent CO_2 from re-entering the atmosphere. For instance, converting hemp biomass into biochar helps maintain a negative carbon footprint, as biochar enriches soil while sequestering carbon (Adesina *et al.* 2020). Hemp fibers used in construction (hempcrete), insulation, or biocomposites provide long-term carbon storage (Collet and Pretot 2014). Additionally, when hemp is processed into biofuels, integrating carbon capture technology can further minimize emissions (Ji *et al.* 2021).

Hemp farming can use regenerative techniques such as crop rotation and cover cropping to enhance soil health, biodiversity, pest and disease management, nutrient optimization, weed control, soil health improvement, and sustainable agriculture. Hemp is cultivated as an auxiliary fiber crop, although it fits best in a crop rotation with cereals or legumes (Kostuik and Williams 2019).

Implementation of hemp in a crop rotation provides allelopathic effects, reducing nematode populations in soil, thereby serving as a nematicide for the crops that are vulnerable to nematodes, such as maize, peas, and potatoes (Rothenberg 2001). Generally, leguminous crops are used as cover crops because they can fix atmospheric nitrogen, improving soil fertility and reducing the need for synthetic nitrogen fertilizers for the main crops. Though hemp cannot fix nitrogen, implementing it as a cover crop in a crop rotation at a thick planting density inhibits weeds and prevents erosion, and its deep root system improves soil structure and porosity (Lotz *et al.* 1991; Struik *et al.* 2000). Hemp has been recognized for its potential in phytoremediation, a process whereby plants can help detoxify contaminated soils by absorbing pollutants or heavy metals by its deep root system, thus aiding land reclamation and environmental remediation (Placido and Lee 2022).

The leaves of the hemp plant were found to accumulate three heavy metals, 1,530 mg/kg of copper, 151 mg/kg of cadmium, and 123 mg/kg of nickel (Ahmad *et al.* 2016). Near the Chernobyl Nuclear Disaster site, hemp was grown in 1986 to aid in the decontamination of the soil (Adesina *et al.* 2020; Ahmad *et al.* 2016; Citterio *et al.* 2003; Placido and Lee 2022). No effect on fiber quality and plant height was observed in recent studies due to contaminated heavy metal soil (Linger *et al.* 2002; Pietrini *et al.* 2019). Proper handling and disposal of hemp biomass after phytoremediation is important to prevent the reabsorption of heavy metals (*e.g.*, copper, cadmium, nickel) back into the environment. Contaminated hemp biomass can be incinerated, reducing it to ashes, which are then safely disposed of in landfills. This prevents metals from leaching back into the soil (Placido and Lee 2022). Studies show that heavy metals do not affect the fiber quality of hemp, so biomass can be used for building materials, insulation, and composites, or any other non-food and non-textile applications (Wu *et al.* 2021). Contaminated biomass can also be considered for composting, pyrolysis, or metal recovery (Rheay *et al.* 2021). Hemp harvested from remediation sites can be safely converted into bioenergy (Kniuipytė *et al.* 2023).

Hemp’s natural resistance to pests and diseases reduces the need for chemicals, promoting healthier ecosystems and minimizing harm to wildlife and waterways (Ajayi and Samuel-Foo 2021). It is drought-tolerant, adaptable to various temperatures, and it conserves freshwater resources by using less input water and requiring minimal maintenance and agrochemicals throughout the growing season (Cherrett *et al.* 2005). No-till farming of hemp is of great interest as it reduces fuel and energy uses, which in turn decreases environmental emissions (Van Der Werf 2004).

Life Cycle Assessment (LCA)

Several LCA studies have been conducted on hemp-based products and field production to determine the environmental burdens in terms of different environmental impact categories, such as acidification, eutrophication, global warming potential, *etc*. However, a direct comparison between them is not possible because of differences in modeling assumptions and system boundaries. Among all the previous LCA articles, building materials, hempcrete, and insulation were the most studied products. A list of different LCA studies on hemp-based products with location, methodology, considered major environmental impact categories and carbon footprint is recorded in Table 5. According to these studies, hemp was found to be one of the least damaging crops as manifested by its reduced impacts on global warming potential, energy usage, eutrophication, and climate change as a value-added product. As hemp requires less fertilizer, it reduces CO_2 and N_2O emissions from fertilizer production and application. Reduced fertilizer input means less nitrate leaching into groundwater and less eutrophication in rivers and lakes (Van Der Werf 2004). Hemp plants require relatively low water. So, it can grow rain-fed and can access groundwater due to its deep root system which eliminates irrigation-related emissions.

