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The Bioenergy Applications of Industrial Hemp: From Biomass Conversion to Renewable Energy Development

Shanyu Chen [1*], Linglong Zhu [1*], Sijie Meng [1], Bing Zhou [4], Wenjun Wang [3], Guanhai Ruan [1], Huijuan Tang [2]
1 Institute of Crops and Nuclear Technology Utilization, Zhejiang Academy of Agricultural Sciences, Hangzhou, 310021, China;
2 Institute of Bast Fiber Crops, Chinese Academy of Agricultural Sciences, Changsha, 410205, China;
3 Institute of Industrial Crops,Heilongjiang Academy of Agricultural Sciences, Harbin, 150000, China;
4 Yunnan Zhiya Biotechnology Co., Ltd, Chuxiong, 67500, China
* These authors contributed equally to this work.
Corresponding emails: 13906520484@163.com; tanghuijuan@caas.cn
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Abstract This study explores the applications of industrial hemp in the field of bioenergy, with a focus on analyzing its potential in biomass conversion and renewable energy development. The research highlights that industrial hemp, with its high cellulose content and robust agronomic characteristics, is a promising source for bioethanol and other biochemicals. Comparative studies show that hemp yields are competitive with other bioenergy crops like switchgrass and sorghum, while requiring fewer inputs. Additionally, the economic analysis suggests that hemp can generate higher gross profits per hectare when both grains and biofuels are considered. Key technical barriers, such as insufficient fermentable sugar and ethanol concentration, have been identified, and innovative approaches for overcoming these challenges are discussed. The findings underscore the significant potential of industrial hemp as a versatile and economically viable bioenergy crop. Effective utilization of hemp biomass can enhance the cost-competitiveness of hemp products and contribute to sustainable energy solutions.
Keywords Industrial hemp (*Cannabis sativa* L.); Bioenergy; Biomass conversion; Bioethanol; Renewable energy; Economic analysis; Sustainable agriculture

1 Introduction

Industrial hemp (*Cannabis sativa* L.) is a versatile and sustainable crop that has garnered significant attention for its potential applications across various industries. Known for its rapid growth and adaptability to diverse environmental conditions, hemp can be cultivated with minimal inputs, making it an eco-friendly alternative to traditional crops (Amaducci et al., 2015; Rehman et al., 2021). The plant's various components, including stalks, seeds, and leaves, can be utilized in numerous products such as textiles, paper, food, and biofuels, highlighting its multifunctional nature (Rehman et al., 2021; Nath, 2022). The resurgence of interest in hemp, particularly in regions like Europe and China, underscores its potential as a renewable resource for both traditional and innovative industrial applications (Amaducci et al., 2015).

The conversion of biomass into bioenergy is a critical component of sustainable energy strategies aimed at reducing reliance on fossil fuels and mitigating climate change. Industrial hemp, with its high biomass yield and efficient resource use, stands out as a promising candidate for bioenergy production (Das et al., 2017; Ji et al., 2021). The plant's high cellulose content makes it particularly suitable for the production of bioethanol and other biochemicals through biological conversion processes (Ji et al., 2021). Additionally, the utilization of hemp biomass for bioenergy can enhance the economic viability of hemp cultivation by providing an additional revenue stream from otherwise underutilized plant residues (Moscariello et al., 2021). The integration of hemp into bioenergy systems not only supports energy sustainability but also contributes to environmental conservation by promoting the use of renewable resources (Crini et al., 2020; Kaur and Kander, 2023).

This study synthesizes existing research on the biological conversion of hemp into biofuels and other value-added products, aiming to highlight the role of this plant in addressing global energy and environmental challenges. It will also discuss the economic, environmental, and social sustainability of hemp as a bioenergy crop, providing insights into its potential for contributing to a sustainable future.

2 Hemp Biomass Composition

2.1 Key components: cellulose, hemicellulose, lignin, and other biopolymers

Industrial hemp biomass is primarily composed of cellulose, hemicellulose, and lignin, which are the key components for bioenergy applications. Cellulose, a polysaccharide consisting of glucose units, is the most abundant component and is crucial for bioethanol production due to its high fermentable sugar content (Zhao et al., 2020; Ji et al., 2021). Hemicellulose, another polysaccharide, consists of various sugar monomers and contributes to the overall sugar yield during biomass conversion (Zhao et al., 2020). Lignin, a complex aromatic polymer, provides structural integrity to the plant but poses challenges in biomass processing due to its recalcitrant nature (Moscariello et al., 2021). Additionally, other biopolymers such as pectin and proteins are present in smaller quantities and can be utilized in various bioproducts.

