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# Industrial Hemp as Precursor for Sustainable Bioproducts: Recent Trends and Prospects

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**Abstract**

The generation of over 150 million tons of hemp waste annually is as much of a sustainability challenge as it is an opportunity for the circular bioeconomy. This review provides a critical analysis of the recent trends in the use of industrial hemp waste as a precursor to producing sustainable bioproducts. The objective is to synthesize the current state of knowledge and to identify the various pathways for valorizing hemp waste beyond the traditional applications. The methodology involved the systematic assessment of the recent literature to identify the applications in textiles, biocomposites, packaging, and, most importantly, advanced areas such as hemp-based carbon materials for storing energy, biomedical materials, and smart biomaterials. Findings showed that hemp waste is a versatile material for creating high-value products, as it shows promise in carbon electrodes for supercapacitors as well as reinforcement for 3D-printed biocomposites. However, there are some limitations in terms of standardization and scalability. The review concludes that future progress depends on multidisciplinary research to optimize conversion and utilization processes, including the development of comprehensive life-cycle assessments and reliable supply chains.

**Keywords:** industrial hemp; bioeconomy; bioproducts; renewable resources; sustainable biomaterials

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## 1. Introduction

Fossil resources depletion over the years has been a major concern for industrial and academic research. Our modern economy is strongly reliant on the linear take-make-consume-dispose models, from food packaging to industry and infrastructure [1,2]. The urgent need for environmental stewardship to save our planet was evident in the "warning to humanity" written in 1992 by about 1700 leading scientists, including 104 Nobel laureates, updated in 2017 with more than 15,000 scientists signing the new document [3]. The current take-make-dispose model of exploiting resources and generating billions of tons of waste is unsustainable not only because the resources are depleting fast, but also the environmental hazards posed by the waste generated [4,5]. It has been estimated that if the status quo is maintained, only 14% of oil and 18% of gas reserves will remain by 2050 [6]. Moreover, according to the United Nations, the current economy produces up to 2.3 tons of municipal solid waste, projected to reach 3.2 billion tons by 2050, and waste management costs up to 361 million, which could reach 640 million if the status quo is maintained [7]. The shift from fossil-based to renewable resources to mitigate embodied carbon and carbon footprints from anthropogenic processes and materials is fundamental to developing a

low-carbon economy [8]. A bio-based circular economy has become widely popular as a sustainable solution because it utilizes renewable resources that are sustainable to the environment [2,4,9,10].

A bio-based economy is defined by the European Union as sectors and systems that rely on biological resources to produce food, materials, and energy, contributing to a circular and low-carbon economy [11]. It uses naturally renewable feedstocks, which not only reduce waste compared to the linear take-make-use-dispose model but also produce sustainable materials. In 2024, the US Department of Energy published the one billion report to assess how the US can sustainably produce one billion tons of biomass resources. The main findings include that the US can produce up to 1.1–1.5 billion tons of annual biomass, triple bioenergy production to cover up to 15% of US energy needs and produce up to 60 billion gallons of renewable biofuels [2,12–14]. Utilization of bio-based resources towards the circular economy has been emerging over the years, not only in the US but worldwide [4]. Bio-based products contributed USD 489 billion to the US economy in 2024 [4]. Industrial hemp cultivation in the US and Europe totaled 28,314 acres and 33,020 hectares, respectively, in 2022 and up to USD 445 million in value [15]. Industrial hemp is projected to have an economic impact of USD 32 billion on the US economy by 2030, according to a report by the National Hemp Association [16]. Woody trees sequester high volumes of atmospheric carbon. Thus, forestation is considered a valuable strategy for reducing atmospheric carbon concentration, with the United Nations' REDD initiative and the Bonn Challenge aiming to restore 350 million hectares of forest by 2030 [17]. Arguably, more wood in the form of living trees is needed amid the growing interest in wood for the development of bio-based products, which could potentially cause a demand-supply conflict soon. As an alternative to wood, renewable raw materials like hemp, kenaf, flax, and jute are attracting attention in various industrial sectors for developing bio-based products due to their fast growth, competitive physical properties, and carbon sinking capabilities [18]. One hectare of hemp that grows in five months can sequester 9–15 tons of carbon dioxide [19]. Hemp is a fast-growing, economically sustainable, and bio-based crop; it takes 100 days for hemp to grow to a stage where it can produce fibers, while it can take decades for woody trees to reach the same stage [20–22]. The multifunctional nature of the various parts of the hemp plant makes it a particularly important plant for a bioeconomy-driven world [23]. Hemp can survive in various climates, although distinct types may perform better in mild, temperate, or warm weather with consistent rainfall or access to irrigation on a well-drained soil with a pH of 6–7.5, improving the overall health of the soil [24,25].

The versatility and sustainability of industrial hemp made it a suitable precursor in the bioeconomy. According to GIACA, a waste revitalization company based in California, up to 150 million tons of hemp waste is generated annually in the US [26]. Research on hemp has been extensively reviewed over the years; for example, a recent review did a thorough review on the economic, environmental, and social sustainability of industrial hemp and concluded that the sustainability potential of hemp is the main reason for its increasing popularity [27]. They also highlight that there are gaps in understanding the social impacts and sustainability of hemp. Another recent review highlighted the past, present, and future of hemp as a biofiber material for industrial applications and maintained that legislation is a major factor impeding hemp cultivation since the 1920s in the US and Europe compared to pre-industrial times [28]. Another current review discussed industrial hemp materials and product manufacturing from an engineering perspective [29]. Most recently, Basak and others also did a thorough critical review on anatomy, agronomic practices, and valorization of industrial hemp, including a summary of life cycle and techno-economic analysis to highlight economic feasibility and environmental performance

towards circular economy [30]. These reviews agree that the versatility of industrial hemp and progress in legislation are mainly responsible for the recent popularity of hemp as a precursor for sustainable bioproducts. Although these reviews have covered the fiber properties, economic sustainability, and even the traditional applications of industrial hemp, a comprehensive analysis that focuses on the valorization of hemp waste for next-generation bioproducts is lacking. This present review aims to fill this gap by looking at current trends and prospects that are not only in the established sectors like construction and automotive industries but also in lesser-known emerging markets like carbon materials for electrochemistry and biomedical applications.

## 2. Hemp Overview

### *2.1. Cultivation*

Industrial hemp (*Cannabis sativa* L.), also commonly referred to as hemp, has been cultivated since time immemorial and is believed to have its origin in Western Asia, spreading thenceforth [31]. The low Δ9-tetrahydrocannabinol content of industrial hemp (<0.3%) makes it nonpsychoactive, distinguishing it from other *Cannabis* species, namely *C. indica* and *C. ruderalis* [32]. Due to its ability to grow needless pesticides, herbicides, and fungicides as well as its wide geographical range of cultivation and diverse end products, hemp is currently being traded in international commodity markets in over 30 countries [27]. Growing up to 0.31 m in a week, hemp cultivation does not require intensive labor during its cropping cycle of approximately 70 to 90 days [33]. The total yield depends on the sowing density, nitrogen level, and harvest time [34–36]. Up to 12 tons of cellulose, 20 tons of stem particles, and 25 tons of fiber yields are obtainable per hectare of cultivated hemp [37]. To maintain the fiber quality in terms of fineness and strength, organic farming is the industrial norm for hemp cultivation [38]. Harvest time depends on the primary cultivation purpose, such as harvesting at the end of flowering for fiber production [38,39]. Hemp fiber cultivation requires 77.63% less cost in fertilization, seeds, field operation, and irrigation than cotton [25]. The ability of hemp to sequester carbon, produce more biomass, and provide a range of end products has made it a very successful commercial crop for various applications with an exponential market growth forecast between 2025 (USD 2143.6 million) and 2034 (USD 12,713.3 million), reflecting a compound annual growth rate of (CAGR) of 21.9% over the forecast period, as shown in Figure 1 [40]. Hemp can be grown to remediate contaminated soils through phytoremediation, hence being considered as a potential cover crop [25,37]. Even hemp leftovers have the potential to function as natural pesticides, miticides, and inhibitors of pathogenic fungi and soil nematodes [41,42]. Hemp is widely regarded as a sustainable crop because it meets the social, economic, and environmental aspects of sustainability.

