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# PRODUCTION OF INDUSTRIAL HEMP: BREEDING STRATEGIES, LIMITATIONS, ECONOMIC EXPECTATIONS, AND POTENTIAL APPLICATIONS

Engin Tilkat[1,a,*], Ayşe Hoşer [1,b], Emine Ayaz Tilkat [1,c], Veysel Süzerer [2,d], Yelda Özden Çiftçi[3,e]

[1]*Batman University, Faculty of Science and Literature, Department of Biology, 72100, Batman, Türkiye.*

[2]*Bingöl University, Vocational School of Health Services, Department of Pharmacy Services, 12000, Bingöl, Türkiye.*

[3]*Gebze Institute of Technology, Department of Molecular Biology and Genetics, 41400, Gebze, Kocaeli, Türkiye*
**Corresponding Author: Engin Tilkat*
*E-mail: etilkat@gmail.com*

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a: ORCID 0000-0002-1654-7655, b: ORCID 0000-0002-8796-8449; c: ORCID 0000-0001-5111-425X,

d: ORCID 0000-0001-5383-4613, e: ORCID 0000-0002-9799-3648

**ABSTRACT.** Industrial hemp, a versatile and sustainable plant, possesses a broad array of applications. It offers fiber from its stems, food from its seeds, and oil from its flowers and seeds. Its importance lies in its contribution to economic, social, and environmental sustainability, thereby playing a crucial role in fostering a sustainable future. The extensive literature on industrial hemp emphasizes its potential as a sustainable resource. This review aims to underscore hemp's significance globally and highlights various aspects of industrial hemp production, encompassing breeding techniques, challenges, economic projections, and potential utilization.

**Keywords:** Industrial hemp production, breeding strategies, sustainability, potential applications.

# ENDÜSTRİYEL KENEVİR ÜRETİMİ: YETİŞTİRME STRATEJİLERİ, SINIRLAMALARI, EKONOMİK BEKLENTİLER VE UYGULAMA ALANLARI

**ÖZET.** Çok yönlü ve sürdürülebilir bir bitki olan endüstriyel kenevir, geniş bir uygulama yelpazesine sahiptir. Saplarından lif, tohumlarından besin ve çiçeklerinden ve tohumlarından yağ sunar. Önemi, ekonomik, sosyal ve çevresel sürdürülebilirliğe yaptığı katkılarda ve böylece sürdürülebilir bir geleceğin geliştirilmesinde çok önemli bir rol oynamasında yatmaktadır. Endüstriyel kenevir hakkındaki kapsamlı literatür, onun sürdürülebilir bir kaynak olma potansiyelini vurgulamaktadır. Bu derleme, kenevirin küresel öneminin altını çizmeyi ve yetiştirme teknikleri, karşılaşılan zorluklar, ekonomik projeksiyonlar ve potansiyel kullanımı kapsayan endüstriyel kenevir üretiminin farklı yönlerini vurgulamayı amaçlamaktadır.

**Anahtar Kelimeler:** Endüstriyel kenevir, yetiştiricilik stratejileri, sürdürülebilirlik, potansiyel uygulamaları.

## INTRODUCTION

Climate change has led to numerous environmental challenges that the world faces. The unsustainable use of natural resources due to overpopulation, global warming, and, declining biodiversity has contributed to these challenges. The seamless cooperation between agriculture, economy, and ecology is crucial for ensuring the protection of our natural resources and their transfer to future generations without any complications. Achieving the sustainability of our environment requires these three components to work in harmony. One promising solution that can address these sustainability issues is industrial hemp. Hemp, with its sustainability potential, has garnered attention as a potential game-changer [1, 2, 3, 4].

Hemp is an incredibly versatile plant with many ecological, agronomic and pharmaceutical benefits. It is a precious resource for diverse traditional and modern industrial products, including fiber, food, oil, and medicine [5]. *Cannabis sativa* L. has been used as an essential source of herbal raw materials throughout history with its fiber, seed, oil, and pleasing and therapeutic properties [6]. Plants produce sticky and distinctive-smelling cannabinoids in glandular trichomes, specialized biosynthetic organs on female flowers and leaves [7]. Numerous research studies have utilized the analysis of trichome metabolism to illustrate variations in trichome characteristics such as size, density, and the relative concentration of cannabinoids [8].

Nevertheless, the specific genetic mechanisms responsible for the developmental changes in trichomes and the subsequent production of cannabinoids remain unidentified. In addition to natural and chemical methods of cannabinoid synthesis [9], there have been reports of heterologous production of cannabinoids [10]. However, a significant challenge in cannabinoid production is the substantial production of unwanted by-products [10, 11]. Industrial hemp and medicinal *Cannabis* have different genotypes**,** chemical compositions, and uses. Hemp has been used for centuries in industrial and food products and is now grown in over 30 countries and traded globally. This review emphasizes many aspects of industrial hemp cultivation, including breedingmethods, difficulties, economic projections, and possible applications, to highlight hemp's significance globally.