2.2 Factors affecting biomass yield: genetics, cultivation practices, and environmental factors

The yield of hemp biomass is influenced by several factors, including genetics, cultivation practices, and environmental conditions. Genetic variations among hemp strains can lead to differences in biomass composition and yield, with some strains being more suitable for bioenergy applications due to higher cellulose content (Ji et al., 2021). Cultivation practices such as planting density, fertilization, and irrigation also play a significant role in determining biomass yield. Optimal agricultural practices can enhance the growth and biomass production of hemp plants (Moscariello et al., 2021). Environmental factors, including soil quality, temperature, and precipitation, further impact the overall yield and quality of hemp biomass. For instance, hemp's drought-resistant nature makes it a viable crop in regions with limited water availability, thereby ensuring consistent biomass production (Zhao et al., 2020).

2.3 Comparison with other bioenergy crops

When compared to other bioenergy crops such as corn stover, sorghum bagasse, and switchgrass, industrial hemp demonstrates several advantages. Hemp biomass has a higher cellulose content, which translates to greater potential for bioethanol production (Zhao et al., 2020). Additionally, hemp's robust growth characteristics and adaptability to various environmental conditions make it a more resilient crop compared to others that may require more intensive agricultural inputs (Ji et al., 2021). The economic feasibility of hemp is further enhanced by its ability to produce valuable co-products such as hemp seed, oil, and fiber, which can offset the costs associated with bioenergy production (Moscariello et al., 2021). Moreover, preliminary calculations indicate that hemp can sustain high biodiesel and bioethanol yields, making it a competitive option in the bioenergy sector.

3 Hemp for Bioethanol Production

3.1 Process of converting hemp biomass into bioethanol

The conversion of hemp biomass into bioethanol involves several key steps, starting with the pretreatment of the biomass to break down its complex structure. Pretreatment methods such as alkaline treatment with NaOH have been found effective in increasing the accessibility of cellulose and hemicellulose for subsequent enzymatic hydrolysis (Wawro et al., 2019; 2021). The pretreatment process aims to remove lignin and hemicellulose, thereby enhancing the digestibility of the cellulose fraction (Robak and Balcerek, 2018; Zhao et al., 2020). Following pretreatment, enzymatic hydrolysis is performed to convert the cellulose and hemicellulose into fermentable sugars, primarily glucose and xylose (Wawro et al., 2019; Chen et al., 2021). These sugars are then fermented by microorganisms, such as Saccharomyces cerevisiae, to produce bioethanol (Wawro et al., 2019; 2021).

3.2 Enzymatic hydrolysis and fermentation pathways

Enzymatic hydrolysis is a critical step in the bioethanol production process, where cellulolytic and hemicellulolytic enzymes break down the pretreated biomass into simple sugars. The efficiency of this step depends on factors such as enzyme type, concentration, temperature, and pH (Wawro et al., 2019; 2021). For instance, the use of commercial enzymes like AP2 has shown high efficiency in releasing reducing sugars from pretreated biomass (Zaafouri et al., 2017). The hydrolysates obtained are then subjected to fermentation, where microorganisms convert the sugars into ethanol. Two main fermentation pathways are employed: Separate Hydrolysis and Fermentation (SHF) and Simultaneous Saccharification and Fermentation (SSF). SHF involves separate stages for hydrolysis and fermentation, while SSF combines both processes in a single step, often resulting in higher ethanol yields (Robak and Balcerek, 2018; Wawro et al., 2019; 2021).

3.3 Challenges and advances in optimizing bioethanol yield

One of the primary challenges in bioethanol production from hemp biomass is the efficient conversion of both hexose and pentose sugars. Traditional yeast strains like Saccharomyces cerevisiae are efficient at fermenting glucose but not xylose, necessitating the use of genetically engineered or alternative microorganisms for co-fermentation (Robak and Balcerek, 2018). Another challenge is the presence of inhibitors formed during pretreatment, which can hinder enzymatic activity and microbial fermentation. Detoxification steps, such as the use of activated charcoal, can mitigate these effects (Robak and Balcerek, 2018; Chaudhary et al., 2021).