Techno-Economic Analysis (TEA)

Hemp is an eco-friendly substitute for cotton because it produces three times more fiber per hectare than cotton, resulting in a 77.6% reduction in agricultural costs when considering four main cost inputs, such as fertilization costs, cost of irrigation, cost of seeds, and pest control costs (Duque Schumacher *et al.* 2020). Due to increased requirements of fertilizer, the production and processing cost of hemp grain is $2913 to 3573 per Megagram (Mg) which is higher than the hemp fiber production cost of $1155 to 1505 per Mg (Khanal and Shah 2024).

Table 5. A List of Different LCA Studies on Hemp-based Products with Location, Methodology, Considered Major Environmental Impact Categories, and Carbon Footprint (Abbreviations: GWP global warming potential); E (eutrophication); A (acidification); T (toxicity); OD (ozone Depletion); FD (fossil fuel depletion); PM (particulate matter); LU (land use); O (others)

Product	Comparator	Location	Functional Unit for Cradle-to-gate LCA	Major Environmental Impact Categories Considered	Carbon Foot-print (kg CO_2eq)	References
Hemp Fiber	Fiber hemp vs. arable crops	France	1 ha of hemp	GWP, E, A, T, LU, O	2330	(Van Der Werf 2004)
	Fiber hemp vs. flax based on different retting	Central-Europe, France, Belgium, Netherlands, Hungary	100 kg of yarn	GWP, E, A, FD, LU, O	1350-1810	(Turunen and Van Der Werf 2007)
	Fiber hemp vs. flax	Spain	1-ton fiber	GWP, E, A, FD, O	1600	(González-García *et al.* 2010a)
	Fiber hemp vs. flax	Spain	1 tonne of non-wood paper pulp	GWP, E, A, T, O	7031	(González-García *et al.* 2010c)
Fiber composite	hemp/PLA vs. flax/PLA vs. polyamide/glass fiber composites	Latvia	1000 × 500 mm large composite	GWP, E, A, T, OD, FD	1.7	(Seile *et al.* 2022)
Pulp and paper	Hemp paper vs. eucalyptus paper	Portugal	1-ton of paper	GWP, E, A, LU	8200-8500	(Da Silva Vieira *et al.* 2010)
	Hemp and flax-based pulping vs. straw-based pulping	China	1-ton of wheat straw pulp	GWP, E, A, T, OD, FD, O	4550	(Sun *et al.* 2018)

Grain	Different hemp varieties	Italy	1 kg seed	GWP, E, A, T, OD, FD, PM, LU, O	0.161-18.720	(Campiglia *et al.* 2020)
Hempcrete	Hempcrete wall with different coatings	France	1 m^2 wall	GWP, E, A, OD, FD, O	-0.016	(Pretot *et al.* 2014)
	different bio-based building element	Belgium	1 m^2 building elements	GWP, PM, LU	14.26-138.02	(Mouton *et al.* 2023)
	Hempcrete vs. traditional brick block	Italy	1 m^3 wall	GWP, T, FD	15.9	(Di Capua *et al.* 2021)
Insulation	Among four bio- based and two nonrenew-able insulations.	Germany	1 m^2 external wall	GWP, E, A, T, OD, FD, PM, LU, O	11.7	(Schulte *et al.* 2021)
	Among natural and synthetic insulating materials	Italy	1 m^3 of the insulating material	GWP, OD, O	630.72	(Rocchi *et al.* 2018)
Ethanol	Among five lignocellulosic materials	Spain	1 km distance driven by a flexi fuel vehicle	GWP, E, A, FD, O	0.0794-0.2370	(González-García *et al.* 2010b)
Biodiesel	Hemp diesel vs. diesel oil	Spain	Consumption of 44.80 L of diesel oil or 47.04 L of hemp diesel in an 18-ton lorry in 50 km	GWP, E, A, OD, FD, O	-2.33	(Casas and Rieradevall I Pons 2005)