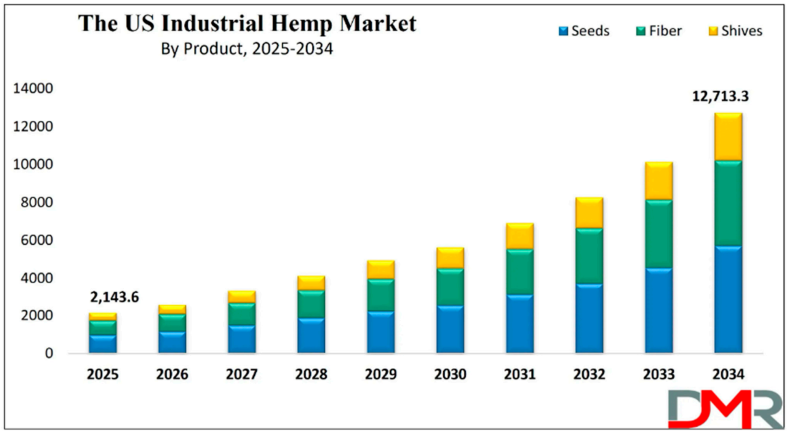



**Figure 1.** Forecast of industrial hemp market size [40].

### *2.2. Components, Composition, and Properties*

#### 2.2.1. Hemp Fibers

Hemp fibers typically constitute only 40–60% of the weight of hemp plant stem of the hemp plant [35]. These fibers are divided into primary fibers that are mainly used for textile production, and secondary fibers, which may be used as insulation and reinforcement in composites. Hemp fiber may consist of approximately 70–74% cellulose, 18–22% hemicellulose, 4–6% lignin, 3% ash, 1% pectin, and 1% wax [25]. A comprehensive description of the anatomy of hemp fiber is detailed in references [43,44]. The properties of hemp fiber include aseptic properties, high absorbency, UV radiation protection, and allergenic effects [25,37,45]. Hemp fibers are a cost-effective and eco-friendly alternative to glass fibers, offering good mechanical strength, high tenacity, and low elongation at break [46]. They also have high damping capacity, making them suitable for producing sports and musical instruments [47]. The cumulative energy demand of hemp fibers is 10% lower than glass fibers [48]. Hemp fibers have significant potential for sustainable biocomposites and green composites production due to their superior mechanical and eco-friendly properties compared to other fibers used as reinforcement [38]. However, harvest time, maturity, selection, and preparation of fibers are crucial for producing high-quality hemp fiber-based composites. A research study found that harvest time and maturity significantly affected the breaking point strength of hemp/epoxy composites [34]. Pretreatment of hemp fibers, such as alkalization, can improve composite quality by removing non-cellulosic impurities and increasing surface roughness [49].

#### 2.2.2. Hemp Seeds

Hemp fibers serve as a versatile and sustainable raw material with applications in multiple industries. In the food and beverage sector, hemp seeds are useful for their rich nutritional profile, which includes high-quality protein, essential fatty acids, and dietary fiber. They are added to healthy foods such as protein bars, plant-based milk alternatives, and cooking oils, catering to the growing demand for nutritious and sustainable food options [50]. The nutraceutical and dietary supplement industry also benefits from hemp seeds, as they are processed into oils, capsules, and powders that support heart health, reduce inflammation, and promote skin health. A research study found that hemp seed protein is highly digestible and contains all nine essential amino acids, making it a valuable dietary supplement [51]. In the cosmetics and personal care industry, hemp seed oil is a key ingredient in moisturizers, serums, and hair care products, due to its anti-inflammatory and hydrating properties [52]. The animal feed industry uses hemp seeds and hemp seed meals as a supplement for livestock and pets for improving overall health and coat condition [53]. In addition to these, hemp seeds or other parts of hemp have been found to be useful in the production of eco-friendly adsorbents to remove dyes from the environment and enhance the sustainability of the textile industry [54], which aligns with the push for sustainable manufacturing [55]. Also, hemp seed oil has been explored as a feedstock for biofuel production, thereby offering a renewable and environmentally friendly alternative to fossil fuels. A research study demonstrated the feasibility of converting hemp seed oil into biodiesel, emphasizing its potential as a sustainable energy source [56]. Finally, the pharmaceutical industry is investigating the therapeutic potential of hemp seeds, particularly their anti-inflammatory and neuroprotective properties, for developing treatments for conditions such as arthritis and neurodegenerative disorders [57,58]. Photographs of hemp seeds, dehulled hemp seeds, and hemp flour are shown in Figure 2.




**Figure 2.** Photographs of (**a**) hemp seeds, (**b**) dehulled hemp seeds, and (**c**) hemp flour [58].

#### 2.2.3. Hemp Shives

This is the woody inner core of the hemp stalk, which is versatile, sustainable, and applicable in multiple industries. In the construction sector, hemp shives are mixed with lime to produce hempcrete, a lightweight, insulating material with excellent thermal and acoustic properties. A research study demonstrated that hempcrete is not only durable but also carbon-negative, which makes it an eco-friendly alternative to traditional building materials [59]. In agriculture, hemp shives are used as a soil amendment and mulching material to improve soil aeration, water retention, and organic matter content [60]. They are also widely used as animal bedding due to their high absorbency and natural antimicrobial properties [55]. In the energy sector, hemp shives are used as feedstock for biofuel production, with studies showing their potential for producing biogas and pellets with lower greenhouse gas emissions compared to fossil fuels [61]. In addition, hemp shives are used in the paper and packaging industry to create durable and biodegradable materials, therefore reducing reliance on wood pulp and synthetic plastics. Their lightweight and porous nature also makes them ideal for composite materials in automotive and furniture industries, where they are combined with resins to produce eco-friendly alternatives to traditional plastics [38]. Additionally, lignin, a significant component of hemp shives, has been shown to reinforce biodegradable polymers like polybutylene succinate (PBS), enhancing their thermal stability and stiffness while contributing to the development of sustainable bio-based composites [62]. Finally, hemp shives have shown potential in environmental remediation, particularly for absorbing oil spills and heavy metals, offering a natural solution for cleaning up contaminated sites [55].

#### 2.2.4. Hemp Hurds

Hemp hurds represent the short, broken woody pieces of the hemp core material, often considered a byproduct of fiber processing. Their chemical composition includes cellulose (34–48%), hemicellulose (21–37%), and lignin (16–28%), making them an attractive feedstock for various applications, such as biochemical production, such as bioethanol, cellulose nanocrystals, and specialty papers [42,63]. The valorization of hemp hurds has gained significant attention in recent years, particularly in the development of sustainable materials [64]. Their high absorbency and porosity make them excellent candidates for animal bedding and industrial absorbents [65]. Research has demonstrated their potential in producing biofuels through various conversion processes, including pyrolysis and fermentation [66,67]. Furthermore, their high cellulose content has led to investigations into their use as a raw material for paper production and cellulose-derived products [68].

### 2.3. Processing

Hemp fibers are produced from the hemp plant in a stepwise process that involves retting, breaking, scutching, and hackling [38]. The growing interest in hemp textiles is driven by the advantages of the hemp plant and societal awareness of the need for bio-based products and sustainable solutions for a circular bioeconomy. This presents an opportunity for businesses and stakeholders to develop the hemp fiber industry by rebuilding and creating new companies capable of producing hemp textiles. However, the traditional linen spinning technology is the bottleneck for the hemp textile value chain, as it requires specialized machines that are difficult to find on the market. Other existing spinning systems, such as cotton or wool spinning technologies, can be adapted for hemp fibers, making the production of pure hemp yarn or blended hemp with relevant natural or synthetic fibers possible [35,42]. The linen spinning system consists of several highly specialized machines dedicated to processing retted bast fibers, while the hackling machine for long fibers and the wet spinning frame are markedly different from relevant machines used in other spinning systems. The linen spinning system has limitations due to the lack of producers interested in the construction of machines and the limited demand for the hackling machine for hemp fibers [35–37].

