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Review

Can the Hemp Industry Improve the Sustainability Performance of the Australian Construction Sector?

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Abstract: Sustainable construction should navigate the trade-offs between minimising pressure on scarce resources and the environment and maximising economic viability and human wellbeing through the whole building lifetime. In the pursuit of improving the environmental performance of the construction sector, there is growing interest in substituting conventional materials with bio-based materials. In the last decade, the use of industrial hemp (*Cannabis sativa* L.) as an aggregate for bio-based materials has attracted significant attention because of its ability to sequester carbon dioxide (CO_2) during plant development, its fast-growing nature, the reduced level of agricultural input requirements and its good technical properties, which could potentially result in better sustainability performance across their life cycle. This review discusses the outcomes published in the scientific literature that have dealt with the use of hemp-based construction materials in the global and Australian construction sectors, with particular emphasis on the evaluation of their sustainability aspects (i.e., environmental, economic and social) throughout their lifetime. Relevant studies were identified from a structured keyword search in the Scopus database. The results found that research on hemp-based materials has mainly focused on assessing the environmental dimension, with an emphasis on greenhouse gas (GHG) emissions and little consideration for economic and social aspects. The existing literature showed a strong geographical bias towards Europe; thus, the outcomes of the life cycle studies conducted may not be representative of Australia. In that line, the development of a region specific of the life cycle sustainability approach is recommended to evaluate whether hemp-based construction materials can assist in achieving GHG targets in a sustainable manner in Australia.

Keywords: sustainable materials; sustainable construction; non-conventional building materials; greenhouse gas emissions; hemp-based materials

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Citation: Rivas-Aybar, D.; John, M.; Biswas, W. Can the Hemp Industry Improve the Sustainability Performance of the Australian Construction Sector? *Buildings* **2023**, *13*, 1504. https://doi.org/10.3390/buildings13061504

Academic Editors: Ahmed Senouci and Walid Maherzi

Received: 28 April 2023
Revised: 1 June 2023
Accepted: 9 June 2023
Published: 11 June 2023

1. Introduction

Increasing population, economic growth, industrialisation and urbanisation have led to the unprecedented expansion of the construction sector [1]. Buildings improve human wellbeing by providing infrastructure for economic and social development. Infrastructure activity, however, has significant detrimental effects on critical processes that regulate the Earth system and support human progress [2,3].

Construction is a global driver of resources depletion and environmental degradation [4]. Globally, the sector consumes 30 to 50% of all virgin materials [5], 36% of final energy [6], 40% of total waste and generates 37% of energy-associated carbon dioxide (CO_2) emissions [7]. In Australia, construction produces 18% of greenhouse gas (GHG) fluxes [8] and 38% of the national waste [9]. Given the current state of affairs, improving the environmental performance of the sector is crucial to maintain the carrying capacity of the planet and to enhance inter- and intra-generational social equity [10].

The sustainability concept advocates for the balance between environmental protection, economic security and societal welfare [11], especially when it comes to maintaining the life support processes of the planet, which is a pre-condition for economic and social progress [12]. This three-fold approach has been popularised as the *triple bottom line* (TBL). As such, sustainable construction should enable the sufficient delinking of the use of nature from economic activity by embracing the life cycle thinking concept for buildings, i.e., the extraction of virgin materials, material production, construction, operation, demolition and end-of-life (EOL) management [13]. The life cycle sustainability assessment (LCSA) has been the preferred tool to investigate the TBL performance of buildings [14]. LCSA is the result of the integration of three main life cycle assessment tools: the environmental life cycle assessment (abbreviated to LCA), life cycle costing (LCC) and the social life cycle assessment (SLCA) [15].

Life cycle research conducted in construction has mainly focused on environmental burdens with an emphasis on energy use and related GHG emissions, since they are seen as the most challenging constraints for the sector [16], with a lack of consideration for economic [17] and social [18] aspects. Most LCA studies have concluded that the operation stage (i.e., heating, cooling, ventilation and lighting) contributed the largest portion of the entire GHG budget of buildings [19,20]. Consequently, the majority of building policies and research have concentrated on mitigating operational GHG emissions by optimising electrical and thermal efficiency by using energy-saving construction materials, efficient end-use appliances, building management systems and renewable energy technologies [21,22]. As a result, energy efficiency improvements are increasingly being implemented in existing and new buildings [23].

As buildings decrease operational GHG emissions, the relative proportion of embodied emissions (i.e., material manufacturing, transportation, construction and EOL) increases within the entire life cycle [24]. In new high energy-efficient buildings, the share of embodied carbon can range between 45 and 50% of the total life GHG fluxes [23]. In the case of existing buildings, the use of new and additional materials to optimise energy performance can increase the total embodied GHG [25].

The traditional assessment focus on operational impacts is now shifting to embodied burdens, with reference to the reduction of GHG emissions related to the construction materials during the building's pre-use stage, i.e., virgin resource extraction and material manufacturing [26], and post-use stage, i.e., landfilling, reuse and/or recycling [27]. The appropriate selection of construction components with improved thermal and durability properties can mitigate embodied GHG by 30% [24].