### *General Characteristics of Industrial Hemp*

*C. sativa* L., which has a history of 10,000 years, originated in Central Asia [12] and was grown in Europe, Africa, and South America for its seeds and edible oil. It spread to Europe during the Middle Ages and was cultivated in Chile in the 1500s and later in North America [13]. *Cannabis* is a diploid (2n = 20), dioecious, and dicotyledonous plant belonging to the Cannabaceae family that can grow up to 3 m in length and has an annual herbaceous form [14]. The cannabis genus can be classified into three distinct species: *C. sativa*, *C. indica*, and *C. rubralis* [15, 16]. The female flowers form long, spike-like clusters, and the male flowers form highly branched ones. The seeds are green-grey in color and oval-shaped (3-5 mm long, 2-3 mm wide), andthe weight of 1000 seeds is between 20 and 25 g [17]. The female plants bloom earlier than the males, and the flowers are greenish-yellow and smaller. The plant boasts a robust taproot system that extends deep into the soil, accompanied by smaller lateral

roots [6]. The outer layer of the stem produces two types of fibers: long sac fibers (phloem fibers) and short woody fibers (xylem fibers) [18]. Hemp is cultivated in numerous countries worldwide, particularly those with moderate climatic conditions [19]. *Cannabis* is cultivated in various countries with temperate climates across the globe. This plant thrives in temperatures ranging from 13 to 22°C and can quickly adapt to different soil types, particularly heavy-alkaline soils. It favors deep and well-aerated soils with a pH of 6, adequate moisture, and nutrient-holding capacity [13, 20].
There are different varieties of *C. sativa* L., such as industrial and medicinal cannabis [21]. The industrial hemp leaves have palmate compound structures with 5–11 leaflets. Compared to medicinal cannabis, the number of branches on the stem varies depending on ecological regions. The stem comprises the outer layers of the epidermis, hypodermis, and chlorenchyma. The outer shell is relatively thin and encloses a woody part surrounding a hollow center. Reports indicate that the percentage of dead tissues in the outermost layer of the vascular cambium can vary significantly, ranging from 12– 48% [22].

Industrial hemp refers to a type of cannabis plant that is grown for its fiber and grain. This plant, along with other variants of the *Cannabis* species, is an upright, annual plant that can grow up to 6 meters tall and is primarily dioecious. There are more than 100 recognized cannabinoids found in the cannabis species, each with different physiological effects on humans.

Over one thousand substances have been discovered in the cannabis plant, as indicated by various studies [23, 24, 25]. Among these compounds, approximately 278 are categorized as cannabinoids and are referred to as phytocannabinoids to differentiate them from non-plant-based endocannabinoids [26, 27]. The primary cannabinoids found in cannabis include THC (tetrahydrocannabinol) , cannabidiol (CBD), cannabichromene (CBC), and their precursors, cannabigerol (CBG) and cannabinol (CBN) [28]. Two of the most extensively researched cannabinoids are CBD and THC. CBD is a non- addictive, non-hallucinogenic compound known for its therapeutic profile, while THC is the psychoactive element responsible for the "high" commonly associated with cannabis use. CBD is marketed in various forms, including bud, oil, and tinctures, as it helps soothe swelling and promote relaxation. However, THC is often used for medicinal and recreational purposes but is illegal in many countries due to its psychoactive effects.

The main difference between industrial and medicinal *Cannabis* is the concentration of THC. Industrial hemp typically has less than 1% THC, while cannabis has 5%. The legitimacy of industrial hemp varies from country to country [29, 30]. Moreover, it is crucial to note that the outer shell represents approximately 30–35% of the stem's dry weight [31]. Industrial hemp includes plants with low THC (less than 1%) [32], while medical cannabis refers to psychoactive *Cannabi*s varieties with high THC. Even some studies report that medicinal cannabis has THC levels of 15–22% [33]. Industrial hemp is also essential for its fiber and seed, which find use in various products. Minor differences in morphological characteristics between industrial and medicinal cannabis, resulting from varying cultural practices, make it possible to distinguish between the two products [34, 18]. Cultivating industrial hemp demands various breeding strategies, economic predictions, and constraints. This plant boasts numerous potential applications across multiple industries.

### *Breeding Strategies of Industrial Hemp*

Breeding strategies in industrial hemp production are essential for enhancing plant characteristics and optimizing yield. These strategies encompass various aspects, including improving fiber quality by focusing on traits like density, fineness, and strength to cater to textile and industrial uses. Another goal is enhancing seed quality, aiming for high yield, oil content, and desirable fatty acid composition. Breeding resistant hemp varieties against common diseases and pests is crucial to reducing crop losses and minimizing chemical interventions. Breeders aim to develop hemp varieties that adapt well to diverse geographical regions and achieve high yields across different environmental conditions. Industrial hemp production involves growing primary sak fiber (phloem fiber) by carefully managing plant density, thinning practices, and irrigation frequency. Factors such as low plant density, excessive irrigation, and moisture can lead to fungal infections, ultimately reducing the fiber's quality and yield. While adequate moisture is crucial for seed germination and the development of young plants, excessive humidity levels above 60% can lead to diseases such as gray mold. It is important to note that the cannabis plant grows best between 40 and 80% relative humidity. Additionally, hemp can endure temperatures below 13°C for 4-5 days after producing the third set of leaves [35].