The hemp decortication system, which involves the separation of the bast and hurds, typically using rollers, was introduced several decades ago to avoid a costly, long-lasting, labor-intensive, and non-inert environment for the retting process [69]. Two methods to improve decorticated fiber quality are the application of the retting process before decortication and the application of degumming after the decortication process. The use of the cotton spinning system for cottoned hemp fibers allows us to produce pure hemp yarn or hemp blends with other cotton-like fibers. However, each technology delivers hemp yarn characterized by different quality parameters [35,37]. The price of hemp fiber depends on climatic and weather conditions and can be more profitable than cotton in medium and high yields [70]. In the US, hemp fiber production costs were 77.63% lower than cotton, as mentioned earlier [24]. However, the literature on the economic viability of industrial hemp for textiles is limited. Comparing the profitability of hemp yarn production is difficult due to the diversity of methods and machines used, and the cost of production depends on the type of production system applied. The lack of specialized industrial machines for hemp fibers makes it difficult to evaluate the universal economic aspects of hemp yarn manufacturing [38]. Figure 3 shows the overall process involved in producing hemp products from a hemp plant.

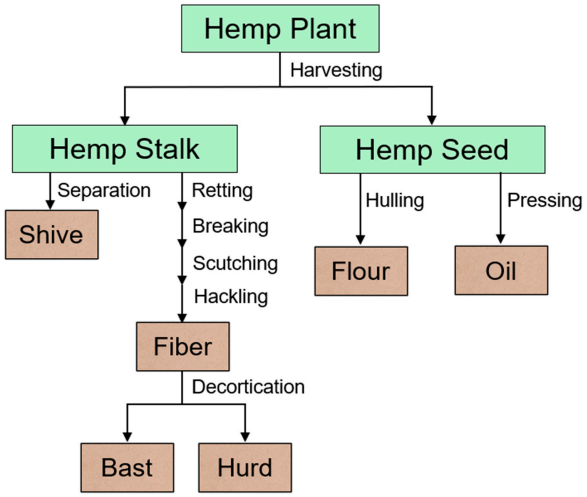



**Figure 3.** Processing of hemp from plant to products.

### *2.4. Hemp Waste Generation in North America*

The fast-growing nature of hemp makes it produce more biomass in a relatively short time compared to woody trees, generating up to 17 tons per hectare per year [71]. According to 9 Fiber, a US company canvassing for a bio-based economy, 900,870 metric tons of hemp waste generated annually in North America is burned and buried, and that 37% growth is projected annually [72,73]. Hundreds of thousands of hemp waste are destroyed annually in Canada [74]. Hemp waste can be repurposed to sustainable bio-based products, saving the world a lot of waste and creating sustainable materials for the circular economy.

## 3. Hemp as a Sustainable Crop

### *3.1. Economic Sustainability*

Economic sustainability in the hemp industry is crucial for maintaining capital and promoting sustainable business practices [28]. Despite the complex nature of hemp, it offers a wide range of products, accounts for a small percentage of food, textiles, personal care products, pharmaceuticals, and nutraceuticals sales, and has experienced a rebound in recent years due to its association with marijuana. However, challenges include regulatory uncertainty, the risk of hemp crops going hot, and the procurement of robust equipment [75]. Agrivoltaics, where solar modules are placed above hemp crops, is a progressive direction for economically sustainable hemp cultivation. The market value for industrial hemp worldwide in 2020 was USD 4.7 billion, and it is predicted to achieve an annual compound growth rate of 22.5% from 2023 to 2028, with revenues of USD 14.6 billion by 2026. The Asia Pacific region is experiencing rapid growth due to easier access to raw materials and increasing global demand [28]. The global industrial hemp market size varies greatly, with estimates ranging from USD 10.0 billion to USD 18.87 billion by 2027. Factors contributing to these estimates include the lack of official global estimates of hemp cultivation, a massive oversupply of cannabidiol (CBD) oil, and the three largest markets: beverage and food, fiber (paper and textiles), and beauty and personal care items. Around 30 European, Asian, North American, and South American countries legally produce hemp, with Canada, China, and the European Union being the top three global markets. The FAO reports that industrial hemp is produced in countries like Pakistan, Chile, Japan, Iran, South and North Korea, Syria, Turkey, and Russia [28]. Canada is the top producer and exporter of hemp-based foods, while China is the leading producer of hemp fiber, accounting for almost 50% of the world's supply [76]. Hemp production in Europe has grown significantly, with France being the top producer, accounting for 70% of the EU's total production. The United States Department of Agriculture (USDA) maintains data on hemp production, with data accumulating in 2021 showing a total planted area of 54,152 acres, 33,480 acres harvested, and a value of USD 824 million [21].

Industrial hemp production has seen significant growth globally, driven by its versatility and sustainability potential, though it generates substantial waste, which presents both challenges and opportunities. According to recent data, global hemp production has increased since the 1990s, with approximately 115,000 tons of hempseed and 86,000 tons of tow waste produced annually in the last decade [77]. Global hemp cultivation is dominated by regions like the European Union, which accounted for over 50% of the global hemp cultivation area in 2021, primarily for seed and fiber production [21]. In 2021, the top six states for cultivated average are Colorado, Montana, Oklahoma, Texas, California, and Minnesota [78]. A major challenge of hemp cultivation is regulatory and legislation issues.

### *3.2. Environmental Sustainability*

Environmental sustainability is crucial for preserving natural resources for social and economic purposes. Hemp contributes to environmental sustainability by benefiting

biodiversity, capturing high amounts of carbon, and requiring minimal herbicides or pesticides. The ecological effect of hemp depends on its cultivation methods and can be carbon neutral or carbon negative. Hemp has been used for bioremediation and has a long shelf life, making it a sustainable choice for farmers. Hemp requires less water and chemical input than cotton and other natural fibers [24]. Historically, the agricultural sector has been dominated by monocrops, with little attention given to ecological friendliness. A report comparing hemp with major monocrops found that hemp shows exceptional biodiversity compatibility [33,79]. It can be concluded that hemp is superior to most major monocrops in its impact on biodiversity and could play a pivotal role in addressing future global needs. Hemp contributes to environmental sustainability by benefiting biodiversity, capturing high amounts of carbon, and requiring minimal herbicides or pesticides. The ecological effect of hemp depends on its cultivation methods and can be carbon neutral or carbon negative. Hemp requires less water and chemical input than cotton and other natural fibers [25,79]. For example, cotton requires 2.5 times more water than hemp per hectare of land cultivated [79–81].

Hemp exhibits reduced ecological effects compared to other plants or raw materials [32]. It can reduce fertilizer and chemical usage, boost soil oxygenation, and be an excellent rotational crop [82]. Hemp also generates eco-friendly materials like heat-insulation and carbon-sequestering polymers [28]. The sustainability of hemp is illustrated in Figure 4, including its low water demand, no pesticide usage, fast growth, water and soil remediation, as well as its carbon sequestrating ability.

