THE MULTIPLE APPLICATIONS OF INDUSTRIAL HEMP (*CANNABIS SATIVA* L.) IN THE CONTEXT OF SUSTAINABLE DEVELOPMENT
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APLICAȚIILE MULTIPLE ALE CÂNEPII INDUSTRIALE (CANNABIS SATIVA L.) ÎN CONTEXTUL DEZVOLTĂRII SUSTENABILE

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ABSTRACT
This review explores the multiple directions of industrial hemp (Cannabis sativa L.) utilization at a global level, highlighting the importance of this crop as a renewable, sustainable, and environmentally friendly resource. While hemp has traditionally been employed for the production of fibers, seeds, and medicinal products, recent studies have expanded its applications into innovative fields such as eco-friendly construction materials (e.g., hempcrete and composite materials), automotive and aerospace industries, cosmetics, biofuels, and others. The remarkable properties of hemp, including low density, superior mechanical strength, carbon sequestration capability, and moisture regulation, helps reduce energy consumption and enhances the performance of construction materials, thereby providing competitive advantages in sustainability-oriented sectors. Moreover, hemp extracts and oils, rich in bioactive compounds (essential fatty acids, vitamins, antioxidants, and cannabinoids), have demonstrated therapeutic potential, reinforcing the role of hemp in the development of food, cosmetic, and pharmaceutical products. Additionally, hemp significantly contributes to phytoremediation by absorbing heavy metals and contaminants from the soil, and hemp fibers stand out for their durability and resistance, being valued in the textile industry for their ecological characteristics and superior performance. Industrial hemp stands out for its high versatility, and its valuable properties along with its favorable environmental impact support its integration into a wide range of sectors, opening promising perspectives for a more sustainable and environmentally responsible future.

REZUMAT
Această lucrare de sinteză explorează direcțiile multiple de utilizare ale cânepei industriale (Cannabis sativa L.) la nivel global, evidențiind importanța acestei culturi ca resursă regenerabilă, sustenabilă și cu impact ecologic redus. În timp ce cânepa a fost folosită tradițional pentru producția de fibre, semințe și medicamente, studiile recente au demonstrat extinderea aplicațiilor sale în domenii inovatoare precum construcțiile ecologice (de exemplu, betonul de cânepă și materialele compozite), industria auto și aeronautică, cosmeticele, biocombustibilii și altele. Proprietățile remarcabile ale cânepei, de la densitatea redusă și rezistența mecanică superioară la capacitatea de sechestrare a carbonului și de reglare a umidității, contribuie la reducerea consumului de energie și la îmbunătățirea performanțelor materialelor de construcție, oferind astfel avantaje competitive în sectoare ce pun accent pe sustenabilitate. Mai mult, extractele și uleiurile din cânepă, bogate în compuși bioactivi (acizi grași esențiali, vitamine, antioxidanți și cannabinoizi), au demonstrat potențial terapeutic, consolidând rolul acestei culturi în dezvoltarea produselor alimentare, cosmetice și farmaceutice. În plus, cânepa contribuie semnificativ la fitoremediere, absorbind metale grele și contaminanți din sol, iar fibrele textile de cânepă se remarcă prin durabilitate și rezistență, fiind apreciate în industria textilă pentru caracteristicile lor ecologice și performanțele superioare. Cânepa industrială se remarcă prin versatilitatea sa ridicată, iar proprietățile valoroase și impactul ecologic favorabil pe care îl are susțin integrarea acesteia într-o gamă largă de sectoare, deschizând perspective promițătoare pentru un viitor mai sustenabil și mai responsabil din punct de vedere ecologic.

INTRODUCTION

Industrial hemp (*Cannabis sativa* L.) is a remarkably versatile plant, with significant social and economic value, being grown for a wide range of purposes, from the production of textile fibers, hurds, and seeds to the extraction of oils, with applications that include medicinal and recreational uses (*Adesina et al., 2020; Cerino et al., 2021; EIHA Conference 2016–2023*). Considered the ideal crop for the circular bioeconomy of the future, hemp is one of the oldest plants cultivated by humanity, with documented use dating back to around 8000 BCE, having played an essential role in the evolution of human agriculture (*Cherney and Small, 2016; Promhuad et al., 2022*). Central Asia is considered the birthplace of domesticated hemp, with the oldest evidence of hemp fiber use discovered in Taiwan (*Manian et al., 2021*). Starting around 2700 BCE, hemp began to be cultivated in China, becoming an important agricultural practice used to obtain various products (*Mariz et al., 2024*).

Industrial hemp can be harvested and valorized in multiple fields, being used in the production of food, feed, pharmaceutical and cosmetic products, construction materials, biodegradable plastics, textiles, paper, biofuels, and as energy source (*Adesina et al., 2020; Cerino et al., 2021; Popa et al., 2021; EIHA Conference 2016–2023; Mariz et al., 2024*). It is estimated that there are approximately 25,000 hemp-derived products, distributed across various industrial and commercial subsectors (*Kraenzel et al., 1998*). Its unique properties, especially its ecological benefits and high yield of natural technical fibers, make hemp a valuable crop for the development of a sustainable, biomass-based economy (*Carus et al., 2013*).

Hemp cultivation areas have shown an upward trend in recent years, both in Europe and globally. In fact, since the late 20th century, hemp cultivation has been revitalized and has emerged as one of the fastest-growing agricultural and industrial markets in recent decades (*EIHA Conference 2016–2023*).

Hemp is a multifunctional crop (*Adesina et al., 2020*), potentially addressing many existing climate and environmental issues. Its versatile nature could transform into billion-dollar markets, especially in the segments focused on reusable, recyclable, and compostable biomaterials. According to statistical evaluations (*EIHA Conference 2023*), the industrial hemp market has a potentially higher value (USD 350 billion) than the cannabis market (USD 233 billion).

Hemp has become a global billion-dollar business, and its market share in the industrial sector has reached new dimensions, with a growing number of publicly listed companies. According to a consumer behavior survey, the wholesale market value of hemp in the United States was estimated at over USD 700 million (*Valizadehderakhshan et al., 2021; Malabadi et al., 2023*). Globally, the industrial hemp market was valued at USD 4.13 billion in 2021, with forecasts indicating an annual growth rate of 16.8% for the period 2022–2030 (*Malabadi et al., 2023*). This expansion is supported by increasing demand from various industries using it, as well as by consumer interest in natural fibers, sustainable products, and hemp seed extracts/products (oil, press cakes, seeds, etc.) recognized for their nutritional and functional properties (*EIHA Conference 2019; Malabadi et al., 2023*).

