INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 16 No. 2 (2024) 1-12
https://publisher.uthm.edu.my/ojs/index.php/ijie

# Hemp as A Sustainable Carbon Negative Plant: A Review of Its Properties, Applications, Challenges and Future Directions

**Nitin Muttil[1,2]*, Sayaad Sadath[1], Darren Coughlan[3], Prudvireddy Paresi[4], Swadesh Kumar Singh[2]**

[1] *College of Sport, Health and Engineering, Victoria University, P.O. Box 14428, Melbourne, VIC 8001, AUSTRALIA*
[2] *Institute for Sustainable Industries & Liveable Cities, Victoria University, P.O. Box 14428, Melbourne, VIC, 8001, AUSTRALIA*
[3] *Greater Western Water, Locked Bag 350, Sunshine VIC 3020, AUSTRALIA*
[4] *Global Professional School, Federation University, Ballarat, VIC 3350, AUSTRALIA*

*Corresponding Author: nitin.muttil@vu.edu.au
DOI: https://doi.org/10.30880/ijie.2024.16.02.001

**Article Info**

Received: 19 September 2023
Accepted: 4 October 2023
Available online: 15 April 2024

**Keywords**

Hemp, carbon negative, sustainability, hempcrete, green building applications

**Abstract**

Hemp is a versatile plant from the Cannabis sativa species, that has gained significant attention in recent years due to its potential to contribute to sustainable development and climate change mitigation. Hemp has the remarkable ability to absorb and store carbon dioxide not just during its growth phase, but also during its application and thus has the potential to be carbon negative. With the alarming global increase in carbon emissions and its implications, the cultivation and application of hemp can be a valuable tool in mitigating climate change. Although hemp is a versatile plant with many countries like Canada and China leading the way in its cultivation, it still faces challenges in Australia in terms of its acceptance, cultivation and widespread application. Much more needs to be done in terms of gaining a better understanding of the potential of hemp, growth opportunities, future prospects and challenges in further developing the industry. This review paper aims to provide a comprehensive overview of hemp's properties, applications, challenges, and future directions in the context of its role as a sustainable carbon-negative plant. The review begins by exploring the unique properties of hemp that make it an ideal candidate for carbon sequestration. The review also examines the diverse range of applications for hemp across multiple industries, ranging from construction materials, paper and packaging to biofuels and edible oil. The review has also identified several challenges and barriers to hemp's widespread adoption as a sustainable carbon-negative plant.

## 1. Introduction

One of the first cultivated crops known to man, hemp is said to have its origins in As**ia [1] Hemp, or Cannabis sativa** L., became a controversial crop because of its genetic similarity to THC-producing plants like marijuana. The molecule in marijuana largely responsible for its psychoactive qualities is Tetrahydrocannabinol (THC), or

delta-9-tetrahydrocannabinol. THC is a psychotropic component that is to some extent found in all hemp types. In contrast to hemp, which is a non-psychoactive variety of Cannabis sativa L., marijuana, or so-called medicinal cannabis, contains between 10 and 30 percent THC [2, 3]. Industrial (i.e. non-therapeutic) hemp has a THC content of less than 0.2-1%. Industrial hemp on the other hand has a significant cannabinoid (CBD) content, which is a non-psychoactive compound known for its potential therapeutic benefits. Industrial hemp, however, is frequently mistakenly associated and compared with marijuana.

Hemp plants have a remarkable ability to absorb carbon dioxide during their growth phase, making it a valuable tool in mitigating climate change. This phenomenon, known as carbon sequestration, refers to the process by which carbon dioxide (CO2) is captured from the atmosphere and stored, thus reducing its concentration in the atmosphere. Hemp has the potential to be carbon negative when considering its entire lifecycle, which means that the cultivation, processing and utilization of hemp result in the removal of more carbon dioxide (CO2) from the atmosphere than what it emits [4, 5]. Hemp's carbon negativity can be attributed to its ability to sequester carbon during its rapid growth phase and its potential for long-term carbon storage. As the plant grows, it absorbs CO2 through photosynthesis and converts it into organic carbon compounds, which make up its biomass. When hemp biomass is harvested and used in various applications, the carbon stored within these products remains sequestered for their lifespan, effectively reducing the overall carbon footprint. In recent years, extensive research has focused on exploring the various applications of hemp such as building material, textiles, biofuels, etc. (which are discussed later). The regulatory landscape has also undergone significant changes, leading to a surge in experiments and literature related to hemp. Notably, the building and construction industry has witnessed significant advancements in utilizing hemp, primarily due to its sustainability and carbon sequestration properties [4, 5]. Hemp-based building materials offer numerous advantages over conventional alternatives. For example, hemp-based concrete has excellent insulation properties that make it an ideal choice as an infill material in construction [6, 7].

Globally, the cultivation of hemp has been experiencing significant growth in recent years. This growth can be attributed to several factors, including the increasing recognition of hemp's potential in various industries, the relaxation of hemp-related regulations in some countries, and the rising demand for sustainable and eco-friendly products. Although many countries across the world grow hemp, there are three mature hemp producing markets, namely Canada, China and the European Union. Compared to these major hemp-producers, the cultivation of hemp is in its infancy in Australia. Most of the commercial hemp production takes place in Tasmania and in 2019-2020, 1600 hectares of hemp was planted in Tasmania. In comparison, only 280 hectares were grown in Western Australia and 200 hectares in Victoria. In contrast with some of the major global cultivators of hemp, over 31,500 hectares was licensed for hemp production in Canada during 2018 [8]

Over the last few years, Australia also has been gradually developing its hemp industry. Hemp cultivation was legalized in Australia in 2017, and since then, the industry has been growing steadily. Thus, there is increasing interest in hemp cultivation, in hemp-based products and their potential economic and environmental benefits in Australia. Much more needs to be done in terms of gaining a better understanding of the potential of hemp, growth opportunities, future prospects and challenges in further developing the industry and this review aims to shed further light on these aspects. This paper is structured as follows. Section 2 presents the properties of various parts of the hemp plant, which makes it such a versatile plant with diverse applications. This is followed by a presentation of some of the key applications of hemp in Section 3. Section 4 attempts to bring out some of the challenges to the widespread use of hemp. This is followed by current trends and future directions in the use of hemp in Section 5. Finally, conclusions drawn from this review are discussed in Section 6.