Recent advances have focused on optimizing pretreatment conditions and enzyme formulations to maximize sugar yields. For example, the use of response surface methodology (RSM) has been effective in determining optimal conditions for enzymatic hydrolysis, leading to significant improvements in glucose release (Wawro et al., 2019; Chen et al., 2021; Wawro et al., 2021). Additionally, innovative approaches such as consolidated bioprocessing (CBP), which integrates enzyme production, hydrolysis, and fermentation in a single step, are being explored to enhance process efficiency and reduce costs (Robak and Balcerek, 2018; Chen et al., 2021).

4 Hemp-based Biodiesel Production

4.1 Extraction and conversion of hemp seed oil for biodiesel

The extraction of hemp seed oil is a critical step in the production of biodiesel. Industrial hemp (*Cannabis sativa* L.) seeds are known for their high oil content, which makes them a viable feedstock for biodiesel production. The oil extraction process typically involves mechanical pressing or solvent extraction methods. Once extracted, the hemp seed oil undergoes a conversion process to transform it into biodiesel. This conversion is primarily achieved through a chemical reaction known as transesterification, where triglycerides in the oil react with alcohol (usually methanol) in the presence of a catalyst to form fatty acid methyl esters (FAMEs), which constitute biodiesel (Li et al., 2010; Yilbaşi et al., 2021).

4.2 Transesterification process and catalysts used

The transesterification process is central to biodiesel production from hemp seed oil. This process can be catalyzed by various substances, including alkali, acid, and enzymes. Base-catalyzed transesterification is the most common method due to its high conversion efficiency and relatively mild reaction conditions. For instance, potassium hydroxide (KOH) and sodium hydroxide (NaOH) are frequently used as catalysts in this process. Optimal conditions for base-catalyzed transesterification of hemp seed oil include a methanol-to-oil molar ratio of 6:1, a catalyst concentration of 0.9 wt.%, a reaction temperature of 45 °C, and a reaction duration of 120 minutes, resulting in a biodiesel yield of up to 96.87% (Yilbaşi et al., 2021).

Enzyme-catalyzed transesterification, using lipases, offers a greener alternative by reducing the formation of by-products and operating under milder conditions. For example, Lipozyme TL IM (Thermomyces lanuginosus) has been identified as an effective biocatalyst for the in situ transesterification of oils with high free fatty acid content (Santaraite et al., 2020). Additionally, heterogeneous catalysts derived from renewable sources, such as calcined banana peduncle ash, have shown promise in biodiesel production, offering high yields and reusability (Balajii and Niju, 2020).

4.3 Comparative analysis with traditional biodiesel feedstocks

Hemp seed oil presents several advantages over traditional biodiesel feedstocks such as soybean and rapeseed oils. One significant benefit is the high polyunsaturated fatty acid content in hemp seed oil, which contributes to a lower cloud point and kinematic viscosity, enhancing the cold flow properties of the biodiesel (Li et al., 2010). Moreover, the unique 3:1 ratio of linoleic to alpha-linolenic acid in hemp seed oil is favorable for biodiesel quality.

Economically, hemp biodiesel production can be competitive with traditional feedstocks. For instance, the production cost of hemp biodiesel can be comparable to soybean biodiesel when the lipid content in hemp biomass is optimized. A study indicated that with a 10% lipid content in hemp, the unit production cost of biodiesel could be as low as $4.13 per gallon, which is on par with soybean biodiesel (Viswanathan et al., 2021). Additionally, hemp's ability to produce significant biodiesel yields per hectare of agricultural land further underscores its potential as a sustainable and economically viable feedstock for biodiesel production (Moscariello et al., 2021; Viswanathan et al., 2021).