In the United States, the market for hemp seeds and fiber is expected to grow at an annual rate of 17.1% between 2023 and 2030, reaching a value of approximately USD 16.75 billion (*Khanal and Shah, 2024*). In 2022, Canada was the world's largest producer of hemp seeds, with a total output of 32,988 tons (*Čolić et al., 2024*). Turkey, also considered a major global hemp producer, has recently increased its investments and support measures for this crop. The country's current strategy aims to expand production to meet the growing needs of various economic sectors (*Aslan, 2024*).

According to data from FAOSTAT, USDA, and TURKSTAT, the global production of hemp for fiber was estimated at 302,000 tons, cultivated on 79,000 hectares. This upward trend reflects not only the increasing demand for hemp-based products but also the ecological and economic advantages of this sustainable crop (*Textile Exchange, 2023*).

The aim of this paper is to analyze the multiple directions of industrial hemp (*Cannabis sativa* L.) utilization, in the context of its agricultural, economic, and ecological potential, highlighting both traditional uses, such as fiber, seed, and oil production, as well as innovative applications in biocomposites, bioenergy, and phytoremediation.

1. Use in human and veterinary medicine/pharmacy

Hemp (*Cannabis sativa* L.) represents a valuable source for medical and pharmaceutical applications due to its rich content of cannabinoids, the main active chemical compounds with unique pharmacological properties, as well as terpenes and flavonoids. This species contains over 100 cannabinoids, among the most important being THC (delta-9-tetrahydrocannabinol) and CBD (cannabidiol), each with distinct therapeutic

applications (*Van Bakel et al., 2011; Andre et al., 2016; Aizpurua-Olaizola et al., 2016; Adesina et al., 2020; Seltzer et al., 2020; Malabadi et al., 2023*).

THC, the main psychoactive cannabinoid, is approved in many European countries for medicinal uses, including the treatment of chronic pain, glaucoma, and disorders associated with multiple sclerosis (*EIHA Conference, 2022*). For example, the market dedicated to medicinal THC in Germany is showing an upward trend in both sales and the number of prescriptions issued. However, several challenges remain to be addressed, including an inconsistent and incoherent legal framework, ambiguous regulations, and regional disparities (EIHA Conference 2022), all of which limit the consistent use of this compound in medicine (*Van Bakel et al., 2011*).

CBD, the main non-psychoactive cannabinoid, is recognized for its anti-inflammatory, neuroprotective, and antioxidant effects (*Sharma et al., 2014; Piomelli and Russo, 2016; Malabadi et al., 2023*). Clinical studies have demonstrated its potential in treating inflammatory conditions, arthritis, diabetes, neurodegenerative diseases, cancer, drug-resistant epilepsy, and pain (*Schultes, 1970; Izzo et al., 2009; Seltzer et al., 2020; Valizadehderakhshan et al., 2021; Malabadi et al., 2023*). In addition, preclinical research suggests that CBD exerts a wide range of biological effects, including anticonvulsant, anxiolytic, anti-inflammatory, immunomodulatory, and antineoplastic activities (*Cerino et al., 2021*), potentially reducing inflammation and oxidative stress, with applications in the treatment of neurodegenerative diseases such as Alzheimer's and Parkinson's (*Cassano et al., 2020; Bhunia et al., 2022*).

Epidiolex, a drug approved by the European Medicines Agency (EMA) and the U.S. Food and Drug Administration (FDA), uses CBD to treat epileptic seizures associated with Lennox-Gastaut and Dravet syndromes (*FDA, 2018*). To date, the U.S. FDA has approved THC-based drugs such as nabilone and dronabinol for the treatment of chemotherapy-induced nausea and vomiting, sleep disorders, and weight loss regulation in HIV-AIDS patients. In Australia, Canada, and several European countries, nabiximol, a combined THC-CBD formulation, has been approved for the treatment of spasticity associated with multiple sclerosis, with positive results confirmed by recent studies (*Mashabela and Kappo, 2024*).

Recent studies explore the application of cannabinoids in oncology therapies, highlighting the potential of delta-9-tetrahydrocannabinol (THC) and cannabidiol (CBD) to inhibit tumor growth, alleviate the side effects of chemotherapy, and induce cellular processes such as autophagy and apoptosis, alongside significant anti-inflammatory effects (*Mashabela and Kappo, 2024*). Various preclinical studies have demonstrated potential anticancer properties of CBD and THC, which are experimentally used in the treatment of cancers such as prostate and breast cancer (*EIHA Conference, 2022; Guggisberg et al., 2022*). Researchers and medical professionals support the use of cannabis extracts in medical prescriptions, especially following the legalization of cannabis in numerous countries (*Mashabela and Kappo, 2024*).

Protein hydrolysates from hemp seeds have been studied for their antihypertensive and antioxidant properties, with promising results in both in vitro and in vivo studies on rats (*Girgih et al., 2011*). In addition, hemp is used in medicinal and therapeutic products, including pharmaceuticals for conditions such as prostate cancer, breast cancer, coronary heart disease, constipation, blood cholesterol reduction, and, experimentally, in the treatment of glaucoma, epilepsy, multiple sclerosis, dystonia, asthma, psychosis, Niemann–Pick disease, and topical infections (*Găucă and Berea, 1997; Hazekamp and Fischedick, 2012*).

McPartland and Russo (2001) emphasize the therapeutic potential of terpenes, describing their role in modulating cannabinoid receptors and regulating neurotransmitters such as serotonin, dopamine, and GABA. This synergistic interaction between terpenoids and cannabinoids opens new perspectives for the treatment of pain and mood disorders.

Essential oils extracted from hemp flowers are valued in the pharmaceutical industry due to their content of β-myrcene and limonene, recognized for their anti-inflammatory and sedative effects (*Gurgel do Vale et al., 2002; Hazekamp and Fischedick, 2012*). Additionally, hemp oils have demonstrated antimicrobial properties and the ability to accelerate wound healing following topical application (*Callaway, 2004; Wylie et al., 2020*). Other terpenes, such as β-caryophyllene, exert anti-inflammatory, analgesic, and anxiolytic effects, being beneficial in the management of conditions such as osteoarthritis, bronchial asthma, and colitis. Their efficacy is closely related to the interaction with inflammation-related receptor channels and the reduction of oxidative stress (*Cerino et al., 2021*).

Hemp is also gaining ground in veterinary medicine due to the therapeutic properties of cannabinoids, especially CBD. Hemp-based products are used to alleviate symptoms in animals, including anxiety, chronic pain, and inflammation (*Wylie et al., 2020*). Recent studies confirm the positive effects of CBD supplements on animals, focusing on reducing inflammation and improving quality of life, particularly for musculoskeletal,

neurological, or epileptic conditions (*Gamble et al., 2018; McGrath et al., 2019; Garcia et al., 2022; Kosukwatthana et al., 2024*).