## 2. Properties of the Hemp Plant

The hemp plant possesses several unique properties that set it apart from other crops and contribute to its wide range of applications. As discussed briefly in the introduction, the hemp plant has a unique ability to absorb and store significant amounts of $CO_2$. The reasons why the hemp plant has impressive carbon sequestration properties are presented first in this section. Every part of the hemp plant, namely its seeds, root, stalks, leaves and flowers, are utilizable without waste [9]. Hence, a discussion on the notable characteristics of different parts of the hemp plant is also presented in this section.

### 2.1 Impressive Carbon Sequestration Properties

In this sub-section, the main reasons why hemp is considered beneficial for carbon sequestration are discussed. Firstly, hemp is an exceptionally fast-growing plant, reaching maturity in just 3 to 4 months. Its quick growth rate means it can capture carbon from the atmosphere more efficiently than many other plants. It has a high biomass yield, meaning that it produces a large amount of organic material. The plant's leaves, stems, and roots all contribute to the overall biomass. As hemp grows, it takes in $CO_2$ from the air during photosynthesis, converting it into organic carbon compounds that make up its biomass. Hemp also has an extensive and fibrous root system that can reach depths of up to 3 meters in the soil. These deep roots enhance the plant's ability to sequester carbon

Int. Journal of Integrated Engineering Vol. 16 No. 2 (2024) p. 1-12

by storing it in the soil for an extended period. Carbon stored in the soil helps to improve soil health and fertility. Hemp is widely used for its versatile fibers, which are incorporated into various products like textiles, paper, construction materials and so on (which are discussed in detail in the next section). When these hemp-derived products are utilized, the carbon stored within them remains sequestered for the duration of their lifecycle, reducing the carbon footprint associated with alternative materials.

Hemp can also be integrated into crop rotation systems, which enhances soil health and promotes carbon sequestration. By implementing regenerative farming practices alongside hemp cultivation, such as minimizing tillage, adding organic matter, and avoiding synthetic fertilizers, the overall carbon sequestration potential can be further optimized [10].

## 2.2 Hemp Seed

The hemp seed is an oval, brownish-grey seed with a length of 3 to 5 mm. The hemp seed is nourishing and may be consumed uncooked. Proteins, important fatty acids (omega-3, omega-6, and omega-9), vitamins E, C, F, and B, as well as minerals (calcium, potassium, magnesium, phosphorus, zinc), are all abundant in it which makes hemp seeds a quality dietary supplement. Oil made from hemp seeds is frequently used in cosmetic formulations or for human use. People can consume hempseed in different forms, such as whole seeds or hulled seeds, as well as in processed products like bread, flour, and protein powder. It is worth noting that the composition of hempseed can vary significantly based on different hemp plant types and environmental conditions, as indicated by various studies [11-13].

## 2.3 Hemp Stalk

The inner part of the hemp stem comprises the hemp stalk, accounting for over 50% of the total plant weight [14]. It possesses intriguing properties as an insulating material. Furthermore, as a biomaterial containing cellulose and woody fibers, hemp fiber stands out among plant-based fibers due to its high cellulose content, ranging from 70% to 74% [15, 16]. Although the hemp stalk contains a lower percentage of cellulose compared to the fibers, the amount is still considerable (34-60%) [17, 18]. Furthermore, Hemp fibers extracted from the hemp stalk due to their essential qualities such as strength and high cellulose content, are ideal for producing exceptionally high-quality paper compared to other plant materials [19-21].