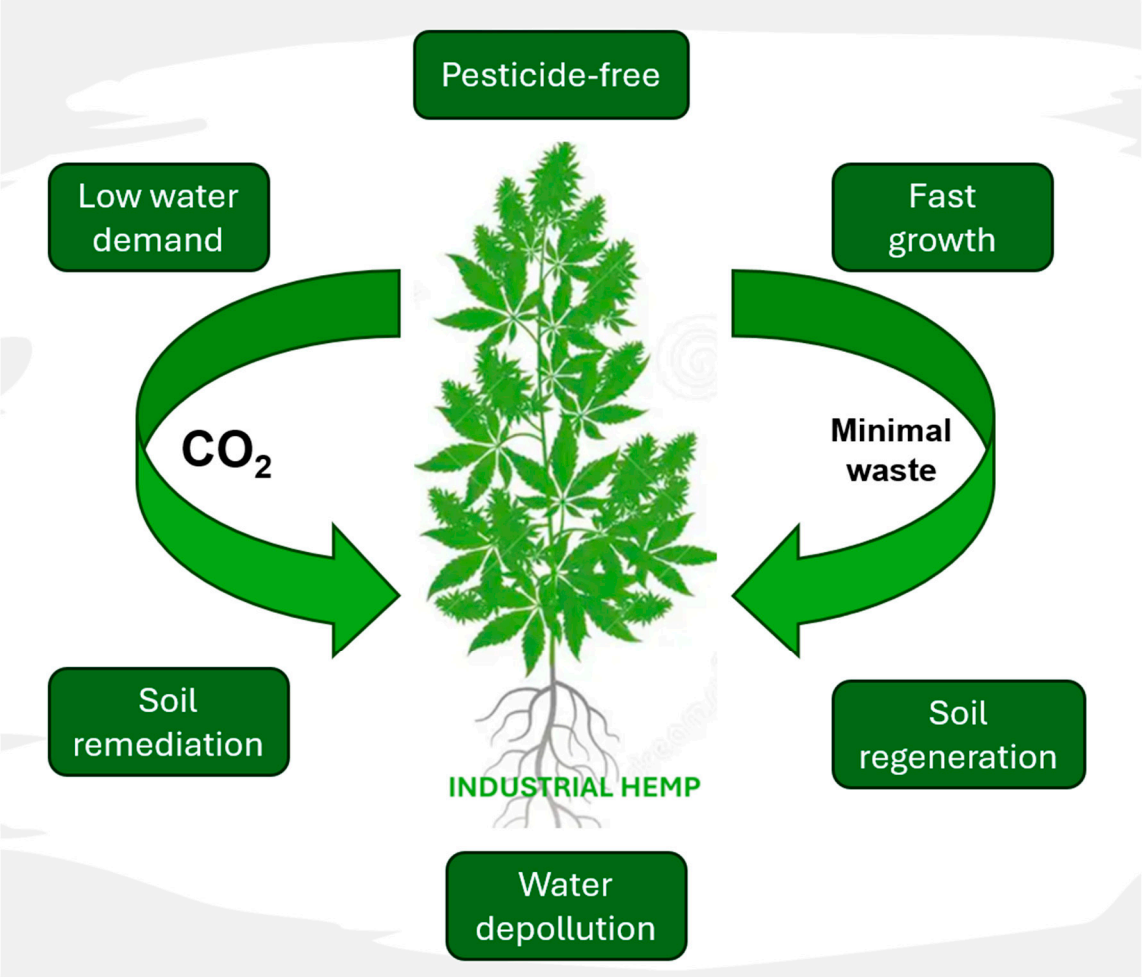



**Figure 4.** Sustainability of hemp plant.

### *3.3. Social Sustainability*

Social sustainability is the maintenance of investments and necessary services for society, and hemp is a key component of this sustainability. Hemp's economic and ecological impacts are evident in its popularity and economic success across various countries. The value of industrial hemp as a raw material is derived from its ability to build local and regional supply chains, which are economically advantageous due to the low cost of shipping hemp stalks and the optimal varieties of hemp grown in each region. This leads to greater economic gain for the farming community and manufacturers, promoting social sustainability [28,79]. However, hemp production also comes with production hazards and workplace health and safety concerns. Large-scale raw hemp handling may lead to persistent breathing problems, exposure to hemp dust, and exposure to certain chemicals, which can lead to health risks and chronic diseases.

## 4. Hemp Bioproduct Application in Textiles

### *4.1. Hemp in Spinning, Weaving, and Finishing*

Hemp fibers are valued in textile production for their strength, durability, and sustainability. In spinning, hemp's long, coarse bast fibers require specialized processing to achieve suitable yarn quality. Decortication and retting soften the fibers, enabling them to be spun into fine or coarse yarns using wet or dry spinning techniques [35]. Blending hemp with softer fibers like cotton or wool enhances yarn flexibility and reduces stiffness, improving suitability for apparel [83,84]. In weaving, hemp yarns are versatile, supporting both plain and twill weaves to produce fabrics ranging from lightweight apparel to heavy-duty canvas. Hemp's natural tensile strength ensures durability, though its low elasticity can pose challenges in achieving uniform tension during weaving [85]. Advanced looms and precise tension control mitigate these issues, producing high-quality textiles. Finishing processes, such as bleaching, dyeing, and softening, enhance hemp textiles' esthetic and functional properties [86]. Enzymatic treatments and mercerization improve softness and dye uptake, while eco-friendly finishes like natural dyes align with hemp's sustainable profile [87]. These processes ensure hemp textiles meet market demands for comfort and environmental responsibility. The various applications of hemp are shown in Figure 5.

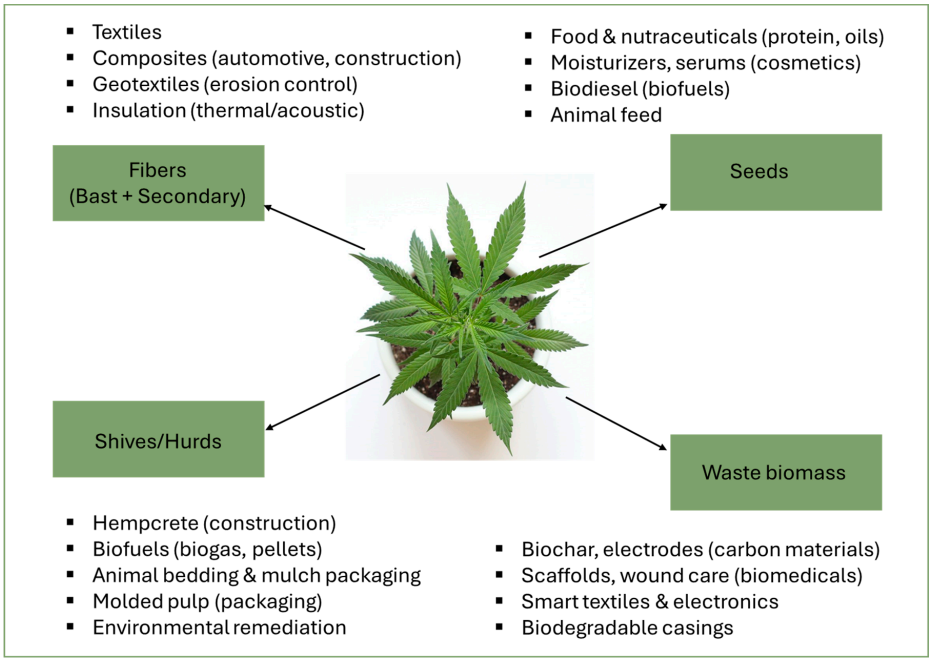



**Figure 5.** Various applications of hemp.

### *4.2. Hemp in Geotextiles*

Hemp fibers, known for their strength and biodegradability, are increasingly utilized in geotextiles for environmental and engineering applications. These hemp natural fiber-based geotextiles serve as sustainable alternatives to synthetic materials in soil stabilization, erosion control, and drainage systems [88]. Hemp geotextiles offer high tensile strength and durability, making them effective for reinforcing slopes and embankments, particularly in areas prone to erosion [89]. Their biodegradability ensures minimal environmental impact, decomposing naturally after their functional lifespan, unlike petroleum-based geotextiles that persist in ecosystems [90]. In agriculture, hemp geotextiles are used as weed suppression mats, reducing the need for chemical herbicides while promoting soil health [91]. Additionally, their moisture retention properties support revegetation efforts in degraded lands, enhancing ecological restoration [92]. The versatility of hemp geotextiles extends to temporary construction applications, such as sediment control barriers, where their natural decomposition aligns with project timelines. These attributes position hemp geotextiles as a sustainable solution for civil engineering and environmental management.

### *4.3. Hemp in Insulation*

Hemp-based insulation materials have gained attention for their sustainable properties and performance in thermal and acoustic applications. Comprehensive studies explored the efficacy of hemp fiber as an insulation material in textile-based construction applications [85,93]. These studies highlight the low thermal conductivity of hemp fiber, which is comparable to conventional materials like fiberglass and mineral wool. This is attributed to the porous structure of hemp fibers, which traps air and enhances thermal resistance. Table 1 shows the properties of major insulation materials in comparison with hemp as an insulation. A previous study also emphasizes hemp's environmental benefits, noting its low embodied energy and carbon sequestration potential during cultivation. Additionally, hemp's natural resistance to mold and pests reduces the need for chemical treatments, enhancing indoor air quality [85,94–98].