A wide range of commercial cannabidiol (CBD)-based products are available for dogs and cats, used to manage conditions such as anxiety, depression, and chronic pain (*Solcan et al., 2023*). Studies conducted by Solcan (2017) and Solcan et al. (2002) recommend these products for the treatment of psychogenic dermatitis and chronic atopic dermatitis, as well as for managing anxiety and depression in companion animals (*Falcă et al., 2011*). Additionally, CBD can be used as palliative treatment in certain tumor diseases (*Solcan et al., 2023*).

2. Uses in human and animal nutrition

Applications in human nutrition

Industrial hemp represents a valuable resource for the food industry due to the exceptional nutritional profile of products derived from this crop. In Europe in particular, hemp has been considered for centuries a traditional source of nutritious food (*Aladic et al., 2015*), being used for the production of oils, flour, protein, dietary fibers, and other functional products such as hemp milk (*Aladic et al., 2015; Lančaričová et al., 2021; Yano and Fu, 2023; Rizzo et al., 2023*).

Various parts of the hemp plant, such as seeds and inflorescences, are valuable sources of food and ingredients for nutritional supplements. While hemp inflorescences are rich in terpenes, polyphenols, and non-psychoactive but biologically active cannabinoids such as cannabidiol (CBD), which exerts anxiolytic, spasmolytic, and anticonvulsant effects (*Mechoulam et al., 2002*), hemp seeds, with their high nutritional value and pleasant nutty flavor, are a valuable source of essential amino acids, fatty acids, minerals, vitamins, fiber, and high-quality protein essential for a balanced diet (*Callaway, 2004; Carus and Sarmento, 2016; Lančaričová et al., 2021; Montero et al., 2023*). Additionally, hemp seed oil is a source of healthy polyunsaturated fatty acids, and hemp sprouts are rich in antioxidants (*Cerino et al., 2021*).

Hemp seeds are rich in high-quality, balanced, easily digestible, and sustainable proteins, containing between 20% and 30% protein, depending on variety and cultivation conditions. They provide all essential amino acids, including arginine, and present a unique protein profile consisting mainly of edestin and albumin (*Callaway, 2004; Kolodziejczyk et al., 2012; Mihoc et al., 2012; Carus and Sarmento, 2016; Montero et al., 2023; Yano and Fu, 2023*). This protein profile makes hemp seeds suitable for use in energy bars, protein flour, and nutritional shakes. Studies show that these proteins may help lower blood pressure, cholesterol, and oxidative stress, having a positive effect on the cardiovascular system and supporting overall immune health (*Callaway, 2004; Girgih et al., 2011a; Girgih et al., 2011b; Montero et al., 2023; Rizzo et al., 2023*).

The benefits of using hemp seeds in food also derive from their valuable lipid composition, containing more than 80% polyunsaturated fatty acids, such as linoleic acid (ω-6) and alpha-linolenic acid (ω-3), in a 3:1 ratio, considered optimal for human health (*Simopoulos, 2002; Oomah et al., 2002; Simopoulos, 2008; Pop et al., 2012; Rezapour-Firouzi et al., 2013; Lančaričová et al., 2021; Montero et al., 2023; Rizzo et al., 2023; Tura et al., 2023*). In addition, hemp seeds are a valuable source of dietary fiber, vitamins, minerals, and contain 20–36% carbohydrates, along with other essential phytonutrients (*Oomah et al., 2002; Callaway, 2004; Sirițanu and Sirițanu, 2007; Rezapour-Firouzi et al., 2013; Aladic et al., 2015; Popa et al., 2021; Yano and Fu, 2023*).

Hemp seeds are also an important source of fat-soluble vitamins, especially vitamin E and vitamin A. Among the present tocopherol isomers (α-, β-, γ-, and δ-), γ-tocopherol is predominant and contributes to the oxidative stability of the oil, while α-tocopherol, though present in lower amounts, is the most biologically active. Moreover, hemp provides a wide range of essential macro- and microelements such as phosphorus, potassium, magnesium, calcium, iron, zinc, and copper, nutrients important for maintaining metabolic and physiological functions (*Montero et al., 2023*).

Due to the absence of gluten, lactose, and genetically modified organisms (GMOs), hemp products are suitable for special diets, including vegetarian, vegan, and paleo (*EIHA Conference, 2016–2023; Wylie et al., 2020*). Recognized for their nutritional value, hemp seeds have become an important source of nutrients, now integrated into current dietary trends and available in most European supermarkets in muesli, chocolate, and other products. These seeds can also be processed into beverages and yogurts similar to soy products (*EIHA Conference, 2016–2023*). In the form of protein flour, cold-pressed oil, dehulled and consumed raw or roasted, hemp seeds are a beneficial food, also having therapeutic applications for various ailments (*Sirițanu and Sirițanu, 2007*). Thanks to their nutty flavor, hemp seed flour is used to enrich bakery products (*Adesina et al., 2020*), helping to increase their protein and fiber content. Some studies suggest that the inclusion of hemp in products such as functional bread or nutritional bars may support digestive and metabolic health (*Popa et al.,*

2021; EIHA Conference, 2016–2023). Innovative food products developed from hemp highlight its role in a healthy and sustainable diet.

In recent years, public-private partnerships in Europe have focused on processing hemp protein into various food forms and textures and developing innovative products, with analyses revealing a very good and complete amino acid profile containing all essential amino acids (*EIHA Conference, 2023*).

High-quality hemp oil is obtained mainly by pressing industrial hemp seeds. This vegetable oil is 100% natural, with a greenish color and fine texture, and is commonly used unheated as a nutritional supplement or olive oil substitute, having a pronounced nutty aroma. Hemp seed oil is not recommended for cooking or frying at high temperatures due to its low smoke point (*Cherney and Small, 2016*). Cold-pressed, this oil stands out for its nutritional value thanks to its content of polyunsaturated fatty acids, phenols, flavonoids, and vitamin E, which give it significant antioxidant and anti-inflammatory properties by neutralizing free radicals (*Simopoulos, 2002; Cherney and Small, 2016; Cerino et al., 2021; Popa et al., 2021; Kaur and Kander, 2023*). Thanks to its distinctive flavor, hemp oil is frequently used in salads, canned goods, pastries, and confectionery, as well as a dietary supplement with benefits for skin and hair health (*Șandru et al., 1996; Cherney and Small, 2016; Gherasim, 2017; Popa et al., 2021; Kaur and Kander, 2023*).

Research conducted by IBA Bucharest highlighted that hemp seed cakes obtained by cold pressing are a valuable source of bioactive proteins, minerals, and total fiber, making them an ideal ingredient for the bakery industry (*Popa et al., 2021*). Thus, the use of these cakes allows for the creation of functional food products capable of supporting and improving health and positively impacting quality of life.

With proper quality management and marketing, the use of hemp seeds and oil in healthy human nutrition will continue to grow (*Carus and Sarmento, 2016*).