Fiber hemp, also called industrial hemp cultivars, contains no more than 0.3% THC in the stems and flower buds. Countries that allow cannabis farming only permit strains with THC levels below this limit. Industrial hemp cultivators prioritize specific breeding traits such as high yield, longer length, increased tensile strength for paper production, fine fiber structure for textiles, higher cellulose content for biofuels, and compatibility with modern processing technologies [36, 33]. To achieve optimal fiber production, utilizing well-ploughed and prepared seed beds is imperative while planting cannabis seeds. The seeds must be placed at a depth of approximately 3 cm and spaced 8–18 cm apart between rows, with a recommended plant density of 100–200 plants/m$^2$ [37, 6]. Lower densities can result in higher stem yield, but higher densities can produce plants with smaller fiber diameters and greater tensile strength, improving stem quality. Furthermore, increasing the number of seeds per unit area has been proven to reduce grass density, positively impacting overall size [38, 39].

It is worth mentioning that scientific data on the water needs of hemp is currently limited. However, a study conducted in Ukraine has definitively established that a yield of hemp can be achieved with 250-280 mm of precipitation during the vegetation period. It is crucial to note that industrial hemp's functional water requirement during the vegetation phase is approximately 600 mm [40, 41]. Irrigation is deemed necessary during the summer months for cannabis based on irrigation trials conducted in locations like Tasmania to compensate for deficiencies in precipitation patterns and overall rainfall [40].

Although scientific studies indicate that hemp requires minimal or nofertilization, it's essential to note that some fertilizer usage may be necessary depending on the soil's natural fertility [37]. Research on fiber crops has revealed that hemp typically requires an optimal amount of nitrogen ranging between 100 and 150 kg N/ha [42, 43, 44]. Still, the amount of fertilizer needed varies based on planting frequency, row spacing, and plant density. To attain maximum grain yield, using an appropriate and controlled amount of nitrogen is crucial, as excessive levels could negatively impact fiber quality. Studies have shown that a balanced nitrogen application can help enhance crop production [45].

Finola® is a highly significant industrial cannabis variety with great importance in Canada, cultivated on over 8000 hectares nationwide. The seeds are harvested at around 70% ripeness with a 15–24% moisture content. It's important to note that harvested seeds can contain up to 15% foreign matter, which is retained during storage. Studies have revealed that Finola® is more prone to spoilage during storage than other plant species due to the foreign matter mixed with the seed and the risk of bacterial contamination post-harvest. Unfortunately, approximately 5% of the seeds become unusable annually due to temperature, bacterial, or fungal contamination during storage [46]. Additional scientific studies are necessary to decrease storage losses and create techniques for safeguarding *Cannabis* seeds [47].

The harvesting of *Cannabis* plants for fiber typically occurs in late July or early August in southern regions of the northern hemisphere and in August or September in northern regions. While machines are utilized for larger areas, it's important to note that clogging can occur due to tough fibers. On the other hand, varieties grown for grains or seeds are harvested upon the ripening of the seeds. The initial step in fiber production involves collecting and air-drying plant stems in the field. After drying, the stems are soaked to eliminate undesirable substances and form fiber bundles. Maintaining appropriate humidity levels during this stage is crucial, as any delay can harm fiber quality. Additionally, dry weather conditions are essential for baling hemp stems, and the weather during harvest season can significantly impact the fiber quality produced [48].

Instead of gathering hemp in the field, it can be processed through watering, and immersing the plant stems in water for a specific time produces more uniform and high-quality fibers. However, this technique is costly, requiring skilled labor, having high labor costs, and having a more significant environmental impact [49]. Due to climate risks and expensive traditional harvesting methods, new systems that involve chopping and anaerobic storage have been developed [50]. In Europe, a plant has been createdthat can process hemp fibers into insulation, sheets, and granules [51]. Harvesting has previously involved cutting the entire stem at the base and bundling or stacking it for drying and processing. Specialized equipment has been developed for this process, and it has become the more common harvesting method today. It is widely acknowledged that hemp has a much smaller carbon footprint than organic cotton and petroleum-based products. This is because hemp is a plant that can be quickly grown organically, thanks to its low impact on the ecosystem [52, 53]. Although hemp fields may experience weed growth during late spring with high air temperatures [54], proper growing conditions such as early planting and sufficient humidity can help suppress weed species without relying on herbicides. However, weed growth may be more prominent in seed cannabis cultivation due to wider inter-row and in-row distances, which hinder the growth of plants with sufficient density to suppress weed growth. Parasitic weeds can also affect cannabis production. Plants such as broom and dodder can hurt productivity, while heather can cause *Cannabis* plants to die before harvest. Nonetheless, this is not expected to be a significant problem as various strains resist these parasitic plants [55]. However, parasitic weeds can indeed harm cannabis production. For instance, broom and dodder can significantly reduce productivity, and parasitic weeds can cause cannabis plants to die early [37]. However, certain *Cannabis* varieties exhibit resistance to these parasitic plants, so it is not expected to pose a significant issue. Nevertheless, weed species like morning glory and vetch can impede cannabis seed production by climbing onto the plants and making it challenging to distinguish seeds of similar size. Additionally, insects can harm cannabis crops by consuming them, which could decrease stem quality. While some researchers do not view this as an economic issue, others suggest a control mechanism, particularly in grain production systems, may be necessary. Studies have demonstrated that damage caused by corn worms can substantially negatively impact cannabis production [56].