**Table 1.** Properties of insulation materials.

| Insulation Material | Thermal Conductivity (w/m·K) | Density ($Kg/m^3$) | Specific Heat Capacity (KJ/Kg·K) | Thermal Resistance ($m^2$·K/W) | Reference(s) |
|---|---|---|---|---|---|
| Aerogel | 0.01–0.02 | 70–150 | 1.05 | 1.8 | [94] |
| Phase change materials | 0.1–0.54 | 530–830 | 1.9–2.22 | - | [99] |
| Vacuum insulation panels | 0.02–0.008 | 150–300 | 0.8 | 4.4 | [92] |
| Gas-filled panels | 0.1–0.035 | 32–38 | - | 0.9–1.9 | [100] |
| Hemp hurd | 0.064–0.094 | 97–118.8 | 1.24–1.27 | 0.6 | [98,99,101] |
| Phenolic foam | 0.018–0.024 | 40–160 | 1.30–1.40 | 1.2–1.3 | [102–104] |

## 5. Hemp in Bio-Based Composites

### *5.1. Automotive Applications*

The automotive industry earnestly began to adopt the use of natural fibers in the late 20th century as environmental consciousness grew and regulations began to be tightened around material recyclability and sustainability [105]. This change became more pronounced around the 1990s when the major automakers like BMW, Mercedes-Benz, and Audi started to incorporate natural fibers like hemp, kenaf, and flax into their vehicle interiors. This was motivated largely by the European Union's End-of-Life Vehicle (ELV) Directive, which was aimed at reducing landfill waste and increasing recyclability [106,107].

Recently, there was a gradual shift from glass fiber composites towards renewable materials with easier end-of-life management. In this context, hemp fiber showed a balance between performance, cost, and environmental benefits [100]. Hemp fibers are attractive for automotive composite applications because of their physical, mechanical, and ecological benefits. Mechanically, they possess high tensile strength and modulus, which allows for a higher load-bearing capacity and reduced material weight, essential for improving fuel economy or battery range in vehicles [100,104–108]. Hemp fiber has a density of around 1.4–1.5 g/cm$^{3,}$ which allows for lighter composite structures compared to glass fiber-reinforced ones, typically exceeding 2.5 g/cm$^3$ [104]. Also, hemp has a porous, hollow microstructure, which provides excellent acoustic insulation and vibration damping, which makes it ideal for applications where noise reduction and passenger comfort are important [37,108]. Biodegradability is also another advantage, especially when hemp is combined with other recyclable materials [104]. In terms of life cycle, hemp plants are capable of absorbing twice as much $CO_2$ as typical forests [109].

The resin used with hemp is important in determining sustainability, processing behavior, and performance of the resultant composite. Thermoplastics like polypropylene are the most used with hemp because of their recyclability and ease of processing [104]. In addition, they also possess good impact resistance as well as water repellency. The challenge with these is that they are fossil-based, which limits their sustainability profile [104,110]. To address this, the industry has been exploring bio-based alternatives like polylactic acid (PLA), polybutylene succinate (PBS), and polyhydroxyalkanoates (PHA) so as to develop fully biodegradable composite systems [111,112]. Thermosetting resins like epoxy and unsaturated polyesters are also being used especially in applications that require dimensional stability and thermal resistance [104]. However, thermosets are typically non-recyclable and are more challenging to integrate into circular production models. Therefore, in the choosing of matrices, producers have to consider tradeoffs between performance reliability, cost, biodegradability, as well as regulatory compliance [104,107]. Hemp-based composites are used in various automotive parts, especially in non-structural and semi-structural applications. The most common use is in interior panels like door trims, dashboards, seat backs, and trunk liners, where producers can take full advantage of hemp's low density, acoustic properties, and tactile feel, all of which provide functional and esthetic benefits [104,107]. Another major benefit of the hemp–thermoplastic blends is that they can be processed using injection molding, compression molding, and thermoforming, which offers flexibility in design and functionality, resulting in panels that are lightweight, cost-effective, and dimensionally stable [104]. Hemp fibers are also used in parcel shelves and headliners, which would benefit from hemp's rigidity and sound absorption characteristics [107]. In systems that possess high thermal and moisture resistance, hemp-reinforced composites can be used in under-the-hood components like battery trays, engine covers, and fuse boxes [107]. Several car manufacturers like Audi (A2), Mercedes–Benz (E–class and A–class), and BMW (7 series) have applied hemp-based composites in several ways, and they serve as case studies to validate the adoption of hemp in the automotive industry [107,113].

One key challenge in the application of hemp fibers is the poor compatibility with hydrophobic thermoplastics. This leads to sub-optimal interfacial bonding between the components and can compromise the mechanical performance of the composites because of poor stress transfer [104]. Various surface modification methods are employed to address this, such as alkaline treatment (NaOH), which removes lignin and hemicellulose and increases surface roughness, and improves the wettability [114]. Silane coupling agents introduce functional groups that can bond with both matrix and fiber and thereby improve compatibility. There is also acetylation, maleated coupling agents (e.g., MAPP for PP), and enzymatic treatments, which have been shown to improve fiber dispersion and moisture

resistance [114,115]. The processing method depends on the design of the part and the choice of matrix. For interior panels, compression molding is widely used and provides good surface finish as well as fiber alignment [116]. For smaller, complex parts, injection molding can be applied. Sheet molding compound (SMC) techniques can also be adapted for thermoset matrices [117]. Overall, careful optimization of treatment and processing is necessary to achieve mechanical integrity as well as manufacturing efficiency [104,116,117].

Hemp-based composites perform competitively in terms of specific mechanical properties when compared with glass fiber-reinforced composites, particularly in applications that prioritize weight savings and sustainability over maximum strength. Although glass fiber composites typically outperform hemp in terms of tensile and flexural values on an absolute basis, the lower density of hemp gives it comparable specific stiffness and impact strength [104,108]. For instance, hemp–PP composites can achieve tensile strengths of 40–60 MPa and flexural moduli of above 3 GPa, which makes them suitable for many interior automotive applications [108,118]. In addition, hemp composites are less abrasive to processing equipment, leading to less wear and therefore less maintenance cost [104]. Also, hemp–based composites have superior thermal insulation and vibration-damping properties [113,119]. Most importantly, from an environmental perspective, natural fiber composites have lower embodied energy, are easier to recycle, and avoid the end-of-life disposal that synthetic fibers are known for [104,118].

In spite of how promising hemp–based composites are, there are still several factors that limit their widespread adoption in the automotive industry. One of such limitations is the water moisture sensitivity, which can reduce dimensional stability and reduce mechanical performance. This is especially a concern in humid or high-temperature environments [104]. Another challenge is the standardization of fiber quality. There are several factors that introduce variability in fiber quality, such as differences in cultivation, harvesting, and processing methods, leading to inconsistencies in composite performance [107]. Yet another limitation is fire resistance, unless the material is treated with fire retardants [119]. Additionally, regulatory compliance demands rigorous validation and certification processes, which are still evolving for bio-based materials [104]. Regardless of these challenges, there are strong prospects for hemp fiber application in the automotive industry, such as technology and research advances in areas of surface treatments, compatibilization, and barrier coating, which improve durability and moisture resistance. With the increasing pressure to decarbonize transport and the growing demand for greener vehicles, hemp composites are well-positioned to play a vital role in the next generation of sustainable automotive products [107,118].