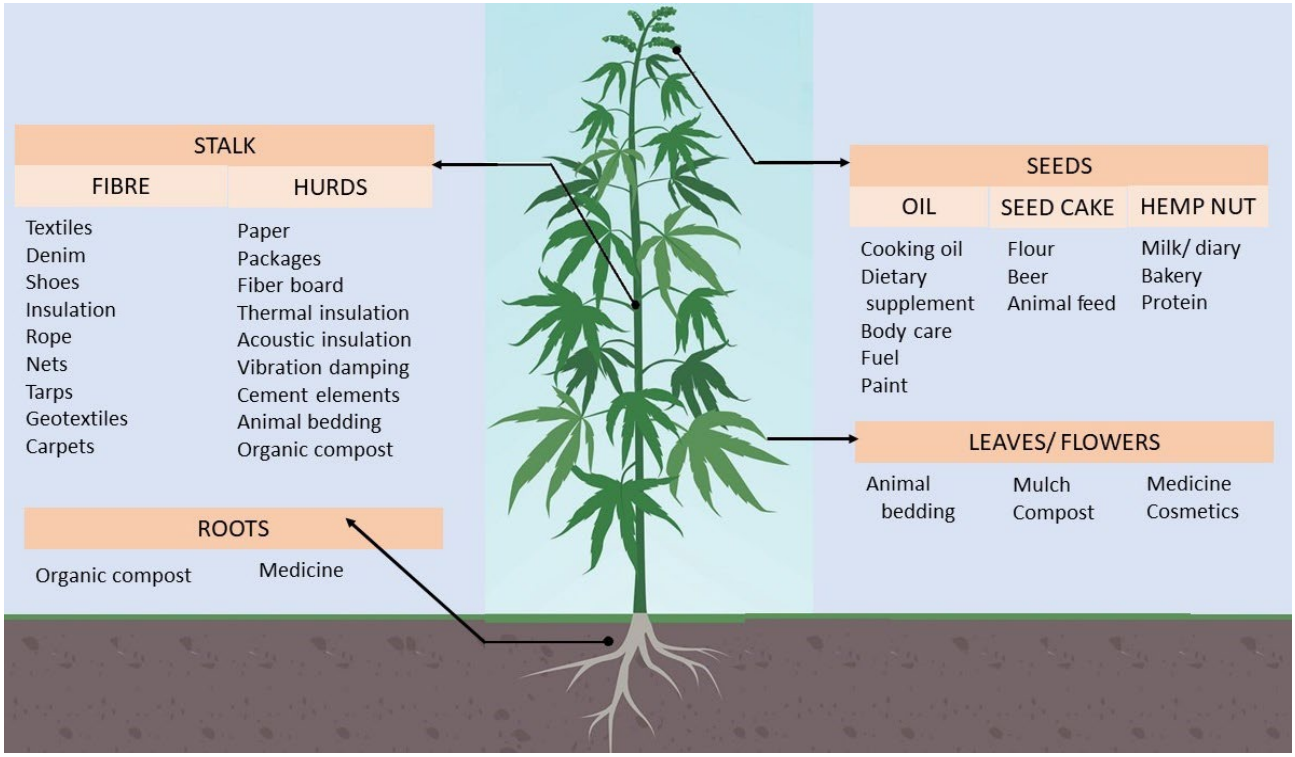


**Fig. 1** *A summary of applications associated with different parts of hemp plant*

## 2.4 Hemp Leaves and Flowers

Hemp leaves and flowers are commonly used for the extraction of cannabidiol (CBD), a non-psychoactive compound known for its potential therapeutic benefits. CBD extraction involves various methods such as solvent extraction, $CO_2$ extraction, or steam distillation, to obtain CBD-rich extracts for use in wellness and health products [22]. CBD derived from hemp flowers and leaves possesses numerous medicinal applications, including its ability to promote sleep, provide relief from chronic pain, and induce relaxation. CBD extraction is not the main application of hemp leaves as the amount is very miniscule compared to hemp flowers, however the hemp leaves have other applications. Hemp leaves may be utilised to make hemp tea, salads and used in animal feed supplements. Figure 1 presents an overview of the diverse applications associated with various parts of the hemp plant and key applications of the hemp plant are discussed in the next section.

## 3. Key Applications of the Hemp Plant

Hemp has a wide range of applications across various industries due to its versatile properties. Some key applications of hemp are presented in this section. It is to be noted that the following are just some of the key applications of hemp, and the versatility of this plant continues to be explored and expanded as more research and development take place in the field of hemp utilization.

## 3.1 Building Material

There is currently a significant growth in the market of so-called “traditional” building materials, in particular mortars made of mixtures of natural fibers (hemp, straw, flax, bamboo, animal hairs,…) and binders (lime, clay, plaster etc), which has raised some interest in the literature [23-29]. Construction is an energy-intensive industry. Building operations and construction activities account for over 40% of all energy use worldwide [30]. The carbon impact of modern insulating materials like rock wool and polystyrene is substantial. It makes sense to look for insulating materials with lower embodied energy. The amount of embodied energy in building materials can be greatly decreased by using semi-finished goods made from straw (fiber and shives) [7]. Hemp-based concrete, also known as hempcrete or Lime-Hemp Concrete, is a construction material that incorporates lime, water, and hemp shives [31]. Hemp shives are a by-product obtained from the processing of hemp stalks for fiber extraction. When combined with lime and water, hemp shives create a unique and sustainable building material with various beneficial properties.

One of its notable advantages is its carbon-negative nature which makes it a sustainable choice for reducing carbon emissions. The production and use of hempcrete result in a net removal of carbon dioxide from the atmosphere. Furthermore, the carbon absorption process continues even after the hempcrete is incorporated into construction. Over the building's lifetime, hempcrete continues to absorb carbon dioxide, storing more carbon than was emitted during the construction phase [32]. Hempcrete exhibits a significantly lower density than typical concrete due to the fact that hemp shivs have a lower density compared to traditional concrete aggregates[33]. Density of hempcrete ranges typically between 200 to 800 kg/m$^3$(depending on hemp shives/binder ratio), compared to 2,000 to 2,500 kg/m3 for ordinary concrete [34]. This makes hempcrete easier to transport and work with, and it also gives it better thermal insulation properties. The thermal conductivity of hempcrete is typically between 0.06 and 0.18 W/mK [34], compared to 2.24 to 3.85 W/mK for ordinary concrete [35] which makes it a superior insulator, enabling it to provide enhanced thermal performance. This helps to maintain cooler indoor temperatures during summer and warmer temperatures during winter in buildings. Figure 2 illustrates the hempcrete applications in wall, floor and roof insulation in construction.

Since the 1980s, hemp shives have been utilised in construction as a lightweight aggregate in composites with a lime, clay, or magnesia binder [36]. A good grade of shives is needed for this. Additionally, they should be cleaned of fiber clumps (a small number of single, short fibers are recommended because they act as micro-reinforcement). Dust (from plant and soil) and fiber clumps increase the need for water and binder, so they should be removed. It uses both finer and coarser fractions, but the combination of shives should have the right graining curve. The shives in dry form can also be used as loose insulation in partitions in a wooden frame building (insulation of walls, floors, ceilings, and roofs) without strictly adhering to the prescribed percentage and fiber content. According to experiments on insulation constructed of flax shives, the degree of shives density will determine the efficacy of the insulation [37].

Int. Journal of Integrated Engineering Vol. 16 No. 2 (2024) p. 1-12

**Fig. 2** *Hempcrete applications in wall, floor and roof insulation in construction [38]*

## 3.2 Biofuel

According to several reports [39, 40], energy crops have a strong potential to increase the percentage of renewable energy. High land use efficiency, or high energy outputs per hectare, is crucial since the amount of land that can be used for food, feed, and energy production is limited. Currently, most of the energy production uses only the grains or seeds from traditional food crops, such as ethanol from wheat grains or biodiesel from rapeseeds. Few of these 'specialised energy crops', like maize in Germany, are now being grown on a large scale in Europe [41]. Even fewer annual crops are available for crop rotations with food and feed crops, which is essential for the sustainability of bioenergy production [42]. In recent years, industrial hemp has gained attention as a potential source of biofuel due to its high biomass yield, fast growth rate, and versatility. Hemp's high land use efficiency and other benefits, such as reduced reliance on pesticides, efficient weed management, and better soil health [43-45], support its use as an energy crop. In 2005, around 200 units, mostly in Europe and North America, used co-firing of biomass with fossil fuels, such as coal [46]. Typically, forestry wood products are the primary fuel used in such plants [47]. However, several power plants currently use agricultural residues as their primary fuel (for example, cereal straw), and more are in the planning stages [48]. Herbaceous biomass with low bulk density has a high transport cost, which restricts its use in such large-scale plants or necessitates densifying the fuel beforehand. The generation of heat and power from the burning of biomass can significantly reduce greenhouse gas emissions [49, 50]. Worldwide manufacture of large-scale biomass-fired boilers for the generation of heat, electricity, or combined heat and power (CHP) is now underway [47].