Research has demonstrated that corn borer larvae have the potential to enhance branching in plants, leading to an increase in both grain yield and weight [57]. Additionally, multiple cuts during the seedling growth stage encourage tillering in plants, leading to higher grain yield despite a decrease in fiber yield [58, 59]. Although some types of nematodes may pose a threat to cannabis, this is generally considered a minor issue that can be effectively resolved through the use of nematode-resistant varieties [37]. Moreover, compounds extracted from cannabis have been proven to effectively combat nematodes, resulting in yield increases of over 10% in soybean fieldsplanted after hemp with low nematode infestation rates. Lastly, it is crucial to note that fungal diseases can rapidly spread after sucking insects damage fruits, especially in environments with high humidity and temperatures [60, 61]. Fungal diseases tend to thrive in warm and humid conditions and can spread quickly when the fruit is damaged by sucking insects [62]. This issue does not significantly affect industrial hemp production systems [63]. Research has shown that hemp production is moreadvantageous than monoculture practices for other plants, despite the sustainability challenges that monoculture production systems may pose [62]. Hemp is frequently used in alternate planting schemes to combat pest and weed difficulties because it is more environmentally friendly than many other crops [64, 65].

### *The Production of Cannabis Worldwide and Turkey's Position*

*Cannabis* cultivation is legally allowed in several countries, with China leading the way in production. China has impressive fiber production, with a total output of 16,575 tons, while France is the largest seed producer, producing 83,000 tons. The largest producer in South America is Chile; France still holds the highest output in Europe. The cannabis market has been developing continuously, despite its historical association. The sector focuses primarily on producing one seed and marijuana in legal countries. The commercial interest in hemp seeds is due to their high protein and essential fatty acid profiles.

Additionally, there is a growing interest in oil production, flour and processed foods, and the health and nutraceutical sectors. It's exciting to see the market share for cannabis growing, especially in the oil cosmetics and body care industries. The global production of cannabis seeds currently stands at an impressive 102,415 tons, withFrance leading the way with an impressive 83,000 tons. The top four seed production countries are France, China, Chile, and Russia, collectively accounting for 98% of the total production. *Cannabis* is becoming an increasingly significant player in the global market [66].

Turkish researchers are just beginning their work on creating value-added products, despite the country being mostly an agricultural culture with attractive future businesses. In 1933, Turkey implemented the Law on Control of Drugs, marking the first legal regulation of cannabis cultivation in the country [67]. While various laws aim to combat drugs in Turkey, the fundamental legal regulations in this area can be classified into three main categories:

a) On September 26, 2004, the Turkish Penal Code was established, bearing the plate number 5237.
b) The Law on the Control of Narcotic Substances was introduced on June 12, 1933, with the numbering of 2313.
c) The Law on Drugs was enacted on June 3, 1986 (84), with the numbering of 3298.

With increasing demand from large segments of society to legalize industrial hemp production in Turkey, legislation for free cannabis as an industrial product has been supported by politicians across the political spectrum. With the regulation on cannabis cultivation and control, which was implemented in 1990 by the Ministry of Agriculture and Forestry, the legal cultivation of cannabis and the places where it can begrown were determined [68]. In 2016, permitted cannabis cultivation started in 16 provinces within the scope of the ‘Regulation on cannabis cultivation and control’ published in the Official Gazette [69]. Although excitement over cannabis is high, mainly because the plant is a potential source of raw materials for high-value industrial, nutritional, and personal care uses, a "forbidden plant" syndrome remains driving the impetus for hemp.

The potential imbalance between supply and demand in *Cannabis* production systems is a critical issue that could severely affect industries relying on hemp products. It's unacceptable for producers to hesitate to invest in a product without a well- established marketing system. To address these concerns, it's imperative to examine the growth of the *Cannabi*s market in other countries. For example, in Canada, growers who did not thoroughly assess the compatibility between their farming and production activities experienced significant losses due to the variation in cannabis seed production between 1998 and 2010. Developing robust models is essential to ensuring the sustainability and profitability of cannabis production. It's time to take action and prioritize the success of this industry [70].

## LIMITATIONS FACED BY THE *CANNABIS* INDUSTRY

Industrial hemp production encounters various limitations and challenges. Regulatory constraints pose obstacles due to varying legal restrictions and licensing requirements across countries, hindering widespread cultivation. The limited genetic diversity of hemp restricts breeding efforts to enhance traits and adaptability. The wind-pollination nature of hemp plants can lead to cross-pollination with cannabis, affecting THC levels and legal compliance. Additionally, labour-intensive and specialized equipment requirements for harvesting and processing hemp fibers present challenges that necessitate the development of efficient techniques for cost-effective production.