Hemp composite is one of the most inexpensive composites in terms of end-of-life treatment, with costs ranging from \$8.77 to 10.2 per kg, \$2.18 to 3.66 per kg, and \$1.52 to 3 per kg for 0.01 kg, 0.1 kg and 1 kg part weight PLA incorporation into hemp fiber, respectively (Haylock and Rosentrater 2018). Hemp has a lower entrepreneurial risk due to its annual production cycle, compared to the longer-term commitments required for perennial energy crops. A study conducted in the Czech Republic determined that the cost of producing hemp biochar by pyrolysis ranges from €452 to 667 per ton without utilizing excess heat and from €381 to 596 per ton with excess heat utilization (Vávrová *et al.* 2022). Hemp biomass containing 10% lipid would be a cheaper option for biodiesel production if hemp can be produced at \$50/ MT. The cost of biodiesel production from hemp is \$4.31 per gallon, which is comparable to soybean biodiesel production of \$4.15 per gallon (Viswanathan *et al.* 2021). Industrial hemp can be made more profitable by using a production plan that considers several co-products. When compared to other growth models, the dual-purpose growing model demonstrated a greater degree of productive efficiency.

According to research findings, the cost of producing hemp stalks from a fiber hemp variety was US \$0.29/kg, whereas the cost from dual-purpose cultivation was slightly higher, at around US $0.41/kg. Moreover, fiber yield was found to be 1480 kg/ha from fiber hemp, whereas from dual-purpose variety, fiber yield was 1275 kg/ha. At the same time, dual-purpose varieties yield 850 kg/ha of grains, which is also comparable to grain-only varieties where the grain yield is around 958.3 kg/ha (Ceyhan *et al.* 2022). While current evidence shows positive returns on concurrent hemp products, hemp must be financially competitive with conventional crops. Future studies should compare hemp's profitability with other crops and consider regional differences, especially in the Global South, which is yet to be analyzed, for more economically viable hemp production systems due to low-input farming and cheap labor (Budhathoki *et al.* 2024).

CONCLUSIONS

This review article has provided a comprehensive analysis of industrial fiber hemp anatomy, current agricultural practices in the context of the US, and the novel applications of hemp into low-carbon bioproducts by analysis of the major findings of recent studies. It explored the cultivation practices and agronomic considerations necessary for successful hemp production, highlighting key factors such as soil requirements, nutrient management, climate, and pest control. In terms of cultivation recommendations, the ideal soil pH for hemp generally falls within the range of 6.0 to 7.5. For fertilizer requirements, hemp typically benefits from nitrogen-rich fertilizer at 150 to 200 kg/ha during the vegetative growth stage and potassium fertilizer at 175 kg/ha. On the other hand, cotton and flax require 50 to 412 kg/ha and 20 to 40 kg/ha of nitrogen, and 110 to 250 kg/ha and 50 to 180 kg/ha of potassium fertilizer, respectively. Late spring with a soil temperature of 13 to 25 °C is optimum for seed sprouting and further vegetative growth. Industrial hemp's ability to sequester significant amounts of carbon dioxide (22 t CO_2/ha by 1 hectare hemp), reduce reliance on synthetic pesticides and herbicides, enhance soil health, prevent erosion, contribute to biodiversity and phytoremediation, makes it a compelling choice for sustainable agriculture. Furthermore, it has an expanding array of applications not limited to textiles, foods, cosmetics, and paper. Hemp industries are moving towards more applications in sustainable materials such as biofuel, biocomposites, biochemicals, bioplastics, and biochar production, not only in sole production but also in more economically feasible co-production systems. However, to achieve successful monetization of hemp products, further LCA US-based LCA studies should be conducted to validate performance with respect to environmental indices.

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