## 3.3 Textiles

For countless centuries, humanity has relied on the versatile hemp fiber to fashion textiles, fabrics, ropes, yarns, rugs, and canvas. To produce a range of durable and comfortable clothing materials, the hemp fibers can undergo a process of spinning, followed by weaving or knitting. Hemp fiber was once a popular choice for fabric in garments due to its strong and versatile nature. However, with the rise of the global cotton industry, hemp gradually lost its prominence in the apparel sector [51, 52]. When we compare hemp fibers to other natural options such as cotton, linen, and nettle, it becomes evident that hemp fibers stand out for their remarkable strength. Not only are they stronger, but they also possess a unique adaptability and sturdiness that sets them apart. Additionally, hemp fibers exhibit excellent water-resistance, further adding to their list of advantageous qualities [51, 53]. Research conducted by Lamberti and Sarkar (2017) [54] highlights that hemp and cotton materials share similar characteristics in terms of colour fastness, stain resistance, ignitability, strength, and elongation. Figure 3 compares the some of the important characteristics of cotton and hemp. This suggests that hemp fabrics can rival cotton fabrics in terms of performance and functionality. By blending hemp fibers with other materials, such as cotton or linen, textile manufacturers can create versatile fabrics with unique textures and enhanced properties, catering to a wider range of consumer preferences. Additionally, hemp is increasingly recognized as a sustainable fabric option for upholstery and furniture, including textiles for chairs, tables, mirrors, and decorative items, making it a versatile choice for various applications. The market for hemp fiber has witnessed significant growth in recent years. In 2019, the market was valued at USD 4.46 Billion, and it is projected to reach USD 43.75 Billion by 2027. This represents a remarkable compound annual growth rate (CAGR) of 33% from 2020 to 2027.

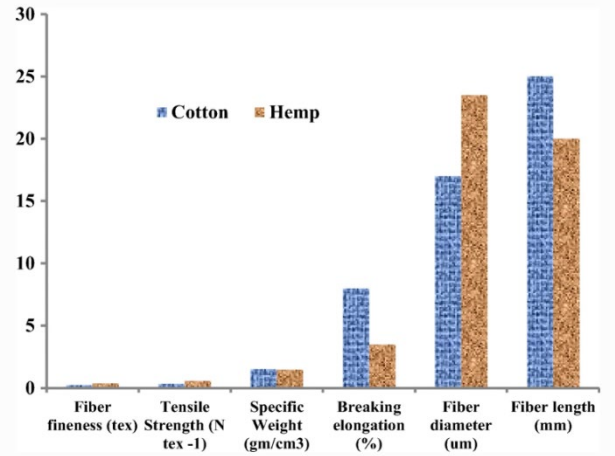


**Fig 3** *Comparison of characteristics of cotton and hemp fiber [55]*

## 3.4 Paper

Hemp fibers have been recognized for their excellent suitability in paper production, offering numerous advantages over traditional wood-based pulp. Its use in the paper industry dates back centuries, and its benefits have gained attention in the past few years. In ancient China, hemp fiber was extensively used for creating paper scrolls [56]. Hemp paper was used in historical events such as the writings of the first holy Bible [25] and the crafting of documents like the Declaration of Independence and the US Constitution [57]. However, the usage of hemp fiber for paper production disappeared over time with the emergence of wood-based paper, advancements in technology, and shifts in market demand.

Following hemp's "rediscovery" in Europe in the 1990s, its fibers have been employed in the manufacturing of specialized pulp and paper products. As a non-wood fiber, hemp possesses outstanding qualities, including excellent pulp physical properties and remarkable tensile strength, which make it an exceptional raw material for crafting specialty paper of high quality [25, 58, 59]. The fibers derived from hemp are renowned as the strongest natural fibers globally, and the abundant and high-quality cellulose content in hemp makes it an ideal foundation for crafting paper of exceptional quality [19-21]. When compared to the conventional wood- or tree-based paper, hemp paper surpasses it in several aspects. Its long and strong bast fibers result in a higher quality paper that is naturally acid-free. Production of hemp paper requires fewer chemicals compared to tree-based paper, ensuring longevity without yellowing or brittleness. Hemp cultivation for paper is faster and more efficient than tree growth. However, hemp pulp is more expensive, costing three to six times more than wood-based pulp due to the fact that only bast fibers are used in paper production. This limits hemp paper usage to limited applications such as forms, currency, and cigarette production.

## 3.5 Edible Oil

Hemp seed oil is highly valued for its nutritional richness and its associated health benefits. Hemp oil is extracted by squashing the hemp seeds under high pressure. A by-product of this procedure, called husk, is also used as fertilizer and cattle feed [56]. The oil has a notable fatty acid composition, typically containing 25 to 35% oil content. Hemp seeds are also a source of various trace minerals, including approximately 20-25% protein, 20-30% carbohydrates, and 10-15% fiber. This comprehensive nutritional profile makes hemp seed oil a valuable dietary supplement and a complete nutritional source as it contains all essential amino acids and fatty acids like linoleic acid (18:2 omega-6) and alpha-linolenic acid (18:3 omega-3). Several studies have reported that fatty acids can help in reducing cholesterol levels and blood pressure, as well as contribute to the prevention of cancer [60] and cardiovascular disorders [61]. Additionally, the oil is also used as a moisturiser in the pharmaceutical and cosmetic industries to lessen the dryness of skin [62].