The *Cannabis* industry faces significant obstacles, particularly legal barriers to growing hemp because of its high THC content. Although some countries have resolved these hindrances at the national level, it remains a challenge to overcome the slow development of public opinion and consumer demand for cannabis, particularly in retail sales. In the early 20th century, hemp cultivation was banned in most Western countries due to concerns about its recreational use. In 1938, the Canadian Opium and Narcotics Act banned all *Cannabis* cultivation, while in the USA, industrial cannabis was classified as a Schedule-1 substance alongside medical cannabis, making hemp production difficult. However, many states changed in 2018. In Canada, there are fewer legal barriers to hemp production [71, 72, 73].

Legal barriers related to THC content hinder the growth of hemp worldwide, necessitating political change at a national level. Even if these barriers are lifted, public opinion tends to change slowly. Consumer demand, especially in retail sales, plays a crucial role in determining the success of the hemp industry. In the early 20th century, hemp cultivation was banned in many Western countries due to concerns about its potential use as a recreational drug. Canada prohibited cannabis cultivation in 1938, but research on industrial hemp was allowed in 1994, leading to commercial cultivation in 1998 under Health Canada's regulations. The United States classified hemp as a Schedule 1 drug, along with marijuana, until 2018, when the classification changed. The legalization of cannabis in Canada in 2018 is expected to bring hemp production restrictions closer to those of other crops [74, 73].

The hemp industry faces economic barriers such as subsidization, price competition, supply, and demand [75]. Established crops have enjoyed infrastructure optimization, extensive knowledge of crop biology, and subsidies, which industrialhemp lacks [76]. Subsidies specifically for hemp production could make it more profitable and competitive. For example, 40% of products are made from wood in the paper-making market, so hemp must be priced competitively to enter the market effectively [77]. Another challenge is the public's association of hemp with marijuana and the stigma surrounding drug use. However, hemp oil has various health benefits, including skincare, hormonal balance, and the potential for managing diabetes, which can improve hemp's perception and overcome some industry barriers.

### Economic Expectations

The economic potential of industrial hemp is significant and has multiple facets:

*Fiber and textile industry:* Hemp fibers are used in various industries, including textiles, paper, construction materials, and composites. As sustainable and eco-friendly alternatives gain popularity, the demand for hemp fibers will grow, providing economic opportunities.

*Food and nutritional products:* Hemp seeds are rich in protein, healthy fats, and minerals. The increasing demand for plant-based protein sources and the growing market for health foods and dietary supplements contribute to the economicexpectations in the food industry.

*CBD extraction:* Hemp-derived CBD has gained attention for its potential health benefits and applications in wellness products. CBD extraction from hemp biomass can create a lucrative market for pharmaceuticals, nutraceuticals, and other CBD-based products.

*Biofuel and bioplastics:* Hemp biomass can be converted into biofuels and used to produce bioplastics, offering sustainable alternatives to fossil fuels and conventional plastics [78, 79].

***Applications of Industrial Hemp***

Hemp is a highly versatile crop with many uses and benefits. It can be processed into various products, making it a valuable commodity in agriculture, textiles, recycling, automotive, furniture, food and beverages, paper, construction materials, and personal care. The plant's stalk, for example, can be transformed into biofuel, auto parts, paper, upholstery, and fibre for cloth and other textile items. Hemp can grow in different climates and even on previously unusable land while purifying the soil by removing heavy metals and other contaminants. Incorporating hemp into crop rotation has increased wheat yields by 10 to 20%. One of the most significant advantages of hemp farming is that all plant parts can be utilized, resulting in less waste and pollution than other crops. For instance, over 80% of Africa's cotton plant mass goes to trash, leadingto significant pollution. In India, burning cotton fields to clear harvest leftovers produces suffocating smoke, contributing to deadly pollution. Developing countries can benefit from sustainable production chains that utilize all parts of the hemp plant, stimulating growth in rural areas and promoting economic diversification. Hemp cultivation has the potential to maximize land use and increase incomes for farmers and rural communities, making it an increasingly popular crop with numerous benefits.

The presence of important phytochemicals is responsible for the medicinal benefits of cannabis. The cannabis plant contains over 545 phytochemicals, with phytocannabinoids being the most prevalent metabolite class. Cannabinoids exhibit a diverse range of structures and bioactivities. *C. sativa* L. is found in various forms and environments across all continents, and its pharmacological properties extend beyond its psychoactive effects. The plant has demonstrated potential for treating and alleviating symptoms associated with numerous diseases, such as cancer, AIDS, multiple sclerosis, spinal cord injury, Tourette syndrome, epilepsy, and glaucoma. As regulatory standards for therapeutic cannabis become more relaxed and controlled clinical trials are conducted, the plant's potential as an antiemetic, appetite stimulant, and analgesic is promising. However, further clinical research is necessary to determine the specific medical conditions for which the plant can be therapeutically beneficial. Scientifically designed trials can contribute to identifying which cannabinoids yield favorable effects and understanding the adverse effects of each cannabinoid [80]. In summary, industrial hemp has a wide range of potential applications across various industries, including:

***Textiles and fashion:*** Hemp fibers can be used to produce fabrics, clothing, accessories, and footwear. Hemp textiles are known for their durability, breathability, and eco-friendly properties.