The use of hemp leaves provides a significant intake of calcium, magnesium, iron, vitamin E, flavonoids, phenols, chlorophyll, and other beneficial compounds, making them an exceptional natural and regional ingredient for teas, infusions, smoothies, or dietary supplements. They are an ideal source of minerals and nutrients in their natural form, especially recommended for vegans, without inducing psychotropic effects (*Simopoulos, 2002; Popa et al., 2021; Teleszko et al., 2022; EIHA Conference 2023*).

Besides its use in medicines, hemp is also used in the production of nutritional supplements such as CBD capsules and tinctures, which represent approximately one-third of the global $1.34 billion CBD market (*Cerino et al., 2021*). These products are marketed for their benefits in reducing anxiety, improving sleep, and supporting the immune system (*EIHA Conference, 2023*). However, regulations regarding hemp-based supplements vary globally, limiting uniform access to these products (*Kaur and Kander, 2023*). In Europe, as a dietary supplement, CBD concentrate was classified as a novel food in January 2019 and therefore must undergo the approval process, which is cumbersome and expensive.

Hemp sprouts/microgreens can also be consumed as food. They are characterized by a high content of organic acids, amino acids, total polyphenols, flavonoids, etc., compounds known for their positive effects on cardiovascular and metabolic health (*Cerino et al., 2021; Montero et al., 2023; Popa et al., 2024*).

Applications in animal nutrition

Hemp plays an increasingly important role in animal nutrition, particularly through seeds and the oil obtained from pressing them. Hemp-based feed is becoming increasingly popular, being a sustainable and healthy alternative to conventional feed. It provides a natural source of protein and also offers essential fatty acids and fiber, contributing to a balanced diet with beneficial effects on animal health (*EIHA Conference, 2023*).

The main market for hemp seeds in animal nutrition is feed for birds and fish, which require high intakes of omega-3 and omega-6 for optimal development (*Carus and Sarmento, 2016*). Unhulled seeds and cakes resulting from oil extraction provide both valuable proteins and essential fatty acids with important nutritional benefits (*Oomah et al., 2002; Constantinescu, 2011; EIHA Conference, 2022*). Some studies also show that including these in laying hens' diets improves the omega fatty acid profile in eggs, thereby increasing the nutritional value of the final product (*Callaway, 2004*).

In the context of rising feed prices and supply challenges, hemp-based products represent a sustainable alternative, offering both economic and nutritional benefits (*EIHA Conference, 2022*).

Recent studies highlight that the inclusion of hemp-derived products in animal feed, including raw hemp oil as a valuable source of polyunsaturated fatty acids, may contribute to supporting overall health by improving cognitive function and reducing inflammation (*EIHA Conference, 2022; Haake et al., 2023; Puttharaksa et al., 2025*).

Against the backdrop of growing global demand for healthy and sustainable food, hemp emerges as a valuable nutritional resource suitable for both human and animal consumption. As the market for hemp-based food products expands, cereal bars, hemp seed butter, and plant-based beverages are gaining popularity in Europe and North America, reflecting the growing interest in natural and ecological diets (*Kaur and Kander, 2023*).

The economic potential of hemp in the food industry is estimated at billions of dollars, and the development of innovative products supports the transition to a more sustainable global food industry. In this context, the turnover in the hemp food segment and related raw materials is growing significantly. The increasing demand for natural food products has stimulated trade in hulled and unhulled seeds, hemp oil, protein powder, and leaves, visible both in retail and the industrial sector. Furthermore, collaboration among farmers, associations, and processors, focused on seed quality as a raw material, contributes to the sustainable consolidation of the hemp food market (*EIHA Conference 2016–2023*).

3. Use in the cosmetic industry

Industrial hemp has become increasingly used in the cosmetic industry due to its active compounds with multiple benefits for skin health, such as essential fatty acids, vitamins, and antioxidants.

Hemp-based cosmetic products, especially those made from cold-pressed seed oil, are appreciated for their ability to hydrate and soothe dry, irritated, or sensitive skin (*Cherney and Small, 2016*). The value of the oil is particularly due to its linoleic, α-linolenic, and γ-linolenic acid content, which have a significant impact on cellular membrane functions (*Vogl et al., 2004*). In addition to its role in restoring the skin's lipid barrier, hemp oil also helps prevent transepidermal water loss, maintaining optimal hydration (*Kaur and Kander, 2023*); it also contributes to the healing of skin inflammations and balancing acne conditions (*Vogl et al., 2004; Sapino et al., 2005*). Furthermore, hemp oil is used in personal care products such as soaps, lotions, and bath gels (*Şandru et al., 1996; Gherasim, 2017; Popa et al., 2021; Malabadi et al., 2023*), as well as in hair care products like shampoos and conditioners (*Adesina et al., 2020*), due to its ability to strengthen hair strands and moisturize the scalp. Vitamin E and essential fatty acids contribute to reducing hair loss and improving hair elasticity (*Popa et al., 2021*).

Cannabidiol (CBD), the main non-psychoactive compound in hemp, is increasingly used in the cosmetic industry due to its antioxidant, anti-inflammatory, anti-wrinkle, and brightening effects (*Karche and Singh, 2019; Chen et al., 2023*). The growing demand for natural and sustainable cosmetics has led to the integration of hemp into innovative formulations such as anti-aging creams, serums, deodorants, and facial masks (*Karche and Singh, 2019; Kaur and Kander, 2023*). Hemp extracts are appreciated for their antioxidant properties, helping to protect the skin against free radicals and reduce signs of premature aging (*Kaur and Kander, 2023*).

4. Use in the construction industry

Industrial hemp stands out as an ecological and sustainable solution in the construction industry due to its remarkable properties, such as thermal and acoustic insulation, durability (*https://www.carmeuse.com/ro-ro/aplicatii/materiale-de-constructii/hempcrete; https://dumbrava47.ro/constructii_verzi/despre-proprietatile-ignifuge-ale-betonului-de-canepa-hempcrete/; Kaboré et al., 2024*) and mechanical strength. Hemp-based construction materials include hempcrete, insulating panels, plasters, and composites for lightweight structures.

An interesting segment of the green materials market is the use of hemp shives (hurds) combined with lime for construction, a segment that holds approximately 16% market share (*Carus and Sarmento, 2016*). Hempcrete, obtained by mixing hemp shives with hydrated lime, is an ecological material (*https://www.casadecanepa.org/betonul-de-canepa*), lightweight yet strong, used in wall, roof, and floor construction (*Asli et al., 2021; Kaboré et al., 2024*). Studies show that this material has a significantly lower environmental impact than conventional building materials (*Pretot et al., 2014*), due to its ability to absorb and store CO_2 and its low embodied energy (*Pretot et al., 2014; Adam, 2024; Kaboré et al., 2024*).