5 Hemp in Biogas and Biohydrogen Production

5.1 Anaerobic digestion of hemp for biogas generation

Industrial hemp has shown significant potential as a feedstock for biogas production through anaerobic digestion (AD). The high biomass yield and resource efficiency of hemp make it an attractive candidate for renewable biomethane production. Various parts of the hemp plant, including fibers, stalks, hurds, leaves, and inflorescences, have been evaluated for their biochemical methane potential (BMP) (Figure 1). For instance, raw hemp fibers have demonstrated a high BMP of (422±20) mL CH_4·g/VS, while hemp hurds, which constitute a significant portion of the plant's dry weight, showed a lower BMP of (239±10) mL CH_4·g/VS. Pretreatment methods such as alkali treatment and mechanical grinding have been found to enhance the BMP of these substrates by up to 15.9% (Matassa et al., 2020). Additionally, fresh leaves of industrial hemp have been documented to yield the highest quantities of methane, highlighting the diversity in methane yields from different parts of the hemp plant (Ingrao et al., 2020).

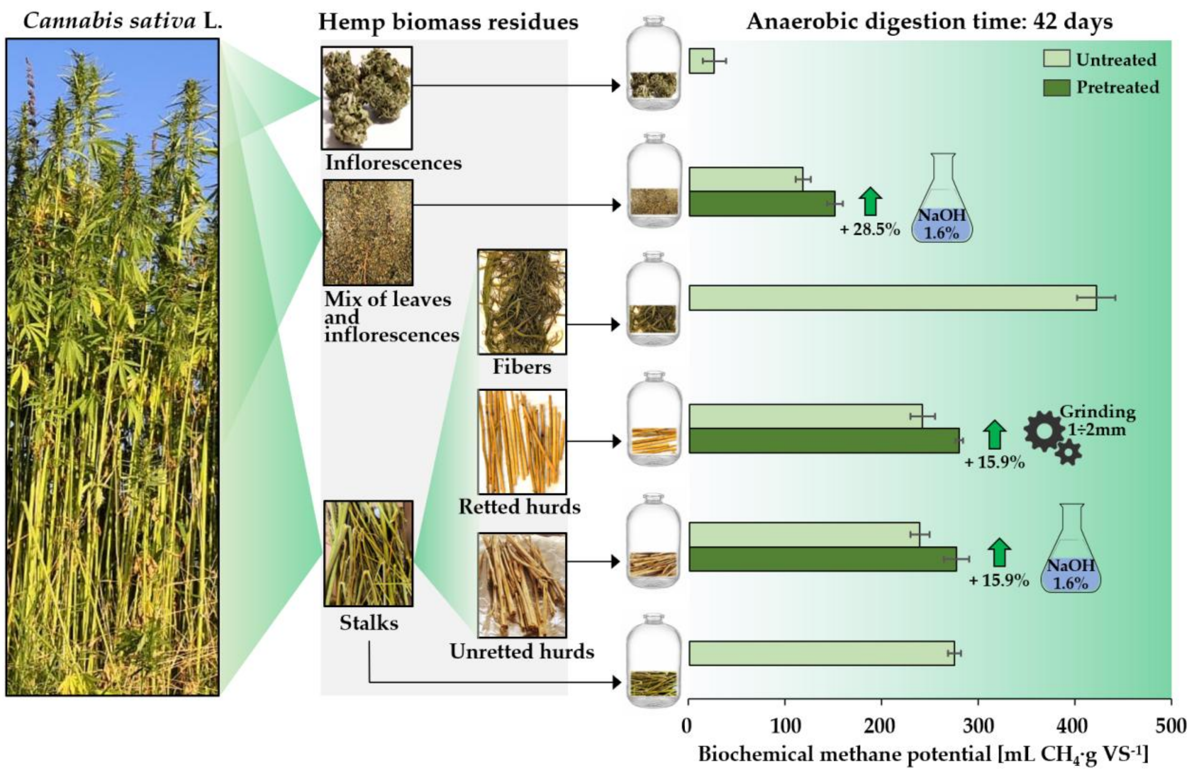

Figure 1 Exploring the biochemical methane potential of cannabis biomass residue (Adapted from Matassa et al., 2020)

5.2 Role of microbial communities and process conditions

The efficiency of biogas production from hemp through anaerobic digestion is significantly influenced by the microbial communities involved and the process conditions maintained. Anaerobic digestion is a complex process that involves various microorganisms following diverse metabolic pathways to decompose organic matter. The biodiversity of these microorganisms, along with factors such as chemical oxygen demand, water content, and total solids, play crucial roles in optimizing biogas yields (Koniuszewska et al., 2020). The microbial processes can be further enhanced by using biological and physicochemical additives, such as enzymes or immobilizing microorganisms on biofilters, to intensify biogas production. Moreover, the integration of anaerobic biorefinery concepts can generate not only bioenergy but also high-value biochemical products from the same feedstock, thereby improving the overall economic feasibility of the process.