***Paper and packaging:*** Hemp fibers can produce paper, offering an environmentally friendly alternative to traditional wood pulp. Hemp-based packaging materials are also gaining popularity due to their biodegradability.

***Construction materials:*** Hemp fibers can be incorporated into materials like insulation, fiberboard, and concrete, offering lightweight, fire-resistant, and sustainable alternatives for the construction industry.

***Personal care products:*** Hemp oil and extracts are used in cosmetics, skincare, and hair care products due to their moisturizing, anti-inflammatory, and antioxidant properties.

***Animal bedding and feed:*** Hemp fibers can be used as animal bedding material, while hemp seeds and oil are valuable ingredients in animal feed formulations.

***Environmental remediation:*** Hemp has the ability to absorb heavy metals and contaminants from soil and water, making it suitable for phytoremediation and ecological restoration projects [81].

It's vital to keep in mind that precise uses and economic viability may differ based on local laws, consumer demand, and technical improvements. Consequently, hemp has enormous potential for applications in its early stages but with significant future growth opportunities (Fig. 1). If industrial hemp production increases and its cost becomes more competitive with birch and pine pulp, it could revolutionize paper-making, providing tremendous benefits to pulp mills.

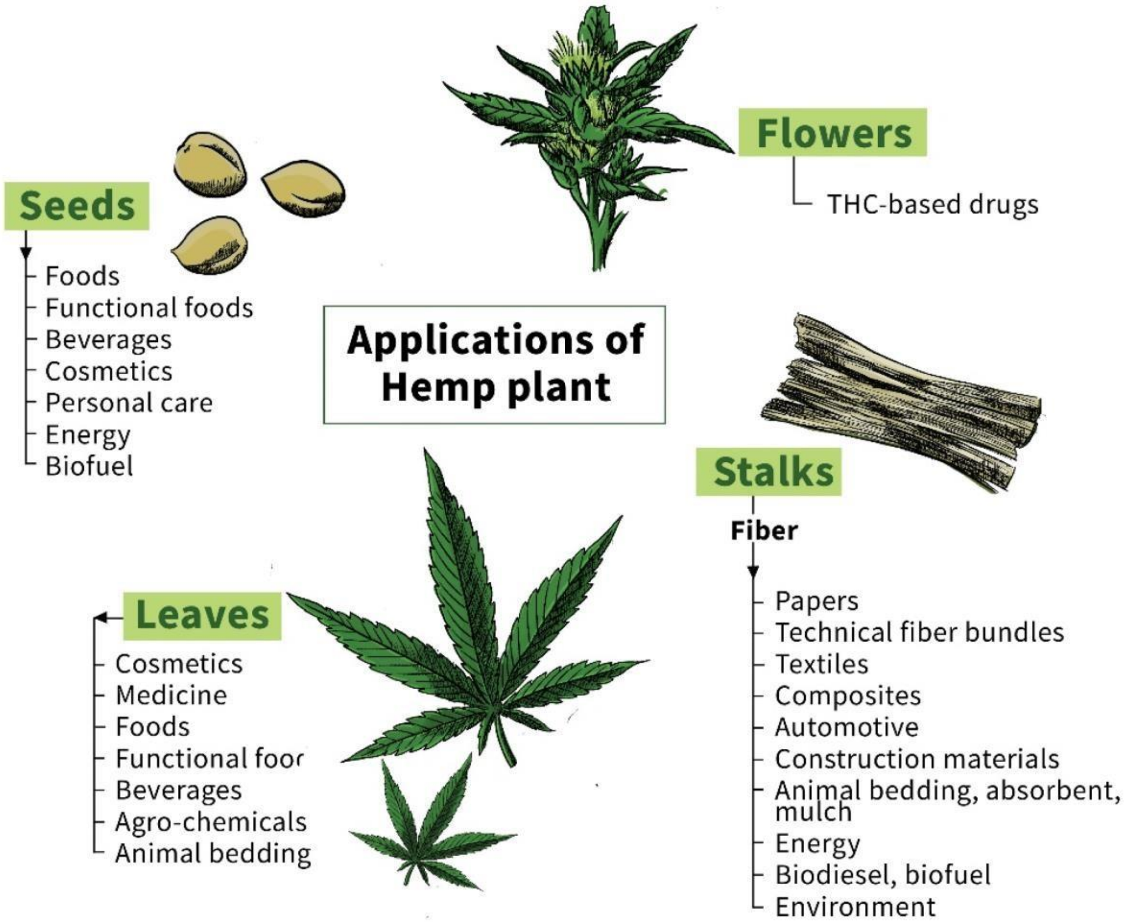


***Fig. 1.*** *Potential applications of industrial hemp. Retrieved from [78].*

Compared to wood paper, hemp paper is of superior quality and can help reduce deforestation. Furthermore, hemp could be a sustainable alternative to cotton, as it can be grown almost anywhere with little water and is economically competitive with cotton while requiring significantly less land and avoiding the need for insecticides or pesticides. Due to its cost-effective nature, the utilization of hemp in the biocomposites sector holds substantial promise, particularly in producing biodegradable packaging, antibacterial materials, and insulating materials. Hemp-lime concrete, composed ofhemp shives and lime, stands out as an excellent insulator, possessing favourable characteristics such as lightweight and flexibility. Furthermore, the pyrolysis products derived from hemp, such as biochar, exhibit potential for fuel blending and find application in non-fuel sectors, including the production of activated carbon. Activated carbon is a valuable material widely used across various industries [82]. Finally, waste generated from industrial hemp conversion and manufacturing processes can be repurposed for creating valuable products such as biofuels and animal feed [56, 71].