The favorable thermal properties of hempcrete (*Limam et al., 2016*) are due in part to its low thermal conductivity and good moisture regulation capacity, contributing to improved hygrothermal comfort and reduced energy demand (*Collet and Pretot, 2012; Palumbo et al., 2016*). Moreover, hempcrete is used in passive house construction thanks to its performance characteristics, being a recyclable, biodegradable, non-flammable, and mold- and pest-resistant material, making it ideal for green building projects (*Vogl et al., 2004; Asli et al., 2021; EIHA Conference, 2018*).

In the same vein, Romania has also successfully combined traditional raw materials, hemp and hydrated lime, with modern technologies for “green” construction and renovation. The resulting material, 100% sustainable and biodegradable, is naturally fire- and pest-resistant, allows water vapor permeability, and "breathes"; in this way, it regulates humidity by absorbing excess moisture and releasing it when levels drop below optimal (*EIHA Conference, 2018*). It is a carbon-negative material that continuously absorbs CO_2, making it ideal for those seeking to minimize environmental impact (*https://app.materlibrary.ro/ro/materiale/SHEMP-0001*).

The hemp shives resulting as a by-product of primary hemp processing can be used as a building material or as sound insulation between drywall panels (*Șandru et al., 1996*), while hemp fibers are used in the production of ecological insulation materials, which provide efficient thermal and acoustic insulation (*Kymäläinen and Sjöberg, 2008*). In 2015, hemp fiber insulation accounted for about 26% of total applications, being the second most important use (*Carus and Sarmento, 2016*). These materials are valued for their ecological properties, being biodegradable, non-toxic, offer high thermal performance, and have a long lifespan, thus contributing to reducing the carbon footprint of the final products (*Carus et al., 2013; Călătan, 2018; Adam, 2024*). Romania, France, and Germany are among the pioneering countries in implementing eco-friendly materials, such as hemp fiber, in building insulation (*Călătan, 2018*).

Beyond construction, other applications include the production of composite panels made from hemp fibers and natural resins for interior components, which are distinguished by their low weight, mechanical strength, and superior durability, being more resistant to rot, fire, fungi, and pests than wood (*Kymäläinen et al., 2005; Kymäläinen and Sjöberg, 2008; Călătan, 2018; Popa et al., 2021*).

Using hemp in construction significantly contributes to reducing the carbon footprint of buildings, optimizing thermo-mechanical performance with minimal resources, and the fully recyclable nature of hemp-based materials supports the transition toward a circular economy (*Adam, 2024*).

5. Use in the automotive and aerospace industries

Industrial hemp is increasingly used in the automotive and aerospace industries due to its distinctive features such as low weight, mechanical strength, sustainability, and low production costs. These properties allow hemp to contribute to reducing the reliance on non-renewable resources and synthetic or petroleum-based materials, thus promoting a more environmentally friendly production model (*Faruk et al., 2012; Balakrishnan et al., 2016; Wellbrock et al., 2020; Balo and Sua, 2024*).

Significant advances in hemp research, supported by the European Commission and member states since the 1990s, have led to the identification of new applications for hemp fibers, such as biocomposites (*Carus and Sarmento, 2016*). In recent decades, the use of hemp fibers in composites as reinforcement material has increased considerably, meeting the demands for the development of biodegradable, sustainable, and recyclable materials (*Shahzad, 2012*).

Use of hemp fibers in the automotive industry

Natural fiber-reinforced biocomposites and/or biopolymers have seen significant development due to multiple advantages - processing efficiency, biodegradability, low cost, low density, high specific strength, and renewable nature (*Faruk et al., 2012; Wellbrock et al., 2020*).

Hemp, recognized as one of the most ecological and traditional natural fibers (*Shahzad, 2012*), has been integrated into the production of vehicle interior components, from door panels and dashboards to headrests, trunk linings, and spare wheel covers, due to its competitive mechanical properties and potential for carbon footprint reduction (*Carus et al., 2013; Carus and Sarmento, 2016; Wellbrock et al., 2020*), especially in mid- and high-class vehicles (*Karus et al., 2006*).

These biocomposite materials are durable and lightweight, have superior mechanical properties (*Karus et al., 2006; Faruk et al., 2012; Carus et al., 2013*), low density, and excellent energy absorption characteristics (*Carus et al., 2013*), thus contributing to energy savings (*Shahzad, 2012*) and improving fuel efficiency through vehicle weight reduction (*Sahib et al., 2023; https://www.energy.gov/eere/vehicles/lightweight-materials-cars-and-trucks*). They also offer favorable crash performance, a high proportion of biomass-based content, and competitive prices for high-quality interior designs (*Carus et al., 2013*). Life cycle assessments show that using hemp fibers as reinforcement can significantly reduce greenhouse gas emissions and increase the recyclability of vehicles (*Faruk et al., 2012; Shahzad, 2012*).

The European automotive industry, especially luxury manufacturers, have already adopted hemp fiber use in visible components like door panels, highlighting the potential of these materials to improve both technical performance and the sustainability of final products (*Shahzad, 2012; Wellbrock et al., 2020*).

Research shows that using hemp fibers as reinforcement in composites significantly improves the ecological characteristics of vehicles due to their low carbon footprint and high recyclability (*Faruk et al., 2012; Shahzad, 2012*).

Use of hemp in the aerospace industry

In the aerospace sector, adopting composites based on natural fibers, such as those derived from hemp, represents a promising strategy for reducing aircraft weight and enhancing sustainability. These materials are characterized by low density, excellent strength-to-weight ratios, and ecological properties (renewable, biodegradable, and recyclable), contributing to reduced fuel consumption and lower greenhouse gas emissions (*Mansor et al., 2019; Singh et al., 2023*).

A study by Balo and Sua (2024) highlights that using natural fibers, such as hemp, in combination with polymers, can significantly reduce the ecological impact of aircraft manufacturing, emphasizing the importance of optimal fiber and polymer matrix selection to enhance both mechanical performance and material sustainability. Moreover, Balakrishnan et al. (2016) demonstrated that fiber-based composite materials are increasingly used in the construction of aircraft and spacecraft due to their benefits, including weight reduction, increased specific strength, extended service life, and decreased corrosion problems.

The findings of these studies underline the significant potential of natural fiber composites in the aerospace industry, providing green solutions that, alongside improved mechanical performance, can support the development of future technologies in the field.

6. Use in agriculture

Industrial hemp is a versatile and environmentally friendly crop with numerous benefits for agriculture. It contributes to improving soil quality, reducing pesticide use, and increasing biodiversity, thus supporting the transition to sustainable agricultural practices. In Europe, hemp is among the few crops that can be cultivated conventionally without agrochemical inputs (Carus and Sarmento, 2016). Compared to cotton, hemp requires less water and is less dependent on phytosanitary treatments, helping to reduce environmental impact (*Malabadi et al., 2023*).