5.3 Potential of hemp for biohydrogen through gasification

Hemp also holds promise for biohydrogen production through gasification processes. Gasification, particularly microwave-assisted gasification (MAG), is a novel and promising technology for converting biomass into biohydrogen and biosyngas. This method offers the potential for high selectivity and efficiency in biohydrogen production, although further research is needed to enhance these aspects and ensure cost-effective industrialization (Arpia et al., 2021). The use of hemp biomass in such gasification processes could contribute to a sustainable bioeconomy by providing a renewable source of hydrogen, which is a clean and efficient energy carrier. The development of optimal operating conditions and system designs for gasification will be crucial in realizing the full potential of hemp for biohydrogen production.

6 Hemp-Derived Biochar for Energy and Soil Health

6.1 Pyrolysis of hemp biomass to produce biochar

Pyrolysis is a thermochemical process that converts biomass into biochar, syngas, and bio-oil by heating it in the absence of oxygen. Hemp biomass, due to its high cellulose and lignin content, is an excellent feedstock for biochar production. The pyrolysis process can be optimized by adjusting parameters such as temperature, heating rate, and residence time to maximize biochar yield and quality. For instance, slow pyrolysis at temperatures ranging from 300 ℃ to 600 ℃ has been shown to produce biochar with high carbon content and stability, which is crucial for its application in soil amendment and carbon sequestration (Hoang et al., 2021; Nan et al., 2021).

6.2 Dual benefits: renewable energy source and soil amendment

Hemp-derived biochar offers dual benefits as a renewable energy source and a soil amendment. During pyrolysis, the volatile components of hemp biomass are converted into syngas and bio-oil, which can be used for energy production, while the remaining solid fraction becomes biochar. This biochar can be applied to soils to improve fertility, water retention, and crop yields. Studies have demonstrated that biochar application increases soil organic carbon, cation exchange capacity, and water holding capacity, leading to enhanced plant growth and reduced need for chemical fertilizers (Lehmann et al., 2006; Mohan et al., 2018; El-Naggar et al., 2019). Additionally, the use of biochar in soil can mitigate greenhouse gas emissions by reducing the release of CO_2, N_2O, and CH_4 from soils (Stewart et al., 2013; Peters et al., 2015).

6.3 Carbon sequestration potential and sustainability implications

The carbon sequestration potential of hemp-derived biochar is significant. Biochar is highly recalcitrant, meaning it decomposes very slowly in soil, thereby locking carbon away for extended periods. This makes it an effective tool for mitigating climate change by sequestering atmospheric CO_2. Research indicates that biochar can sequester up to 50% of the carbon from the original biomass, compared to much lower retention rates from burning or natural decomposition (Woolf et al., 2010; Ghodake et al., 2021). Furthermore, the application of biochar to soils not only sequesters carbon but also enhances soil health and productivity, contributing to sustainable agricultural practices. The integration of biochar production with bioenergy systems can create a carbon-negative process, where more carbon is sequestered than emitted, thus offering a sustainable solution to both energy production and climate change mitigation (Sohi, 2013; Stewart et al., 2013).

7 Case Studies

7.1 Example 1: hemp bioethanol project in Europe

The cultivation of industrial hemp in Europe has seen significant political support, particularly for bioenergy applications (Figure 2). A notable project involves the production of bioethanol from hemp biomass. The high cellulose content of hemp makes it an excellent candidate for bioethanol production. Studies have shown that hemp biomass can be effectively converted into bioethanol, with various pretreatment technologies enhancing sugar recoveries and ethanol yields (Amaducci et al., 2015; Zhao et al., 2020; Ji et al., 2021). The economic feasibility of such projects is also promising, with hemp showing competitive bioethanol yields compared to other energy crops like corn and sorghum (Das et al., 2017; Viswanathan et al., 2021).