## 3.6 Activated Carbon

The global demand for activated carbon is consistently rising due to its widespread use as adsorbent for air filtration, wastewater treatment, and water treatment [63-65]. Traditionally activated carbons is produced from a range of carbonaceous sources, and raw materials such as wood, coal, coconut shells, and certain polymers [66]. However, recent studies have explored the use of hemp biomass as an alternative precursor for activated carbon production [67]. Williams and Reed [68, 69] has reported the physical activation of activated carbon fibers using steam and the chemical activation of Zinc Chloride of hemp fibers. The benefit of the possible reusability of a

Int. Journal of Integrated Engineering Vol. 16 No. 2 (2024) p. 1-12

leftover material makes the use of hemp wastes to make activated carbon highly practical. In a study conducted by Wang et al. [70], activated graphene was successfully synthesized using hemp-bast fiber through hydrothermal processing and chemical activation techniques. They found that the hemp-derived graphene exhibited a high surface area with significant number of mesopores and displayed an excellent capacitance and energy density performance in an organic electrolyte at varying temperatures. However, they solely used the hemp-bast fiber (20–25% of the hemp biomass), neglecting the hemp stem (75-80% of the hemp biomass). Later, Sun et al. [71] used both bast (the outside fibrous part of the stem) and hurd (inside pulp of the stem) and prepared a high-performance activated carbons for electrochemical capacitors via hydrothermal processing and chemical activation. They achieved excellent electrochemical performance metrics, including a specific capacitance of 160 F/g, and a high energy density of 19.8 Wh/kg at a power density of 21 kW/kg.

## 4. Challenges in the Widespread Use of Hemp

Although hemp is a versatile plant with numerous applications, it still faces challenges in Australia in terms of regulatory issues, cultivation of the plant as well as in its applications. The challenges identified in this review are presented below:

### 4.1 Regulatory/ Legal Constraints

The regulatory issues surrounding the cultivation of hemp and hemp-derived products can be complex and inconsistent. Different jurisdictions may have varying regulations regarding the cultivation, manufacturing, labelling, and marketing of hemp products. This lack of consistency among different regions further complicates the situation and can present obstacles for farmers and organisations due to the varying regulations and restrictions. Despite the differences between hemp and marijuana, some laws still treat them as the same, which can create confusion and challenges for the growers. The constraints can also limit market access and create compliance challenges for businesses operating in the hemp industry. This legal uncertainty makes it difficult for farmers to confidently invest in the cultivation of hemp and limits the industry's potential for growth. For example, in Victoria, Australia, Cannabis is classified as a ‘prohibited substance’ under the Commonwealth Poisons Standard, except where separately specified. Part IVA of the Victorian *Drugs, Poisons and Controlled Substances Act 1981* (the Act) provides for the issuance of Authorities for low-THC cannabis. For the purposes of Part IVA of the Act, low-THC cannabis is cannabis where the leaves and flowering heads do not contain more than 0.35 per cent THC. As hemp is a regulated plant, a person must hold an Authority under Part IVA of the Act to cultivate, process, sell or supply low-THC cannabis and low-THC cannabis seed [8].

### 4.2 Lack of Awareness

Despite the increasing popularity of hemp, many people still associate hemp with marijuana due to their shared botanical origins. Public awareness and education about the differences between hemp and marijuana, particularly regarding the low-THC content of hemp, are crucial to dispelling misconceptions and reducing stigma. Furthermore, there is also a lack of awareness among consumers about the various products that can be derived from hemp. This can hinder market demand and adoption, particularly for niche or specialized hemp products.

### 4.3 Lack of Guidelines and Quality Control

Maintaining consistent quality across hemp-derived products can be challenging due to non-availability of guidelines. Factors such as variations in cultivation practices, genetics, and processing methods can impact the quality and effectiveness of hemp-based products. Ensuring standardized quality control measures is essential for building consumer trust and confidence.

### 4.4 Limited Cultivation Infrastructure

The infrastructure for hemp cultivation, processing, and manufacturing is relatively underdeveloped in Australia. This includes a shortage of specialized equipment, processing facilities, and skilled labour, which can impede the efficient and cost-effective production of hemp products.

### 4.5 Limited Market Development

Establishing a robust and sustainable market for hemp products is another challenge in Australia. Building consumer demand, securing reliable distribution channels, and creating a diverse range of value-added hemp products are essential for long-term market viability.

### 4.6 Insufficient Research and Development

While there is growing interest in hemp research and development, further scientific studies are needed to explore the plant's potential and expand its applications. Research into genetics, agronomy, processing techniques, and product development can drive innovation and support the industry's growth.

### 4.7 Lack of Investment

Access to capital and financing options can be challenging for hemp businesses in Australia, particularly for startups or small-scale growers. Limited financial support and investment opportunities can hinder the expansion and scalability of hemp operations.

## 5. Current Trends and Future Directions

The hemp industry is undergoing strong growth in Australia, with innovative technologies improving production and a range of value-added products being developed. The cultivation of hemp is being explored as a sustainable farming practice and there has been a notable increase in hemp cultivation across Australia. As discussed in earlier sections of this paper, hemp requires minimal water and pesticides compared to many other crops, making it an attractive option for farmers seeking more environmentally friendly alternatives. As a rotational crop, hemp can also contribute to soil health and biodiversity, further enhancing its appeal within the agricultural community. Farmers are recognizing the potential of hemp as a profitable and sustainable crop. With the relaxation of regulations and improved access to licenses, more agricultural land is being dedicated to hemp cultivation. This section presents the current trends and future directions in the hemp industry.

### 5.1 Upcoming Markets in the Hemp Industry

The current trends in the development and application of hemp-based products are discussed in this section.

#### 5.1.1 Textile Industry

Hemp fibres are increasingly being integrated into the fashion and textile industry. Designers and brands are recognizing the unique properties of hemp, such as its durability, breathability, and natural resistance to pests. Hemp fabrics are being used to create sustainable and eco-friendly clothing, footwear, accessories, and home textiles, catering to the growing demand for ethical and environmentally conscious products.

#### 5.1.2 Sustainable Construction

Hemp is making its mark in the construction industry as a sustainable alternative to traditional materials. Hempcrete, a mixture of hemp fibres and lime, is being used in the construction of eco-friendly buildings. Hempcrete offers excellent insulation, moisture regulation, and carbon sequestration properties, making it an attractive choice for environmentally conscious builders and architects.

#### 5.1.3 Health and Wellness

The therapeutic potential of hemp-derived products, particularly CBD (cannabidiol), has captured the attention of the health and wellness sector. CBD is believed to have various beneficial properties, including pain relief, relaxation, and stress reduction. As a result, CBD-infused oils, creams, capsules, and dietary supplements are gaining popularity, with consumers embracing hemp-based alternatives for general well-being.