Phytoremediation capacity

Hemp is known for its ability to regenerate depleted soils due to its deep root system, which improves aeration and reduces compaction, thereby optimizing soil structure and fertility (*Struik et al., 2000*).

Hemp also provides significant environmental benefits, being considered a hyperaccumulator, a plant capable of accumulating metals or other compounds (aromatic hydrocarbons, radioactive contaminants, etc.) in its tissues hundreds or thousands of times more than other species. Due to this characteristic, hemp can be used in phytoremediation processes (*Citterio et al., 2003; Reeves et al., 2017; Rheay et al., 2020; Malabadi et al., 2023; Sunoj Valiaparambil et al., 2023*).

This plant can remediate contaminated soils by accumulating heavy metals such as lead (Pb), zinc (Zn), nickel (Ni), and cadmium (Cd) in its roots (*Linger et al., 2002; Ivanova et al., 2003; Adesina et al., 2020; Rheay et al., 2020; Sunoj Valiaparambil et al., 2023; Visković et al., 2023; Guo et al., 2024*), allowing the plant to be harvested together with hazardous compounds (*Adesina et al., 2020*). A notable example is the use of hemp in 1986 for decontaminating soil in the area affected by the Chernobyl nuclear disaster (*Citterio et al., 2003*), demonstrating hemp's efficiency in phytoextraction. In this context, hemp has been repeatedly used to remediate polluted sites, particularly through phytoremediation targeting the accumulation of heavy metals such as copper (Cu), cadmium (Cd), chromium (Cr), cobalt (Co), zinc (Zn), iron (Fe), nickel (Ni), mercury (Hg), lead (Pb), arsenic (As), silver (Ag), and platinum (Pt), commonly found in contaminated areas (*Moscariello et al., 2021*).

Although hemp can accumulate heavy metals in roots and shoots, studies show that the stems and seeds used for fiber and biomass production contain low concentrations of inorganic contaminants, especially heavy metals, without reaching phytotoxic thresholds. Thus, these parts remain suitable for valorization, even when grown on contaminated soils (*Kurczyński and Wcisło, 2024*).

Carbon sequestration and CO_2 capture

A particularly important feature of hemp is its capacity to capture and store carbon. When used as an alternative to carbon-based raw materials, hemp enables the sequestration of substantial amounts of CO_2 in both the stem and the roots, through biosequestration (*Adesina et al., 2020; Popa et al., 2021*). Due to its rapid growth and development, hemp is one of the fastest carbon-to-biomass converters, one hectare of hemp can absorb up to 22 tons of CO_2 (*Adesina et al., 2020; Kurczyński and Wcisło, 2024*). Most of the carbon is stored in the harvested stem, and less in the roots and leaves (*Adesina et al., 2020*). On the other hand, in their study,

Finnan and Styles (2013) show that hemp has one of the highest CO_2 absorption rates among agricultural crops, with about 1.5–2.0 tons of CO_2 absorbed per hectare annually.

One potential application of hemp biomass is its conversion into biochar. According to Günther (2019), hemp cultivation can produce at least 13 tons of biochar per hectare per year. This biochar has the potential to increase soil carbon sequestration and reduce greenhouse gas emissions, thus contributing to climate change mitigation (*Lehmann et al., 2006*).

The resulting biomass contributes to long-term carbon storage, especially when used in construction materials such as hempcrete (*Arehart et al., 2002; Jami et al., 2016; Jami and Kumar, 2017; Kumar et al., 2021; Sunoj Valiaparambil et al., 2023*).

Cover crop role

Hemp is frequently used as a cover crop due to its rapid growth and weed-suppressing capacity. This practice helps protect soil from erosion, retain moisture, and reduce the need for herbicides. Furthermore, after harvest, hemp biomass can be incorporated into the soil, enriching it with organic matter and essential nutrients (*Linger et al., 2002; Malabadi et al., 2023*).

Role in crop rotation

Including hemp in crop rotations helps reduce the incidence of pests and diseases specific to other crops. Studies show that this plant can reduce the need for pesticides (*Adesina et al., 2020*) due to its natural weed-suppressing ability and disease resistance (*Adesina et al., 2020; Struik et al., 2000*). Vigorous hemp crops, with their fast growth rate, suppress weeds without chemical interventions, and the plant is not significantly affected by pests or diseases requiring pesticide use. Moreover, hemp adapts well to organic farming systems (*Carus and Sarmento, 2016*).

Mulch and compost production

Hemp stalks and leaves can be used for producing mulch and compost, providing an organic source of natural fertilizer. These materials improve soil water retention and add essential nutrients, reducing the need for chemical fertilizers (*Struik et al., 2000; Linger et al., 2002; Carus et al., 2013*).

Animal bedding

Hemp stalks and hurds are frequently used as animal bedding due to their excellent absorbency. This natural material reduces moisture and odors in shelters, providing a healthier environment for animals. Moreover, hemp bedding is biodegradable and can later be composted, contributing to a sustainable agricultural cycle (*Linger et al., 2002*).

Use for biofertilizers

Recent research highlights hemp's potential to be utilized in biofertilizer development, through microbial degradation of plant residues that support the growth of beneficial soil microorganisms (*Donati et al., 2025*).

Use of residues in plant protection

Some residues from hemp processing can be valorized as botanical insecticides, miticides, or repellents, being integrated into ecological pest management programs (*Adesina et al., 2020; Benelli et al., 2018*). Hemp oil and plant residues can be used as natural insecticides and pesticides in organic agriculture (*Hall et al., 2014; Benelli et al., 2018*). Hemp also produces essential oils with insect-repellent properties and antifungal effects (*Kurczyński and Wcisło, 2024*).

Valorization in circular agricultural systems

Integrating hemp into circular agricultural systems is promoted through the reuse of residual biomass to produce natural fibers and other value-added products, thus reducing resource waste and supporting the transition toward a sustainable bioeconomy (*Jayaprakash et al., 2022*).

7. Use in the textile industry

Industrial hemp is one of the oldest plants cultivated for textile fiber production, having been traditionally used in the textile industry. Due to its high mechanical strength, durability, and reduced environmental impact, hemp represents a sustainable alternative to synthetic fibers and cotton. Life Cycle Assessment (LCA) evaluations indicate that, compared to cotton and other natural fibers, hemp requires significantly less water and pesticides and has a lower environmental impact across most analyzed categories, especially when processing stages are optimized (*Van der Werf and Turunen, 2008; Mariz et al., 2024*). Moreover, thanks to its high yield and low agricultural input requirements, hemp is also an economically viable option, with agricultural costs estimated to be more than 75% lower compared to cotton (*Schumacher et al., 2020*).