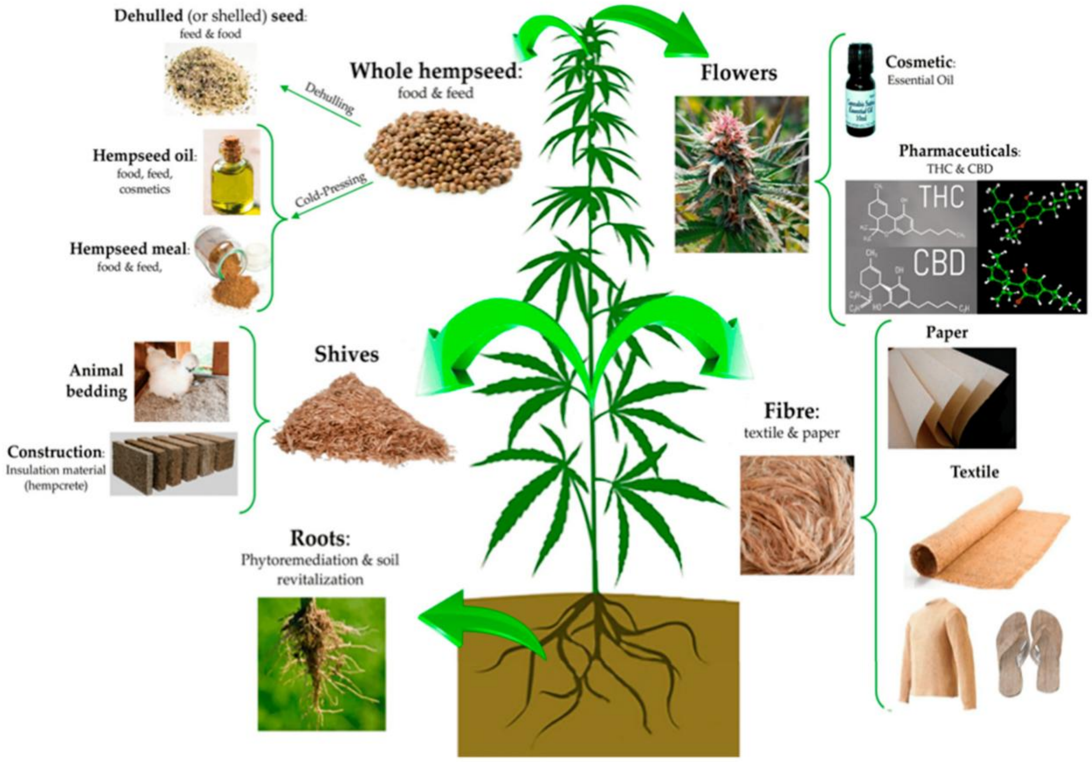

Figure 2 Industrial applications of hemp plant. (Reproduced with permission from Farinon et al., 2020) (Adopted from Ji et al., 2021)

7.2 Example 2: hemp biodiesel pilot in North America

In North America, a pilot project has been initiated to produce biodiesel from industrial hemp. This project leverages the lipid content of hemp biomass to produce biodiesel. Simulation results indicate that hemp with a lipid content of 2% can yield up to 3.95 million gallons of biodiesel annually, with production costs comparable to soybean biodiesel when lipid content is increased to 10% (Viswanathan et al., 2021). The project also explores the co-production of bioethanol from the carbohydrates in hemp, enhancing the overall economic viability (Moscariello et al., 2021; Viswanathan et al., 2021).

7.3 Example 3: hemp-based biogas production in China

China has been exploring the potential of industrial hemp for biogas production through anaerobic digestion (AD). Different hemp biomass residues, including fibers, stalks, and hurds, have been evaluated for their biochemical methane potential (BMP). Raw fibers have shown the highest BMP, while pretreatment methods have been effective in enhancing methane production from other residues (Ingrao et al., 2020; Matassa et al., 2020). The integration of hemp cultivation for biogas production aligns with China's goals for sustainable energy and waste management (Amaducci et al., 2015; Matassa et al., 2020).