### *5.2. Construction Applications*

The construction sector, responsible for nearly 40% of global energy demand and 30% of energy-based $CO_2$ emissions, is seeking eco-friendly, sustainable, carbon-negative materials to replace carbon-positive materials [120]. Natural resources like hemp have been used in building materials since ancient times [31,121]. Hemp-lime composite, a composite made from mineral binder and plant-based aggregates, has gained attention as a natural building material. Its properties depend on binder type, aggregate-to-binder ratio, aggregate size and porosity, and compaction level. Hempcrete has proven acceptable for non-load-bearing insulation in walls, floors, and roofs [13,28]. Construction of buildings and roads consumes half of the global raw materials and energy, contributing to climate change. The UK's construction sector emits 47% $CO_2$ and requires a focus on green building design to reduce emissions. Hempcrete, a lighter, hygrothermal, and acoustic filling material, can be a better choice due to its carbon sinking properties and shorter regrowth cycle compared to traditional concrete walls [13]. Research has shown that

higher compaction can increase mechanical strength, but it compromises thermal insulation and acoustic behavior [122,123]. Relative humidity (RH) also influences compressive strength, with the best compressive strength achieved at 50% RH. Increasing binder content gradually leads to a lower strain level, although it has been suggested for producing panels or building blocks [124,125]. Mechanical strength of hempcrete varies with the change in binder type [126,127], with starch-based binders and cement resulting in higher compressive strength than lime binder [128]. Magnesium phosphate cement (MPC) shows increased mechanical performance, while magnesium oxychloride cement can achieve two times stronger hempcrete without compromising density, thermal conductivity, and carbon negativity [129–132]. Aggregate size can also affect compressive strength in the long run, with smaller particle sizes achieving better coating by binder than bigger particles. Incorporating flax fiber for hemp-flax concrete can increase density, leading to better mechanical strength and lower shrinkage [13]. Building materials like hempcrete play a crucial role in ensuring human comfort in living spaces. They can absorb, release, and store moisture, which is crucial for indoor comfort. Hempcrete, being highly porous and hydrophilic, can absorb up to 270% water after a few minutes and 400% water of its weight after 48 h immersion [133–135]. It is more permeable than other construction materials and can work as a moisture buffering material due to its fast moisture transport and retention ability and high permeability.

Hempcrete is not degradation-proof against long-term exposure to rain or extreme humidity, but it can be used in building envelopes to regulate hot waves in summer and reduce heat loss in winter. It has a high moisture permeability and can delay fire spreads by entangling charred hemp in a brittle [29]. The thermal conductivity of hempcrete is affected by formulation, density, water content, mold growth, and aging. Lower density results in lower thermal conductivity and better insulation. Moisture content affects thermal performance, and changes in binder type do not significantly affect thermal conductivity and specific heat capacity. Hempcrete inherits high porosity in the structure, resulting in a higher sound absorption coefficient. Retted hemp performs better than unretted hemp, and hydraulic lime binders contribute better to sound absorption capability than cement binders. Smaller particle size performs better, while higher binder content or denser material strongly reduces the sound absorption capacity of hempcrete. Hemp is versatile and compatible with many composite systems, and that is why even the construction industry has found great use for it. It is application is seen in hemp-based engineered materials such as hempcrete, hemp-lime blocks, hemp fiberboards, and hemp-reinforced composites for insulation panels, and wall systems, as the sustainable construction industry attempts to benefit from hemp's low density, favorable thermal conductivity, breathability, and inherent carbon sequestration during growth and curing [49,128–136]. These attributes make hemp a multifunctional building material for both structural and non-structural green building applications [135,136]. It is the structural and environmental properties of hemp that make it appealing for sustainable construction. Hemp-based composites show low thermal conductivity as stated earlier, which makes them effective for wall, roof, and floor insulations [135,137,138]. Hempcrete improves indoor air quality and reduces the need for active HVAC systems because of its high porosity and vapor permeability [138]. Hemp panels have also been shown to possess good acoustic properties, which makes them useful in wall partitions and acoustic barriers. Lime-bound hempcrete has been shown to achieve fire resistance ratings of up to 1 h, and overall, hemp construction materials passively sequester $CO_2$, which supports progress towards the development of net-zero energy buildings [128,135,137,138]. There are various ways in which hemp is being used to add value in the construction industry. The most common is hempcrete, which is produced by mixing hemp hurds with a lime-based binder and water. The mixture is typically formed

into blocks and panels for insulation or infilling walls or cast in place [136–138]. As a low-density method for improving toughness and crack resistance, hemp is incorporated into gypsum or lime panels, fiberboards, and cement composites [136]. Hemp can be formed into mats, which are combined with polymers or resins to create sandwich panels [139]. Hemp is also being used to replace mineral wool or fiberglass as hemp wool and hemp batt insulations [138,139]. In addition, hemp–plastic composites are used for non-load-bearing applications like decking, cladding, and trim boards, especially where esthetics is important [136,140].

The target application and performance determine the processing methods for hemp-based construction materials. Hempcrete can be formed in place using temporary formwork, just like concrete, or it can be sprayed using pneumatic methods or made into blocks and panels, which are cured under controlled conditions to achieve dimensional precision [127,137]. Treated, chopped, or milled hemp fibers can be introduced into cement or gypsum matrices as reinforcement, which may offer lower tensile and compressive performance compared to traditional reinforcement, but offers the benefits of a higher strength-to-weight ratio and favorable thermal properties, which are great for low to mid–rise buildings that must account for hemp's lower load-bearing capacity [137,138,141]. When hemp-based materials are compared against conventional building materials, their advantages are in environmental and thermal benefits and not necessarily in structural strength. For instance, concrete can reach compressive strength of over 30 MPa while hempcrete only manages about 0.5–1.5 MPa, which makes it more of an insulation or buffering material, and not strictly structural [137,138]. However, thermal-wise, hempcrete records lower conductivity than concrete, which makes it a superior insulation material. Hemp materials also perform better than synthetic materials in terms of breathability and environmental emissions, as the acoustic damping, non-toxicity, and vapor permeability of hemp combine to create a healthier indoor environment [136,138].

### *5.3. Packaging Applications*

The growing concern over plastic pollution on the depletion of scarce fossil resources has led to the exploration of bio-based and biodegradable packaging materials. Hemp is considered a great candidate for bio-based packaging as it has a rapid growth cycle and low input requirements. It also aligns with circular economy goals, reducing landfill pressure and microplastic pollution. For these reasons, hemp–based materials are gaining attention in both rigid and flexible packaging applications [30,142]. Both the bast fibers and the hurds contribute valuable properties in packaging. The bast fibers, which are rich in cellulose, are used as reinforcement in polymer matrices like PLA, PBS, starch blends, and PHA to improve their tensile strength, dimensional stability, and toughness [30,112]. Hemp hurds are used as lightweight filler material for improving stiffness, thermal insulation in bio-composites, molded pulp, or foamed products [112]. These components are usually applied in formulations for making trays, containers, clamshells, and cushioning materials. However, optimizing the properties of these products depends heavily on compatibility with the matrix as well as the dispersity of the fibers. This is why several surface treatment methods and compatibilization techniques are employed in natural fiber composites [111,112]. There is a wide variety of packaging formats that use hemp, such as rigid thermoformed or injection-molded trays, flexible films, and foamed cushion systems. Polystyrene is being replaced by hemp hurds-incorporated molded pulp for packaging as a compostable alternative [143,144]. Hemp–cellulose films blended with PLA or starch are being developed as well for flexible packaging, although there are still limitations in terms of poor barrier properties against water and oxygen, especially for high–moisture food packaging [143,145]. The common manufacturing methods include thermoforming,

injection molding, extrusion, and wet-molding for pulp-based forms. There are also newer techniques, like 3D printing and compression foaming, which are being explored for custom applications [144,146]. Despite the positives, there are still a few limitations to large-scale adoption of hemp in packaging materials. For example, the rigorous safety and migration testing required for food contact approval and the lack of harmonized standards can make certification difficult [147]. Also, sticking to the bio-based route may prove expensive, as bio-based plastics are still more pricey, thus limiting the adoption in price-sensitive markets [148]. Also, there is a variation in hemp quality which results from regional differences in cultivation and processing, making it challenging to standardize formulations. However, the momentum is still being driven by policy shifts against single-use plastics, the rising consumer awareness, and growing investments and research in green materials.