Hemp fiber is recognized as one of the strongest and most durable natural fibers (*Adesina et al., 2020*), exhibiting higher tensile strength than cotton, with values between 550–1110 MPa, compared to 287–800 MPa

for cotton (*Mariz et al., 2024*). These properties make hemp suitable for a wide range of applications, from technical and coarse textiles to fine fabrics (*Bâlteanu, 2001*). Due to its high cellulose content (68–75%) and favorable mechanical properties such as tensile strength (310–900 MPa) and stiffness (Young's modulus of 30–80 GPa), hemp fiber is considered a viable option for durable textile applications (*Elfaleh et al., 2023*). In addition, hemp exhibits natural antimicrobial properties, making it suitable for functional textiles such as sportswear or underwear (*Mariz et al., 2024*).

To be effectively utilized in industry, fiber quality is assessed based on factors such as biochemical composition, mechanical properties, degree of processing and retting, performance under various stresses, morphological characteristics, and industrial spinnability (*EIHA Conference, 2016–2023*).

Modern technologies, such as enzymatic retting, allow for the production of finer and more flexible fibers capable of competing with cotton and other natural fibers. These advances have facilitated the integration of hemp into the fashion industry, including sustainable collections launched by well-known designers and brands (*Carus et al., 2013*).

The combination of hemp fibers with other natural fibers, such as wool or silk, has opened new opportunities for producing premium textiles that blend the durability of hemp with the finesse and aesthetics of other materials (*Shahzad, 2012*).

The growing demand for sustainable textile products has stimulated the development of the hemp industry, particularly in Europe and Asia. Countries such as China, France, and Canada are leading in hemp fiber production and processing, while emerging markets are exploring innovative applications for this versatile resource (*Faruk et al., 2012*).

8. Use in the energy industry

Climate change and the depletion of fossil resources make the identification of sustainable energy solutions a global priority. The increased energy demand in recent decades, along with the extraction and processing of conventional fuels, has caused significant negative environmental effects, including biodiversity loss and the acceleration of climate change (*UNEP, 2020*). In this context, innovative technologies and advances in green energy have opened new pathways for addressing these global challenges (*Chang et al., 2024*). At the core of this energy transition lies the need to replace fossil fuels with renewable sources, with biomass energy emerging as a promising and versatile alternative (*Liu and Huang, 2024*).

One of the major global issues is represented by greenhouse gas emissions, especially carbon dioxide (CO_2) and nitrogen oxides (NO_x). CO_2 is primarily released during fossil fuel combustion, while NO_x is generated during high-temperature combustion processes (*Zuo et al., 2024*). In this regard, the European Union has set the goal of achieving climate neutrality by 2050, with an intermediate objective of reducing emissions by at least 55% by 2030 compared to 1990 levels (*European Commission, 2021*).

According to the Production Gap Report, although most governments have committed to climate neutrality, projections indicate that by 2030, fossil fuel production will double the amount compatible with the 1.5°C threshold set by the Paris Agreement. Estimates suggest that by 2030, fossil fuel production could exceed the 1.5°C-compatible level by over 110% and the 2°C-compatible level by 69% (*Achakulwisut et al., 2023*). In this context, lignocellulosic materials such as hemp are gaining recognition as low-carbon renewable resources, used not only for energy generation but also for the production of bioproducts and biofuels (*Forfora et al., 2024*).

Hemp biomass as an energy resource

Hemp is a promising resource for energy production due to its high biomass yield and its capacity to generate biodiesel, biogas, bioethanol, and solid fuels (*Kraszkiewicz et al., 2019; Rheay et al., 2020*). Currently, hemp biomass can be used to generate heat and electricity, produce vehicle fuel, and be compressed into briquettes or pellets (*Prade et al., 2012*).

With a lignocellulosic composition rich in cellulose and lignin, hemp proves to be an excellent material for biochar (BC) and biofuel production, supporting the development of renewable energy applications (*Minhas et al., 2025*). Its high cellulose content (50 - 70%) is comparable or even superior to that of other agricultural residues, such as wheat straw (35 - 45%) or *Miscanthus* (40 - 60%) (*Roman, 2025*).

Biogas from hemp waste

The plant residues resulting from hemp processing can be valorized through anaerobic digestion, a process that produces biogas while reducing methane emissions, thus having a positive environmental impact (*Finnan and Styles, 2013*). According to studies by Adamovics et al. (2014), hemp leaves have proven to be

the most efficient part of the plant for biogas production. In experiments on hemp biomass, hydrothermal pretreatment significantly increased methane yields compared to untreated material, as the process breaks down rigid cell structures, allowing anaerobic microbes better substrate access, stimulating enzymatic activity, and accelerating digestion (*Mamimin et al., 2024*). The resulting methane-rich biogas (CH_4) can be used for producing electricity and heat or upgraded to biomethane suitable for gas grids or as an alternative fuel. The nutrient-rich digestate can be applied as natural fertilizer, supporting sustainable agricultural practices (*Chang et al., 2024*).

Hemp harvested in autumn provides a higher biomass yield, and enzymatic treatment of the residues has been shown to enhance methane production (*Prade et al., 2012b; Asquer et al., 2019*). Although biogas/methane yields from hemp are lower than those from corn silage, the lower cost of hemp straw and its favorable behavior during anaerobic digestion make it an economically viable option (*Asquer et al., 2019*).

Biofuels

Industrial hemp is a versatile source for producing various types of biofuels. These can be classified by physical state into solid (compressed biomass and biochar), liquid (bioethanol, biodiesel, bio-oil), and gaseous (biogas, biohydrogen, bio-syngas) fuels, all obtained from renewable feedstocks (*Suhara et al., 2024; Addison et al., 2024*). First-generation biofuels remain the most viable option in today's industry, ideal for large-scale production and commercialization due to the constant availability of raw materials (*Suhara et al., 2024*).

Hemp bioethanol

Bioethanol is obtained by fermenting renewable biomass, followed by distillation and dehydration. While in the past the main raw materials were predominantly crops such as corn or sugarcane, nowadays agricultural waste and by-products, including those derived from hemp, are increasingly being used (*https://www.sterlingsihi.com/cms/ro/Romania/home/piete/sectorul-industrial/produse-alimentare/productia-de-biodiesel-si-bioetanol/producerea-bioetanolului.html*).

Hemp biomass has a high content of cellulose and glucans, which facilitates the production of fermentable sugars and, consequently, a higher bioethanol yield (*Zhao et al., 2020*). Thus, hemp is considered one of the most valuable fiber sources, appreciated for its applications in the production of biochemicals, biogas, bioethanol, and biohydrogen (*Brar et al., 2024*). Studies show that efficient pretreatment of the biomass and the use of conventional yeasts, such as *Saccharomyces cerevisiae*, can lead to good ethanol yields, which can subsequently be recovered through fractional distillation. The remaining solid fraction after fermentation can be used in thermochemical processes such as pyrolysis (*Zhao et al., 2020*).