8 Hemp in Advanced Biofuel Technologies

8.1 Prospects of hemp in cellulosic ethanol and second-generation biofuels

Industrial hemp has shown significant potential as a feedstock for cellulosic ethanol and other second-generation biofuels due to its high cellulose content and robust agronomic characteristics. Studies have demonstrated that hemp can yield ethanol at rates comparable to other lignocellulosic feedstocks such as switchgrass and sorghum, with the added benefit of requiring fewer inputs (Das et al., 2017). The biological conversion of hemp biomass into bioethanol has been explored extensively, highlighting its potential to address both energy and environmental challenges (Ji et al., 2021). The effective utilization of all components of lignocellulosic biomass, including cellulose, hemicellulose, and lignin, is crucial for the economic viability of cellulosic ethanol production (Menon and Rao, 2012). Moreover, the flexibility in feedstock selection and the sufficient availability of hemp biomass make it a promising candidate for the commercialized mass production of advanced-generation biofuels (Lin, 2022).

8.2 Use of hemp in bio-refineries: integrating multiple energy products

The concept of biorefineries, where multiple energy products and high-value chemicals are produced alongside biofuels, is gaining traction. Hemp biomass, including its hurds, leaves, and inflorescences, can be integrated into biorefinery processes to produce a variety of products such as bioethanol, biodiesel, biomethane, and biopolymers (Moscariello et al., 2021). This integrated approach not only enhances the economic viability of biofuel production but also adds value to the conventional production of hemp fibers and seeds. The production of value-added co-products alongside biofuels through integrated biorefinery processes necessitates selective pretreatment technologies to efficiently liberate fermentable sugars from the biomass (Agbor et al., 2011). Additionally, the development of biorefineries that produce both ethanol and other high-value chemicals from lignocellulose can significantly lower the production costs of cellulosic ethanol, making it more competitive with fossil-derived fuels (Rosales-Calderon and Arantes, 2019).

8.3 Challenges and future directions in advanced biofuel technologies

Despite the promising prospects, several challenges remain in the utilization of hemp for advanced biofuel technologies. One of the primary barriers is the high cost and complexity of the pretreatment processes required to make lignocellulosic biomass amenable to enzymatic hydrolysis (Zhao et al., 2020). Innovative research approaches, such as pretreatment optimization and co-fermentation of hexose and pentose sugars, are being explored to overcome these technical barriers (Jin et al., 2019). Additionally, the genetic engineering of plants to produce cellulases and hemicellulases, and to reduce the need for pretreatment through lignin modification, offers a promising path to making cellulosic ethanol more affordable (Sticklen, 2008). Future research should focus on improving the efficiency of these processes and developing more cost-effective technologies to fully realize the potential of hemp in advanced biofuel production. The continuous exploitation of promising biomass feedstock sources, such as industrial hemp, is crucial for the rapid and steady development of advanced-generation biofuels (Lin, 2022).

9 Economic and Environmental Impacts of Hemp Bioenergy

9.1 Cost-benefit analysis of hemp bioenergy production

Industrial hemp presents a promising economic opportunity for bioenergy production due to its high biomass yield and the potential for multiple revenue streams. Studies have shown that hemp can generate significant profits when both hemp grains and biofuels from hemp stems are considered. For instance, a comparative cost analysis indicated that industrial hemp could yield higher per hectare gross profit compared to other bioenergy crops like kenaf, switchgrass, and biomass sorghum, primarily due to its dual-purpose nature of providing both grain and biofuel (Das et al., 2017). Additionally, the production of bioethanol and biodiesel from industrial hemp has been found to be economically viable, with potential revenues ranging from €75 to €868 per hectare per year depending on the specific bioenergy product (Moscariello et al., 2021). This economic feasibility is further supported by the high biodiesel yield and related revenues, making hemp a competitive option in the bioenergy market.

9.2 Environmental advantages: carbon neutrality, land use efficiency

Hemp bioenergy production offers several environmental benefits, particularly in terms of carbon neutrality and land use efficiency. Hemp cultivation has been shown to have a net greenhouse gas (GHG) abatement potential comparable to perennial bioenergy crops, with a mid-yield estimate of 11 t CO_2 eq./ha/year, which is significantly higher than traditional annual energy crops like oil seed rape and sugar beet (Finnan and Styles, 2013). This high GHG abatement potential underscores hemp's role in reducing carbon emissions and combating climate change. Furthermore, hemp's ability to integrate into food crop rotations without competing with food supplies enhances its land use efficiency, making it a sustainable option for bioenergy production.