***Bioenergy from Industrial Hemp***

The potential of industrial hemp in the bioenergy industry is highly promising due to its versatility in various energy production methods and the extraction of other valuable products. Co-producing hempseed oil with bioethanol, biodiesel, seed cake, and methane has proven a highly efficient and profitable option. Co-producing biochar and other bioenergy is also a viable and lucrative option. While the commercial-scale implementation of pyrolysis for utilizing hemp biomass is still pending, it presents considerable potential for enhancing the profitability of various applications. Notably, this process can significantly improve the utilization of fibres that generate biomass waste [6, 83, 84, 85].

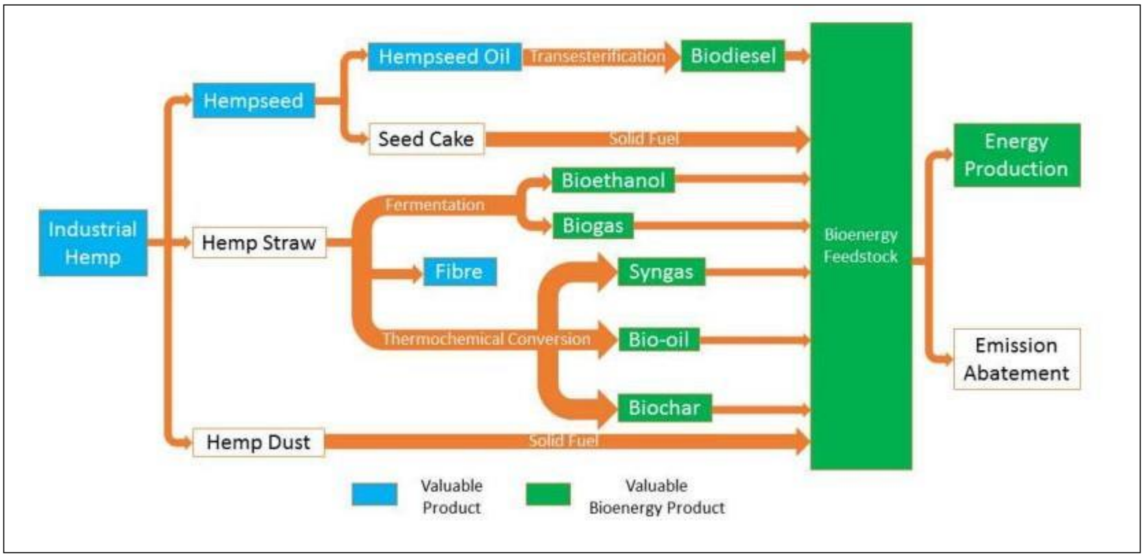


***Fig. 2.*** *Industrial Hemp-based energy production [75]*

The utilization of industrial hemp as a source of bioenergy is highly advantageous due to its remarkable biomass and energy yields, surpassing those of other biomass feedstocks such as cereal grains [76, 86, 87]. It is well-regarded as a superior feedstock for bioenergy purposes, as emphasized by the applications of hemp in the bioenergy sector, as demonstrated in Fig. 2.

***Liquid Fuels***

Biofuels derived from industrial hemp are commonly produced through conversion processes like transesterification, anaerobic digestion, and pyrolysis. These fuels can be seamlessly blended with traditional fuels like diesel and gasoline and are mandated by some countries to contain a minimum renewable fuel content. Industrial hemp stands out as an up-and-coming source of biodiesel, with conversion rates reaching as high as 97% for hempseed oil [88, 89, 90, 91, 92].

Industrial hemp is a promising source for producing economically competitive biodiesel. Using its by-products, hemp can maximize its potential for producing hemp biodiesel. Hempseed oil is crucial for this process, but the remaining hemp straw and seed can be repurposed for various applications. Another viable option for generating liquid fuel from industrial hemp is using pyrolysis to produce hemp bio-oil, which can then be upgraded via hydrodeoxygenation to create hydrocarbon-rich fuels. Moreover, industrial hemp boasts high cellulose and low lignin content, making it an ideal candidate for bioethanol production. When almost fully matured, industrial hemp achieves peak potential for bioethanol production, resulting in the highest glucose conversion rate. Pre-treatment processes involving acids or steam can improve glucose and ethanol yields, with estimated ethanol yields ranging from 206-250 L/mg dry matter. Compared to other herbaceous species, industrial hemp offers a higher ethanol yield on a dry matter basis. While the co-production of ethanol and methane may slightly reduce the ethanol yield, it also yields methane as a co-product. Not only does hemp produce similar bioethanol yields to other crops like kef, switchgrass, and sorghum, but it also offers greater profitability through the co-production of grain [93, 87, 94, 95].