Bioethanol is produced by fermenting sugars extracted from biomass sources such as corn, sugarcane, agricultural residues, and wood. Yeasts or bacteria convert these sugars into ethanol, which can be used either on its own or blended with gasoline (*Sartaj et al., 2023*). Biomass sources can be converted in various ways to serve as energy sources, thus contributing to reducing greenhouse gas emissions and replacing fossil fuels in sustainable energy generation (*Chang et al., 2024*). In this regard, second-generation bioethanol, obtained from lignocellulosic materials, has become a promising alternative due to the availability and lower cost of raw materials (*Viswanathan et al., 2020*).

Biodiesel production

Biodiesel can be obtained through several methods, including blending, micro-emulsification, thermal cracking and, most commonly, transesterification (*Bhonsle et al., 2025*). This process involves the reaction of triglycerides (from vegetable oils, waste oils, or animal fats) with an alcohol, usually methanol, in the presence of a catalyst, resulting in biodiesel and glycerol (*https://www.hielscher.com/ro/biodiesel_transesterification_01.htm*). The feedstocks may come from first-generation sources (edible vegetable oils) or second-generation sources (waste oils, non-edible animal fats) (*Sartaj et al., 2023*).

In this context, hemp seeds represent a promising resource for biodiesel production due to their oil content, which can be transformed through transesterification into a renewable, biodegradable, and non-toxic biofuel (*Osman A. et al., 2024*). Hemp biodiesel is a viable alternative to conventional diesel, being non-flammable, low in emissions, and having excellent combustion properties, in compliance with international standards ASTM D6751 and EN 14214 (*Prade et al., 2011; Patel et al., 2016; Sunoj Valiaparambil et al., 2023*).

According to recent literature, industrial hemp can produce up to 789 liters/ha of biodiesel, with a conversion rate of 75.9% (*Parvez et al., 2021; Abreu et al., 2022*), and increasing the lipid content to 10% could potentially double the output (*Viswanathan et al., 2020*). It is also estimated that this crop could yield up to 3.95 million gallons of biodiesel annually (*Visković et al., 2024*). Among the technical challenges is the high

viscosity of hemp oil, which can be effectively reduced through physicochemical pretreatments or ultrasonic processing (*Moscariello et al., 2021*).

A major advantage of biodiesel is that it can be used in existing diesel engines without significant modifications, making it a practical and sustainable solution for reducing fossil fuel dependence (*Singh et al., 2024*). Blends such as B5 (5% biodiesel, 95% diesel) and B20 (20% biodiesel, 80% diesel) are already widely used, helping to reduce carbon emissions and enhance energy sustainability (*Osman W. et al., 2024*). Tests conducted on hemp biodiesel revealed thermal efficiencies between 15.98% and 24.97%, lower carbon monoxide and hydrocarbon emissions, and performance comparable to commercial diesel (*Addison et al., 2024*).

Compared to bioethanol, biodiesel offers superior environmental benefits and greater energy efficiency (*Suhara et al., 2024*). In the study conducted by Ahmad et al. (2011), non-edible hemp oil was transesterified using a base catalyst, and the final product was analyzed using GC-MS, FT-IR, and NMR methods, revealing characteristics that comply with international standards and indicate good fuel quality.

Solid biofuels

The densification of hemp biomass plays a key role in the development of sustainable solid biofuels (*Roman and Grzegorzewska, 2024*). Dried hemp biomass can be compressed into briquettes or pellets without the need for chemical additives, as the lignin naturally present in the plant acts as a binder (*Kolodziej et al., 2012; Popa et al., 2021*). The energy properties of hemp are comparable or even superior to other solid biofuel sources such as cereal straw or wood (*Prade et al., 2012a*). Hemp briquettes have a calorific value of approximately 18,000 kJ/kg, higher than that of wood, and are characterized by rapid combustion and low sulfur emissions (*Kolodziej et al., 2012*).

Studies show that factors such as moisture content and particle size significantly influence processing efficiency and the quality of the final product. For example, briquettes exhibit higher vertical strength, while pellets are more durable during handling and transport. To obtain high-quality solid biofuels, it is essential to control moisture levels, analyze density, and conduct resistance tests (*Roman and Grzegorzewska, 2024*).

The compactness and durability of briquettes are influenced by different factors, especially lignin content. Thus, dioecious hemp, with its higher lignin content, is better suited for briquetting, particularly in northern regions (*Kraszkiewicz et al., 2019*). Additionally, in the case of these biofuels, the presence of heavy metals does not pose a major risk, as long as the resulting ash is not used as fertilizer (*Alaru et al., 2013*).

Beyond its direct energetic benefits, the use of hemp in the bioenergy sector contributes to reducing greenhouse gas emissions, capturing carbon dioxide (CO_2) during the growth period, and improving soil quality, thus reinforcing the ecological value of this crop in the transition towards a sustainable energy system (*Citterio et al., 2003; Iványi and Izsáki, 2007; Adesina et al., 2020; Amaducci et al., 2015*).

9. Other uses

Hemp is a sustainable alternative to wood for paper production. Its long fibers provide high strength to the resulting paper, which can be used for documents, packaging, and industrial products. Hemp processing requires fewer chemicals and less water than wood-based paper production, thus reducing environmental impact (*Enarevba and Haapala, 2024*).

Hemp is also used in the production of industrial filters, carpets (*Tutek and Masek, 2022*), braids, fine fabrics, twine, sacks, mats, insulating materials, and other products (*Șandru et al., 1996; Gherasim, 2017; Leonte et al., 2022*).

CONCLUSIONS

Industrial hemp (*Cannabis sativa* L.) is increasingly emerging as a strategic crop in the context of the global transition toward sustainability, due to its remarkable versatility, economic value, and low environmental impact. The analysis of its various applications reveals significant potential that transcend traditional uses and extends into emerging fields such as green construction, renewable energy, the pharmaceutical industry, as well as environmental protection, through its phytoremediation capacity and contribution to carbon sequestration.

Through its ability to provide durable textile fibers, composite materials, biofuels, therapeutic products, and by contributing to soil regeneration and the reduction of greenhouse gas emissions, hemp offers coherent and sustainable solutions to today's economic, ecological, and social challenges. Its integration into sustainable agricultural systems and diversified value chains strengthens its strategic role in current policies aimed at combating climate change and advancing the transition toward a circular bioeconomy.

Future prospects include the development of a dedicated market for high-quality hemp-based products, with focus on health, innovation, and sustainability, as well as raising awareness among the public and decision-makers about the multifunctional nature of hemp and its role in delivering innovative solutions to current economic, social, and environmental challenges.

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