In addition to its carbon neutrality, hemp's high biomass yield and resource efficiency make it an ideal candidate for bioenergy systems. For example, hemp can produce up to 100 GJ/ha/year, which can be utilized in various bioenergy applications such as bioethanol and biodiesel production, contributing to significant emissions reductions (Parvez et al., 2021). The environmental advantages of hemp are further highlighted by its potential to improve soil health and biodiversity when used in bioenergy production, as it can enhance microbial biomass and plant species richness (Donnison et al., 2021).

9.3 Socio-economic benefits for rural and industrial development

The cultivation and processing of industrial hemp for bioenergy can provide substantial socio-economic benefits, particularly for rural and industrial development. Hemp's versatility and high market potential can stimulate economic growth in rural areas by creating new job opportunities and supporting local economies. The increased demand for hemp-related products, such as cannabidiol oil and hempseed, has already led to a rise in hemp production, which can further drive rural development (Ji et al., 2021).

Moreover, the establishment of hemp-based biorefineries can add value to conventional hemp production by utilizing low-value residues like hurds, leaves, and inflorescences for bioenergy and high-value bioproducts (Moscariello et al., 2021). This not only enhances the economic viability of hemp cultivation but also promotes sustainable industrial development by reducing waste and maximizing resource utilization. Additionally, the integration of hemp into existing agricultural systems can provide farmers with a profitable alternative crop, thereby diversifying income sources and enhancing the resilience of rural economies (Kaur and Kander, 2023).

10 Future Prospects and Research Directions

10.1 Areas for improvement in bioenergy conversion efficiency

The efficiency of bioenergy conversion from industrial hemp can be significantly enhanced through various technological and methodological advancements. Current research highlights several technical barriers, such as insufficient fermentable sugar and ethanol concentration during conversion processes, which need to be addressed to improve overall efficiency (Zhao et al., 2020). Optimizing pretreatment methods, such as alkaline treatment and enzymatic hydrolysis, has shown promise in increasing sugar recoveries and ethanol yields (Wawro et al., 2021). Additionally, integrating advanced bioconversion techniques like co-fermentation of hexose and pentose sugars can further enhance bioethanol production (Zhao et al., 2020). Exploring novel valorization schemes, such as the production of microbial protein and biopolymers, can also add value to the bioenergy conversion process (Moscariello et al., 2021).

10.2 Genetic improvements for bioenergy traits in hemp

Genetic improvements in industrial hemp can play a crucial role in enhancing its bioenergy traits. Selective breeding and genetic engineering can be employed to develop hemp varieties with higher biomass yield, increased cellulose content, and improved resistance to environmental stressors (Amaducci et al., 2015; Ji et al., 2021). For instance, Polish varieties like Tygra and Rajan have been identified as promising raw materials for bioethanol production due to their favorable chemical compositions and high ethanol yields (Wawro et al., 2021). Further research into the genetic basis of these traits can lead to the development of superior hemp cultivars optimized for bioenergy applications. Additionally, understanding the relationships between hemp genetics, metabolomics, and contaminant partitioning can aid in the development of hemp varieties suitable for combined phytoremediation and bioenergy production (Rheay et al., 2020).

10.3 Policy support and industrial scalability for hemp bioenergy

Policy support is essential for the large-scale adoption and industrial scalability of hemp bioenergy. In regions like Europe, political support for bioenergy has already fueled numerous studies and initiatives aimed at maximizing hemp biomass production for bioenergy purposes (Amaducci et al., 2015). Implementing favorable policies, such as subsidies for bioenergy crops, tax incentives for biofuel production, and grants for research and development, can significantly boost the hemp bioenergy sector. Economic analyses indicate that industrial hemp can generate higher per hectare gross profit compared to other bioenergy crops, making it a viable option for large-scale biofuel production (Das et al., 2017; Viswanathan et al., 2021). Moreover, integrating hemp into existing agricultural systems without competing with food supplies can enhance its appeal as a sustainable bioenergy crop (Finnan and Styles, 2013).

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Conflict of Interest Disclosure

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