## 6. Hemp in Carbon Materials

The need for high-performance carbon materials for applications in energy storage, composite fibers, adsorbents for water purification, and heavy metals removal has increased in recent times [149]. Carbon-based materials include biochar, biomass carbon, activated carbon, carbon fibers, and carbon nanotubes. The exceptional properties of these materials rely on their light weight, high strength, and great thermal stability. Several studies have reported the use of renewable feedstocks, like hemp, as a precursor to these carbon materials. A recent study reported the use of hemp-derived activated carbons in supercapacitors [150]. It was found that activated carbons produced from hemp hurds perform better than hemp bast, capacitance and capacitive retention increase with an increase in surface area, with excellent electrochemical performance. The use of hemp-based carbon in electrodes and capacitors has also been reported by other researchers [151–154]. Hemp hurds were also reported as a sustainable precursor carbon anode in sodium ion batteries, and this material can be recycled up to 300 cycles at 96% capacity retention [115].

Hemp carbon materials have also been widely used as an adsorbent to remove hazardous metals [155]. Hemp-derived activated carbon performed better than flax and sisal-derived activated carbon [156,157]. A study reported that the adsorption of organic pollutants using N-doped hemp porous carbon was twice as good as activated carbon [158]. Hemp-based activated carbon was used as a sustainable approach to adsorb dyes [56]. Lastly, another related study reported a successful simultaneous adsorption of metals and dye using hemp porous carbon [120].

## 7. Emerging and Prospective Use of Waste Hemp as Raw Material for Sustainable Bioproducts

Industrial hemp is increasingly recognized as a sustainable and renewable material for bioproduct manufacture and waste biomass valorization across different industries. Hemp biomass, mostly from seeds, stalks, and hurds, can be converted into biofuels such as biodiesel, bioethanol, and biogas. These renewable energy sources are important in the aviation and transportation industries, specifically in policymaking and technological development (carbon footprint monitoring and efficient engine design). Furthermore, advances in thermochemical processes can transform industrial hemp biomass waste into bio-oil, biochar, synthesis gas, and phenols to produce higher-quality, carbon-neutral, and advanced renewable biofuels [159,160]. Industrial waste can also be utilized in the construction industry to produce sustainable materials such as hempcrete and hemp composites. Recent innovations in this field include hemp-derived pectin for reinforcing structural wood products like lumber and plywood [24]. Hemp waste, specifically defatted hempseed, can also be used in food industries as a sustainable source of proteins, amino acids, and bioactive compounds. Its use for novel food formulations, such as plant-based meat, gluten-free

bread, and protein isolates, was recently explored [161]. Proteins isolated from hemp waste was shown to exhibit unique properties for food processing, including emulsification and membrane formation [58]. Water extracts from waste industrial hemp were shown to exhibit antimicrobial properties against pathogens like *Candida* species and antioxidative effects on colon cancer cells under oxidative stress. Detailed information regarding the psychoactive and medicinal properties of hemp-derived cannabinoid extracts is already established, while studies on the functional and antimicrobial effects of hemp extracts are currently gaining traction and are leaning towards the advancements in the sustainable use of waste industrial hemp in biomedical applications [162]. Innovative waste industrial hemp-based bioproducts help transform industries by offering sustainable alternatives to traditional products. From biodegradable composites used in food packaging to biomedical applications, industrial hemp is paving the way for an eco-friendly future. While industrial hemp fiber has secured its place in several established industries, its most exciting prospects lie in advanced technology sectors where its unique properties can be used to create novel, high-value materials. Research at the frontiers of materials science, energy storage, and biomedical applications is aiming to elevate hemp from a sustainable commodity to a high-performance specialty material [163]. This transition hinges on innovative processing and modification techniques that unlock its full potential.

In terms of advanced composites applications, the aspiration for the use of waste industrial hemp fibers is to move beyond interior car parts and into primary structural components where an exceptional strength-to-weight ratio is important. This includes applications in aerospace, wind turbine blades, and high-performance sporting goods. A key area of research is the development of Carbonized Hemp Fiber (CHF). This process involves heating hemp fiber to relatively elevated temperatures in an inert atmosphere, which pyrolyzes the organic components and leaves behind a carbon structure. The resulting CHF composites exhibit enhanced thermal stability and hydrophobicity (water resistance), making them far more durable and suitable for harsh operating environments than composites made with untreated hemp fiber [163]. The same research shows that several major hurdles prevent the immediate adoption of hemp in these safety-critical applications. First, there is still a performance gap; while the specific properties of hemp are good, the absolute strength and stiffness of hemp fiber composites are currently lower than aerospace-grade carbon fiber composites. Second, and more critically, the inherent variability and lack of standardized grading for natural fibers are unacceptable in an industry that demands absolute reliability and predictability [38]. Finally, achieving flawless manufacturing, ensuring complete impregnation of fibers by the resin (wet-out) and eliminating microscopic voids or defects, is essential for structural performance and remains a significant challenge [164]. Hemp fiber-reinforced composites demonstrate significant potential for structural applications. Recent studies show that hemp fibers exhibit a high crystallinity of 82.10%, surpassing other natural fibers, with a significant molecular orientation angle of 6.06°, making them highly desirable for engineering applications [165,166]. Integrated with polymer matrices, hemp composites achieve flexural strength improvements from 53.654 MPa in neat epoxy to a minimum of 139.834 MPa in reinforced samples [165]. The outlook for industrial hemp utilization in advanced composites applications requires a multi-pronged research approach. This includes optimizing the carbonization process to create CHF with mechanical properties that more closely rival traditional carbon fiber. A promising approach involves the development of hybrid composites, which could combine layers of hemp fiber (for bulk, stiffness, and cost reduction) with layers of carbon or glass fiber (for ultimate strength and surface finish), creating a material that balances performance, cost, and sustainability [166–171]. Finally, significant work is needed in advanced material characterization, non-destructive testing, and predictive modeling to build the

robust database of material properties required to overcome the reliability gap and achieve certification for use in structural applications.

Meanwhile, in terms of using waste industrial hemp fibers in energy applications, one of the most disruptive potential uses for hemp is in the field of energy storage, particularly as a raw material for the electrodes in supercapacitors [172]. Supercapacitors, or electrochemical double-layer capacitors (EDLCs), store energy by forming an electrostatic layer of ions at the interface of a conductive electrode and an electrolyte. They can charge and discharge faster than batteries and endure hundreds of thousands of cycles, making them ideal for applications requiring rapid power delivery, such as regenerative braking in electric vehicles or stabilizing power grids fed by intermittent renewables like wind and solar [173]. The key to a high-performance supercapacitor is an electrode material with an exceptionally high surface area [174–177]. Previous research has demonstrated that hemp bast fiber, often considered a waste product from processing, can be converted into a form of activated carbon (AC) with a porous structure that is optimized for this application. Studies have shown it can achieve a specific surface area of over 2200 $m^2/g$ and energy densities as high as 40 Wh/kg, performance comparable to or even exceeding that of state-of-the-art graphene-based electrodes [178]. Another research has found that hemp-based supercapacitors outperform commercial models by a factor of two to three [175]. The most cogent aspect of this processing technology is the cost. Graphene is expensive to produce. In contrast, the process for converting hemp waste into high-performance activated carbon is simple and scalable. This creates the potential for "graphene performance at activated carbon prices", a breakthrough that could dramatically lower the cost of high-performance energy storage [156,179]. The conversion process typically involves two main steps. First, hemp fiber is subjected to pyrolysis (also known as carbonization), where it is heated to elevated temperatures (around 500 °C) in an inert, oxygen-free environment to create a stable biochar. Second, this biochar undergoes an activation step, where it is treated with a chemical agent (such as potassium hydroxide, KOH, or sodium hydroxide, NaOH) and reheated to higher temperatures (400–800 °C) [180]. This activation step etches away parts of the carbon structure, creating an intricate network of micropores and mesopores that results in the extremely high surface area required for supercapacitor performance [174]. The outlook for this application should focus on the optimization of the synthesis process to precisely tailor the pore size distribution and surface chemistry of the activated carbon to match the ionic size of specific electrolytes, which can further boost performance. The development of continuous, large-scale production methods will be crucial for commercialization. Additionally, research is needed to investigate the long-term cycling stability and degradation mechanisms of these hemp-based electrodes to ensure they meet the durability requirements for applications like grid storage and electric vehicles.