### *Gaseous Fuels*

According to Fig. 2., industrial hemp shows significant potential as a valuable source of gaseous fuels, specifically biogas. To achieve optimal biogas production, experts recommend harvesting hemp during the period between September and October, when its biomass dry matter reaches its peak, particularly in colder regions [96]. Despite its relatively low conversion efficiency, hemp outperforms other crops, such as maize and sugar beets, in terms of producing higher-quality products [97]. Additionally, when fertilized with mineral fertilizer and digested, hemp requires less energy input than other crops like sugar beet, maize, triticale, and wheat [98]. However, the economic viability of utilizing hemp for biogas is lower due to its lower methane conversion efficiency and higher demand for fertilizers compared to other biogas crops [99, 98]. Experts recommend combining hemp with digested material as a co-product to maximize the advantages of using hemp for biogas.

Furthermore, hemp, a lignocellulosic biomass, is an excellent source of biohydrogen production [100]. A study conducted in Canada demonstrated that cellulose extracted from hemp residue, after removing lignin, hemicelluloses, pectins, and wax, can be used as a feedstock to produce bioethanol and biohydrogen. [101]. Additionally, hemp bio-oil can be effectively used for biohydrogen production through the process of steam reforming [102].

### *Solid Fuels*

Solid biofuels derived from industrial hemp, such as briquettes, pellets, and biochar, offer various options for energy production. Briquettes and pellets require minimal processing and can be used for localized heating purposes. The optimal period for harvesting hemp for solid fuel production is between February and April, when the moisture content of the biomass is at its lowest. Solid hemp biofuel provides the highest energy yield compared to other biofuels like biogas and liquid biofuels. It has an energy yield of approximately 100 GJ/ha/y, surpassing that of lucerne and clover grass ley, but falls short of competing crops like sugar beet and maize [103]. Moreover, the minimal growth requirements of hemp make it a competitive option compared to higher-yield crops, and its adaptability offers various opportunities for co-production. Through the process of pyrolysis, industrial hemp biomass can be converted into biochar, which can serve as fuel, fertilizer, or even an additive to enhance the properties of products like concrete while simultaneously sequestering carbon. Combined with conventional fuels like coal, biochar for energy purposes achieves increased process efficiency and reduces the volatilization of potentially harmful elements. Incorporating industrial hemp biochar into fuel blends has the potential to effectively reduce emissions from fossil fuel combustion, utilizing existing infrastructure [104, 105].

## RESULTS

The potential of the cannabis plant to develop a wide range of products is increasing daily. Hemp has become a commercially grown product with immense potential in Canada, America, the Netherlands, and many European countries. A better understanding of its production systems, yield potentials, production costs, harvesting, transportation, storage, and processing methods is crucial to improving the competitiveness of the developed products in existing and new markets. In areas where cannabis production has just started, adaptation studies are required to determine the most productive varieties. New harvesting and processing systems are also needed to increase yield and quality. The use of industrial hemp as a vital fiber source has grown thanks to the development of natural fiber technologies. It is now used in mixed composites for automotive parts and new lighter fiber products with excellent structural properties compared to glass and resin-based fibers used in household and construction materials. Seeds and seed products have significant potential in emerging cannabis product markets. Hemp seeds and essential oil products are used in nutritional and nutraceutical supplements, functional foods, cosmetics, therapies, and medical applications of cannabinoids. The potential for the use of hemp in new energy and environmental applications is also expanding. Agricultural innovations that reduce harvest costs require high-quality fibers for these fiber-based end-use technologies.

The field of hemp agronomy has seen a surge in research. However, there is still limited agreement on crucial aspects such as hemp's water and nutrient requirements and its performance in tropical and low-latitude conditions. It is necessary to gather new experimental evidence and employ advanced phenotyping and data acquisition tools to address these knowledge gaps. The combination of practical experimentation and modeling approaches is emphasized in this review to generate a wealth of informative outputs. This comprehensive information will facilitate the formulation of new research hypotheses and guide future studies on hemp. Furthermore, emerging evidence highlights the potential of hemp in areas such as phytoremediation, carbon sequestration, and bioenergy. Breeding initiatives are currently underway to develop hemp genotypes with low or zero THC content and wide-ranging and stable adaptability. However, there is a pressing need for standardized methods that offer high consistency and precision in detecting and quantifying cannabinoids. Regarding economic optimization, techniques such as data envelopment analysis can be employed to maximize hemp production while considering factors such as THC content, agronomic considerations, and economic factors. Overall, hemp is an adaptable crop with great potential for multiple uses. It can grow in a variety of soil types and temperatures.

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