#### 5.1.4 Food and Beverages

Hemp seeds and hemp-derived ingredients are increasingly being used in the food and beverage industry. Hemp seeds are rich in protein, healthy fats, and essential nutrients, making them a popular addition to granolas, protein bars, smoothies, and baked goods. Hemp oil is also used for salad dressings, cooking, and as a nutritional supplement.

### 5.2 Regulatory Developments

The legal aspects surrounding hemp cultivation and its derived products is evolving worldwide and especially in Australia. As governments recognize the economic and environmental benefits of hemp, regulatory frameworks are being established to facilitate its growth. It is expected that the regulatory and licensing framework for hemp cultivation and hemp products would be further streamlined in Australia to benefit the expansion of the hemp industry. Such future developments in regulations may further unlock the potential of hemp, allowing for expanded cultivation, research, and commercialization opportunities.

### 5.3 Sustainable Agricultural Practices and Innovative Applications

Hemp is renowned for its ability to thrive in diverse climates with minimal water and pesticide requirements. As sustainability becomes a focus point, the cultivation of hemp is expected to adopt even more environmentally friendly practices. This includes regenerative farming techniques, organic cultivation methods, and efficient water management, further enhancing the ecological footprint of hemp production. As our understanding of hemp expands, researchers are exploring innovative applications beyond traditional uses. Hemp fibres could find their way more into advanced materials, such as bio-composites, biofuels, sustainable construction materials, and even nanotechnology. These breakthroughs may revolutionize multiple industries and pave the way for hemp-based sustainable and eco-friendly alternatives in the future.

## 6. Conclusions

Hemp (Cannabis sativa species) has gained significant attention as a promising plant with the potential to contribute to sustainable development and carbon sequestration. This review paper has presented an overview of hemp's properties, applications, challenges, and future directions in the context of its role as a sustainable carbon-negative plant. The key conclusions drawn from this study are as follows:

Unique properties of hemp – The review has brought out the unique properties of hemp that make it an ideal candidate for carbon sequestration. Hemp's rapid growth, high biomass production, and deep root system contribute to its carbon sequestration capabilities, allowing it to absorb and store substantial amounts of carbon dioxide ($CO_2$) during its growth cycle. Such unique properties of hemp have the potential in making it a valuable tool in combating climate change. This review also highlights the importance of hemp's carbon-rich fibers and their potential for long-term carbon storage in various applications, such as textiles, construction materials, and biofuels.

Diverse range of applications – Owing to its versatile properties, hemp has a wide range of applications across various industries. From textiles to construction materials, paper and packaging, biofuel and edible oil, and water/ wastewater treatment, hemp's versatility and potential for sustainable development has been presented in this review.

Challenges to hemp's widespread use – The review also identified several challenges and barriers to hemp's widespread adoption as a sustainable carbon-negative plant. These challenges include legal and regulatory frameworks, limited infrastructure, lack of public awareness, and the need for further research and development. The review emphasizes the importance of supportive policies, investment in research, and public education to overcome these barriers and unlock the full potential of hemp.

Future directions – This review has identified future directions for harnessing hemp's potential as a sustainable carbon-negative plant. It calls for continued research into hemp cultivation practices, processing techniques, and product innovation to optimize carbon sequestration and minimize environmental impacts. Collaboration among stakeholders, including farmers, researchers, policymakers, and industry players, is essential to create an enabling environment for the growth of the hemp industry and the realization of its carbon-negative potential.

## Acknowledgement

The authors fully acknowledged Victoria University, Greater Western Water and Federation University for supporting this work.

## Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

## References

[1] S. Amaducci *et al.*, "Key cultivation techniques for hemp in Europe and China," *Industrial Crops and Products,* vol. 68, pp. 2-16, 2015.
[2] K. Pacaphol and D. Aht-Ong, "Preparation of hemp nanofibers from agricultural waste by mechanical defibrillation in water," *Journal of Cleaner Production,* vol. 142, pp. 1283-1295, 2017.
[3] J. Sawler *et al.*, "The genetic structure of marijuana and hemp," *PloS one,* vol. 10, no. 8, p. e0133292, 2015.
[4] T. Jami, S. Karade, and L. Singh, "A review of the properties of hemp concrete for green building applications," *Journal of Cleaner Production,* vol. 239, p. 117852, 2019.
[5] T. Jami, D. Rawtani, and Y. K. Agrawal, "Hemp concrete: carbon-negative construction," *Emerging Materials Research,* vol. 5, no. 2, pp. 240-247, 2016.
[6] H. Binici, O. Aksogan, and C. Demirhan, "Mechanical, thermal and acoustical characterizations of an insulation composite made of bio-based materials," *Sustainable Cities and Society,* vol. 20, pp. 17-26, 2016.