The unique combination of hemp's physical properties and the biochemical activity of its derived compounds has opened a new frontier for its use in biomedical applications. The fiber itself is biocompatible and biodegradable, while compounds like CBD possess well-documented anti-inflammatory, antioxidant, and regenerative properties [181]. In tissue engineering, the goal is to create a porous, three-dimensional scaffold that mimics the body's natural extracellular matrix (ECM). This scaffold provides a temporary structure for cells to attach to, proliferate on, and regenerate damaged tissue [182]. Hemp fibers can be processed into non-woven mats and combined with hydrogels (such as alginate) to create such scaffolds [183]. These materials are biodegradable, meaning they are gradually broken down and absorbed by the body as new tissue grows in their place. The most advanced research in this area demonstrates a synergy between hemp fiber and its cannabinoids. Research has shown that embedding CBD-loaded microparticles into a hemp-based hydrogel scaffold creates a "smart" biomaterial that is not only structurally supportive

but also therapeutically active. The scaffold provides physical cues for cell growth, while the slow release of CBD can reduce inflammation, stimulate cell migration and collagen synthesis, and even induce the differentiation of stem cells into bone-forming osteoblasts. This makes these types of materials highly promising for applications in bone and soft tissue repair [184]. The same principles apply to advanced wound care. A composite of hemp nonwoven fabric and an alginate hydrogel creates a dressing that is highly absorbent, breathable, and leverages hemp's natural anti-inflammatory properties to accelerate the healing process [183]. Furthermore, textiles made of hemp fibers can be functionalized by applying CBD extract directly to the fabric surface. This creates clothing with potential therapeutic benefits for the skin, such as improving hydration and elasticity or helping to manage conditions like psoriasis and eczema [185]. The path to clinical application requires extensive research, including optimizing the scaffold's architecture (e.g., pore size, interconnectivity) for specific tissue types, from skin to bone to neural tissue. Understanding and controlling the release kinetics of active compounds like CBD from these scaffolds is critical for therapeutic efficacy. Further in vivo studies are needed to confirm the long-term safety, biocompatibility, therapeutic, and regenerative effectiveness of these materials [185,186]. While specific hemp fiber integration in smart textiles requires further research, the broader smart textile industry is rapidly advancing toward multifunctional composites that embed sensing and communication capabilities. Delignified hemp fiber cellulose acetate exhibits a higher degree of substitution after esterification, leading to decreased stiffness and tensile strength but an increase in flexibility [187]. The natural properties of hemp fibers, including their flexibility, breathability, and sustainability, make them excellent candidates for integration with electronic components in wearable devices [188–191].

The proliferation of consumer electronics has created a massive and growing environmental problem: electronic waste (e-waste). Conventional plastics used for device casings are derived from petroleum, are not biodegradable, and often contain toxic additives. Industrial hemp offers a compelling solution in the form of strong, lightweight, and fully biodegradable bioplastics [171,172,192]. These materials are produced by extracting the high concentration of cellulose from hemp stalks and processing it into a polymer. The resulting bioplastic is remarkably robust while also being lighter [193–195]. Current applications, while still niche, include casings for consumer electronics, speakers, and even the body of an electric guitar [141,143,147,196]. Also, hemp fibers can serve as a flexible, sustainable substrate for electronic textiles (e-textiles) or "smart fabrics". By coating the fibers with conductive materials, such as graphene oxide or conductive polymers like polypyrrole, it is possible to create fabrics with integrated sensing capabilities [197–201]. This technology aligns with the concept of transient electronics: devices designed to perform a specific function for a limited time and then harmlessly dissolve or biodegrade [201,202]. Potential applications are limitless, including single-use medical sensors that monitor wound healing and then degrade, or widespread environmental sensors for precision agriculture that can be deployed across a field and never need to be collected [202]. Hemp fiber-reinforced polypropylene and polycarbonate composites were successfully developed for 3D printing applications. These sustainable composites maintain reliable mechanical properties while providing environmental benefits, opening new possibilities for the manufacturing of sustainable products [203]. The development of alkali-treated hemp fiber-reinforced polycarbonate composites for 3D printing shows promise for architectural applications, with optimal treatment yielding superior interfacial bonding between fibers and matrix materials [204]. In the future, research priorities should include developing scalable manufacturing processes for hemp-based products, including the utilization of industrial hemp waste, establishing quality standards, and creating sustainable supply chains.

## 8. Future Outlook, Barriers, and Recommendations

The research priorities of sustainability, scalability, and standardization are direct responses to the biggest challenges keeping these laboratory breakthroughs from gaining commercial viability. The performance of hemp-derived carbon in supercapacitors is promising, but the processes of pyrolysis and chemical activation are still quite sensitive to variations in feedstock and processing parameters. This makes it a challenge to reproduce results on a large scale. Likewise, for biomedical applications, the jump from laboratory-scale success to approved medical devices is a long one that requires standardized, rigorous tests for biosafety, controlled release of active compounds, and biodegradation rates. The variation in the quality of feedstock is also a significant limitation for advanced composites and 3D printing filaments. This lack of consistency is also a major deterrent for industries like automotive and aerospace, where absolute predictability is a requirement. As for smart textiles and transient electronics, although their prototypes are quite compelling, their functional longevity, durability under real-world conditions, and cost-effective methods are still largely unproven. The future of these high-value applications will depend on a multidisciplinary approach. The immediate focus must shift from simply proving a concept to process reliability as well as economic feasibility. It will also require creating deeper collaborations between agronomists, chemists, material scientists, and industry engineers to optimize the entire value chain, from farm to high-tech products. Despite the potential that hemp has shown for applications in the textile industry, the modernization of its processing is still a significant hindrance to its competitiveness. The industry currently relies on outdated or repurposed machinery for spinning, which leads to high cost and inconsistent fiber quality, thereby limiting widespread adoption. Also, while it is a practical short-term solution to blend hemp with other fibers, it reduces the overall sustainability benefits of using hemp. For hemp to become a mainstream textile fiber, future efforts must be invested in developing dedicated processing technologies, as this will both improve efficiency and effectiveness and drive down cost. This includes investing in optimized spinning and decortication designed specifically for hemp's properties. Also, a stronger case should be made for hemp in terms of environmental benefits by designing and executing comprehensive life-cycle assessment studies that compare hemp's footprints directly to those of established materials like cotton and synthetic fibers. As for the application of hemp in bio-based composites, the expansion and widespread application of hemp into more structural and more demanding roles is constrained by three fundamental material-level challenges, which include susceptibility to moisture, natural variation in fiber qualities, and limited fire resistance. One of the more promising paths to addressing these issues is the development of hybrid composites, which combine hemp with more stable fibers, thereby leveraging the strengths of both materials. The industry also needs to develop grading standards for natural fibers in order to ensure consistency, as well as to build manufacturer confidence. In addition, long-term research should aim for fully bio-based composites by developing more plant-derived resins to move beyond simply using biofibers in conventional plastics.

## 9. Conclusions

This review explores the use of industrial hemp as a precursor for sustainable bioproducts and demonstrates hemp's versatility as a renewable resource, including applications in bioplastics, biofuels, construction materials, and textiles, among others. We found that its rapid growth, low environmental footprints, and ability to sequester carbon make it a compelling alternative to traditional resource-intensive materials. Furthermore, advancements in processing technologies and breeding strategies have enhanced hemp's viability, improving yield and quality for diverse industrial applications. Despite these advance-

ments, challenges such as regulatory hurdles, limited infrastructure, and market acceptance remain. Future prospects hinge on continued research, policy support, and investments in scaling up production to fully harness hemp's potential by fostering innovation and collaboration. Industrial hemp can play an important role in the circular bioeconomy, leading to sustainability and resilience in global materials systems.

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