[7] L. Zampori, G. Dotelli, and V. Vernelli, "Life cycle assessment of hemp cultivation and use of hemp-based thermal insulator materials in buildings," *Environmental science & technology,* vol. 47, no. 13, pp. 7413-7420, 2013.
[8] "Industrial hemp taskforce." Agriculture Victoria. https://agriculture.vic.gov.au/crops-and-horticulture/cannabis-in-victoria/industrial-hemp-taskforce (accessed on 1st June 2023).
[9] H. Yano and W. Fu, "Hemp: A Sustainable Plant with High Industrial Value in Food Processing," *Foods,* vol. 12, no. 3, p. 651, 2023.
[10] J. Visković *et al.*, "Industrial hemp (Cannabis sativa L.) agronomy and utilization: a review," *Agronomy,* vol. 13, no. 3, p. 931, 2023.
[11] M. Irakli, E. Tsaliki, A. Kalivas, F. Kleisiaris, E. Sarrou, and C. M. Cook, "Effect of genotype and growing year on the nutritional, phytochemical, and antioxidant properties of industrial hemp (Cannabis sativa L.) seeds," *Antioxidants,* vol. 8, no. 10, p. 491, 2019.
[12] C. D. Porto, D. Decorti, and A. Natolino, "Potential oil yield, fatty acid composition, and oxidation stability of the hempseed oil from four Cannabis sativa L. cultivars," *Journal of Dietary Supplements,* vol. 12, no. 1, pp. 1-10, 2015.
[13] E. Vonapartis, M.-P. Aubin, P. Seguin, A. F. Mustafa, and J.-B. Charron, "Seed composition of ten industrial hemp cultivars approved for production in Canada," *Journal of Food Composition and Analysis,* vol. 39, pp. 8-12, 2015.
[14] T. Colinart, P. Glouannec, and P. Chauvelon, "Influence of the setting process and the formulation on the drying of hemp concrete," *Construction and Building materials,* vol. 30, pp. 372-380, 2012.
[15] E. Gümüşkaya, M. Usta, and M. Balaban, "Carbohydrate components and crystalline structure of organosolv hemp (Cannabis sativa L.) bast fibers pulp," *Bioresource technology,* vol. 98, no. 3, pp. 491-497, 2007.J. P. Manaia, A. T. Manaia, and L. Rodriges, "Industrial hemp fibers: An overview," *Fibers,* vol. 7, no. 12, p. 106, 2019.
[16] A. Evrard, "Transient hygrothermal behaviour of lime-hemp materials," *Université catholique de Louvain,* vol. 625, p. 626, 2008.
[17] A. B. Thomsen, S. Rasmussen, V. Bohn, K. V. Nielsen, and A. Thygesen, *Hemp Raw Materiala: The Effect of Cultivar, Growth Conditions and Pretreatment on the Chemical Composition of the Fibres*. Risø DTU-National Laboratory for Sustainable Energy Roskilde, Denmark, 2005.
[18] M. P. Aubin, P. Seguin, A. Vanasse, G. F. Tremblay, A. F. Mustafa, and J. B. Charron, "Industrial hemp response to nitrogen, phosphorus, and potassium fertilization," *Crop, Forage & Turfgrass Management,* vol. 1, no. 1, pp. 1-10, 2015.
[19] G. A. Lower, "Flax and hemp: From the seed to the loom," *Mechanical Engineering Magazine,* vol. 1, no. 2, 1937.
[20] E. Malachowska, P. Przybysz, M. Dubowik, M. Kucner, and K. Buzala, "Comparison of papermaking potential of wood and hemp cellulose pulps," *Annals of Warsaw University of Life Sciences-SGGW. Forestry and Wood Technology,* vol. 91, 2015.
[21] R. Pavlovic *et al.*, "Quality traits of "cannabidiol oils": cannabinoids content, terpene fingerprint and oxidation stability of European commercially available preparations," *Molecules,* vol. 23, no. 5, p. 1230, 2018.
[22] R. Kozlowski, M. Wladyka-Przybylak, M. Helwig, and K. Kurzydłoski, "Composites based on lignocellulosic raw materials," *Molecular Crystals and Liquid Crystals,* vol. 418, no. 1, pp. 131-151, 2004.
[23] Z. Li, X. Wang, and L. Wang, "Properties of hemp fibre reinforced concrete composites," *Composites part A: applied science and manufacturing,* vol. 37, no. 3, pp. 497-505, 2006.
[24] P. Ranalli and G. Venturi, "Hemp as a raw material for industrial applications," *Euphytica,* vol. 140, no. 1-2, pp. 1-6, 2004.
[25] J. W. Roulac, *Hemp horizons: the comeback of the world's most promising plant*. Chelsea Green Publishing Company, 1997.
[26] H. Savastano Jr, P. G. Warden, and R. S. Coutts, "Potential of alternative fibre cements as building materials for developing areas," *Cement and Concrete composites,* vol. 25, no. 6, pp. 585-592, 2003.
[27] R. Siddique, "Properties of concrete incorporating high volumes of class F fly ash and san fibers," *Cement and Concrete Research,* vol. 34, no. 1, pp. 37-42, 2004.
[28] E. M. Young, "Revival of Industrial Hemp: A systematic analysis of the current global industry to determine limitations and identify future potentials within the concept of sustainability," *Master's Degree of International Environmental Science. Sweden: Lund University,* 2005.
[29] I. E. Agency and E. i. B. a. C. Program, "Towards Net Zero Energy Solar Buildings," 2013.
[30] R. Bevan and T. Woolley, "Hemp lime construction," *A guide to building with hemp lime composites, Bracknell,* 2008.
[31] S. Barbhuiya and B. B. Das, "A comprehensive review on the use of hemp in concrete," *Construction and Building Materials,* vol. 341, p. 127857, 2022.

[32] F. Collet and S. Pretot, "Thermal conductivity of hemp concretes: Variation with formulation, density and water content," *Construction and building materials,* vol. 65, pp. 612-619, 2014.
[33] Y. Abdellatef, M. A. Khan, A. Khan, M. I. Alam, and M. Kavgic, "Mechanical, thermal, and moisture buffering properties of novel insulating hemp-lime composite building materials," *Materials,* vol. 13, no. 21, p. 5000, 2020.
[34] I. Asadi, P. Shafigh, Z. F. B. A. Hassan, and N. B. Mahyuddin, "Thermal conductivity of concrete–A review," *Journal of Building Engineering,* vol. 20, pp. 81-93, 2018.
[35] S. Allin, *Building with hemp*. SeedPress, 2005.
[36] P. Brzyski, P. Kosiński, A. Zgliczyńska, P. Iwanicki, and J. Poko, "Mass Transport and Thermal Conductivity Properties of Flax Shives for Use in Construction Industry," *Journal of Natural Fibers,* vol. 18, no. 7, pp. 995-1006, 2021.
[37] A. F. Ahmed, M. Z. Islam, M. S. Mahmud, M. E. Sarker, and M. R. Islam, "Hemp as a potential raw material toward a sustainable world: A review," *Heliyon,* p. e08753, 2022.
[38] G. Fischer *et al.*, "Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures, Part II: Land use scenarios," *Biomass and bioenergy,* vol. 34, no. 2, pp. 173-187, 2010.
[39] M. Hoogwijk, A. Faaij, B. Eickhout, B. De Vries, and W. Turkenburg, "Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios," *Biomass and Bioenergy,* vol. 29, no. 4, pp. 225-257, 2005.
[40] K. Ericsson and L. J. Nilsson, "Assessment of the potential biomass supply in Europe using a resource-focused approach," *Biomass and bioenergy,* vol. 30, no. 1, pp. 1-15, 2006.
[41] T. Amon *et al.*, "Methane production through anaerobic digestion of various energy crops grown in sustainable crop rotations," *Bioresource technology,* vol. 98, no. 17, pp. 3204-3212, 2007.
[42] I. Bocsa and M. Karus, *the cultivation of hemp: botany, varieties, cultivation and harvesting*. Hemptech, 1998.
[43] L. Lotz, R. Groeneveld, B. Habekotte, and H. Van Oene, "Reduction of growth and reproduction of Cyperus esculentus by specific crops," *Weed Research,* vol. 31, no. 3, pp. 153-160, 1991.
[44] S. Montford and E. Small, "Measuring harm and benefit: The biodiversity friendliness of Cannabis sativa," *Global biodiversity,* vol. 8, no. 4, pp. 2-13, 1999.
[45] F. Al-Mansour and J. Zuwala, "An evaluation of biomass co-firing in Europe," *Biomass and bioenergy,* vol. 34, no. 5, pp. 620-629, 2010.
[46] A. Faaij, "Modern biomass conversion technologies," *Mitigation and adaptation strategies for global change,* vol. 11, pp. 343-375, 2006.
[47] P. Ottosson, H. Bjurström, C. Johansson, S. Svensson, and J. Mattsson, "Förstudie–Halmaska i ett kretslopp," ed: Stockholm, Sweden: Värmeforsk. (Miljöriktig användning av aska), 2009.
[48] P. Börjesson, L. Gustavsson, L. Christersson, and S. Linder, "Future production and utilisation of biomass in Sweden: potentials and CO2 mitigation," *Biomass and Bioenergy,* vol. 13, no. 6, pp. 399-412, 1997.
[49] L. Gustavsson *et al.*, "Using biomass for climate change mitigation and oil use reduction," *Energy policy,* vol. 35, no. 11, pp. 5671-5691, 2007.
[50] P. Bouloc, S. Allegret, and L. Arnaud, *Hemp: industrial production and uses*. CABI, 2013.
[51] E. Small and D. Marcus, "Hemp: A new crop with new uses for North America," *Trends in new crops and new uses,* vol. 24, no. 5, pp. 284-326, 2002.
[52] M. Zimniewska, "Hemp fibre properties and processing target textile: A review," *Materials,* vol. 15, no. 5, p. 1901, 2022.
[53] D. Lamberti and A. Sarkar, "Hemp fiber for furnishing applications," in *IOP Conference Series: Materials Science and Engineering*, 2017, vol. 254, no. 19: IOP Publishing, p. 192009.
[54] M. Rehman *et al.*, "Evaluation of hemp (Cannabis sativa L.) as an industrial crop: A review," *Environmental Science and Pollution Research,* vol. 28, no. 38, pp. 52832-52843, 2021.
[55] R. Robinson, *The great book of hemp: the complete guide to the environmental, commercial, and medicinal uses of the world's most extraordinary plant*. Inner Traditions/Bear & Co, 1996.
[56] T. Karche, "The application of hemp (Cannabis sativa L.) for a green economy: A review," *Turkish Journal of Botany,* vol. 43, no. 6, pp. 710-723, 2019.
[57] P. Bajpai, *Biotechnology for pulp and paper processing*. Springer, 2012.
[58] D. Danielewicz and B. Surma-Ślusarska, "Properties and fibre characterisation of bleached hemp, birch and pine pulps: a comparison," *Cellulose,* vol. 24, no. 11, pp. 5173-5186, 2017.
[59] W. Leonard, P. Zhang, D. Ying, and Z. Fang, "Hempseed in food industry: Nutritional value, health benefits, and industrial applications," *Comprehensive reviews in food science and food safety,* vol. 19, no. 1, pp. 282-308, 2020.
[60] S. S. Borhade, "Chemical Composition and Characterization of Hemp (Cannabis sativa) Seed oil and essential fatty acids by HPLC Method," *Archives of applied science research,* vol. 5, no. 1, pp. 5-8, 2013.
[61] S. Sapino, M. E. Carlotti, E. Peira, and M. Gallarate, "Hemp-seed and olive oils: Their stability against oxidation and use in O/W emulsions," *International Journal of Cosmetic Science,* vol. 27, no. 6, pp. 355-355, 2005.

[62] R. I. Kosheleva, A. C. Mitropoulos, and G. Z. Kyzas, "Synthesis of activated carbon from food waste," *Environmental Chemistry Letters,* vol. 17, pp. 429-438, 2019.
[63] A. Samsuri, F. Sadegh-Zadeh, and B. Seh-Bardan, "Characterization of biochars produced from oil palm and rice husks and their adsorption capacities for heavy metals," *International Journal of environmental science and technology,* vol. 11, pp. 967-976, 2014.
[64] M. Yousefi *et al.*, "Modification of pumice with HCl and NaOH enhancing its fluoride adsorption capacity: kinetic and isotherm studies," *Human and Ecological Risk Assessment: An International Journal,* vol. 25, no. 6, pp. 1508-1520, 2019.
[65] A. M. Puziy, O. I. Poddubnaya, A. Martínez-Alonso, F. Suárez-García, and J. M. Tascón, "Surface chemistry of phosphorus-containing carbons of lignocellulosic origin," *Carbon,* vol. 43, no. 14, pp. 2857-2868, 2005.
[66] J. Rosas, J. Bedia, J. Rodríguez-Mirasol, and T. Cordero, "HEMP-derived activated carbon fibers by chemical activation with phosphoric acid," *Fuel,* vol. 88, no. 1, pp. 19-26, 2009.
[67] P. T. Williams and A. R. Reed, "Pre-formed activated carbon matting derived from the pyrolysis of biomass natural fibre textile waste," *Journal of Analytical and Applied Pyrolysis,* vol. 70, no. 2, pp. 563-577, 2003.
[68] P. T. Williams and A. R. Reed, "High grade activated carbon matting derived from the chemical activation and pyrolysis of natural fibre textile waste," *Journal of analytical and applied pyrolysis,* vol. 71, no. 2, pp. 971-986, 2004.
[69] H. Wang *et al.*, "Interconnected carbon nanosheets derived from hemp for ultrafast supercapacitors with high energy," *ACS nano,* vol. 7, no. 6, pp. 5131-5141, 2013.
[70] W. Sun, S. M. Lipka, C. Swartz, D. Williams, and F. Yang, "Hemp-derived activated carbons for supercapacitors," *Carbon,* vol. 103, pp. 181-192, 2016.