The existing literature highlights the choice of construction elements as the most straightforward pathway towards the building's sustainability [1]. Sustainable construction materials are defined as solutions that exhibit lower environmental burdens without affecting the functional integrity. These materials should also pose less pressure on scarce resources, be harmless to human health, have a longer life and minimise operation and maintenance costs throughout the whole building's life cycle [28,29]. Life cycle assessment tools such as LCA, LCC, SLCA and the integration of the three into LCSA have assisted researchers in ascertaining the most sustainable materials with reduced embodied and operational burdens.

In Australia, Ximenes and Grant [30] performed an LCA study assessing the different components of a residential house. The authors reported that structural elements, such as bricks and concrete, accounted for up to 17% and 31% of whole-life GHG emissions, respectively. They estimated that the use of wood as a replacement for concrete in the sub-floor could decrease the total GHG fluxes by 31 to 56%. More recently, Jayalath, Navaratnam [31] compared the entire-life GHG emissions of the cross-laminated timber and reinforced concrete used as structural elements in mid-rise residential buildings in Australia. The authors reported that buildings using timber as structural material exhibited around 30% less carbon emissions compared to reinforced concrete buildings.

In the current market, there is a rich array of non-conventional materials that display lower impacts than their traditional counterparts [32]. Sustainable alternatives that have minimised burdens across their lifetime include materials that are or contain reused and/or recycled components and bio-based materials. From these options, bio-based materials present opportunities to mitigate the exhaustion of non-renewable resources [33] and reduce both embodied and operational impacts [34]. While traditional materials accumulate substantial embodied CO_2 during manufacturing and have minimal carbon storage capacity [35], their bio-based counterparts generally exert lower embodied GHG emissions and can sequester carbon during plant growth through photosynthesis [36].

Bio-based construction materials are formed by a plant-origin aggregate (e.g., flax, hemp, ramie, straw) mixed with an inorganic or organic binder [37]. The plant component acts as the reinforcing element, whereas the binder is used as a matrix. In the plant world, there are around 2000 different fibrous crops with the potential to be applied for bio-based materials [38]. Among them, industrial hemp (*Cannabis sativa* L.) stands out because of its fast growth, ability to withstand an array of climatic conditions and good thermal, hygric and acoustic insulation properties [39]. As a result of continuing research and industrial development, hemp has become the most used plant in bio-based construction materials [40], as well as the most studied [41].

Despite the increasing availability of non-conventional sustainable materials in the market, there are barriers to increasing their demand and use [42]. Adoption barriers include a lack of understanding of their environmental advantages, potential higher costs, potential higher use of labour and implications for the occupational health and safety of workers [43,44].

Australian Context

Australia's per capita GHG is the largest in the world [45] and the country has recently pledged a 43% GHG reduction target by 2030 as a pathway to achieve carbon neutrality by 2050 [46]. It is urgent for Australia's construction sector to reduce energy and material consumption to assist in the transition towards a net-zero emissions future [47,48].

Carbon-intensive materials, such as concrete and steel, dominate the Australian building landscape [43,49]. The majority of the current building stock has followed the Building Code of Australia (BCA) to achieve the required structural performance, regardless of the environmental impacts [50]. Since 2003, the National Construction Code (formed BCA) has adopted energy efficiency policies to reduce operational GHG emissions, neglecting mechanisms for mitigating the embodied impacts [8,20,51].

2. Research Motivation and Research Objectives

Under a business-as-usual scenario, Australia's built environment is expected to reduce the total life cycle GHG emissions by almost 80% by 2050, with embodied emissions contributing to 85% of the total fluxes [52]. In addition, there is no indication from the government that it will change this scenario through the implementation of enforcing instruments or incentives that address embodied GHG emissions [53]. The governance of embodied burdens requires promoting the use of sustainable materials to turn Australia's net-zero pledges into reality [8,43,48]. As such, hemp-based materials could offer several benefits to the Australian construction sector to meet the emission targets by reducing embodied emissions. In addition, hemp-based materials can help to alleviate the pressure over scarce non-renewable resources [54].

This context generated the question as to whether the hemp industry can improve the sustainability performance of the Australian construction sector. Research objectives have been defined to warrant a thorough review that addresses the research question. The first objective is to develop a detailed and concise examination of the advantages, drawbacks and latest progress of the use of hemp as an aggregate for construction materials at a global and national level. The second objective is to review the application of sustainability assessment tools for hemp-based construction materials and their main results. The third objective is to determine the research gap(s) so that key objectives can be developed for Australia's hemp industries to further reduce their GHG emissions from the infrastructure sector in a sustainable manner.

3. Review Methodology

To accomplish the objectives of this article, a scoping review of the existing literature was conducted using predefined keywords in the Scopus database. The data range was set for studies published between January 2000 and May 2023. The search was performed for keywords including 'hemp' AND 'construction material' OR 'building material' within their title, abstract or keywords; a following search was performed within the previous results with the keywords 'sustainability' OR 'life cycle assessment'; and in the same manner, another search was conducted within the previous results using the keyword 'Australia' (see Figure 1). A total of 470 publications were obtained for the first set of terms, 129 for the first following search and zero results for the second following search. Then, a new search was performed with the keywords 'Hemp' AND 'Australia'. After evaluating the title and abstract of the retrieved articles, 96 studies were considered and 409 were excluded because they failed to match with the objectives of this review.

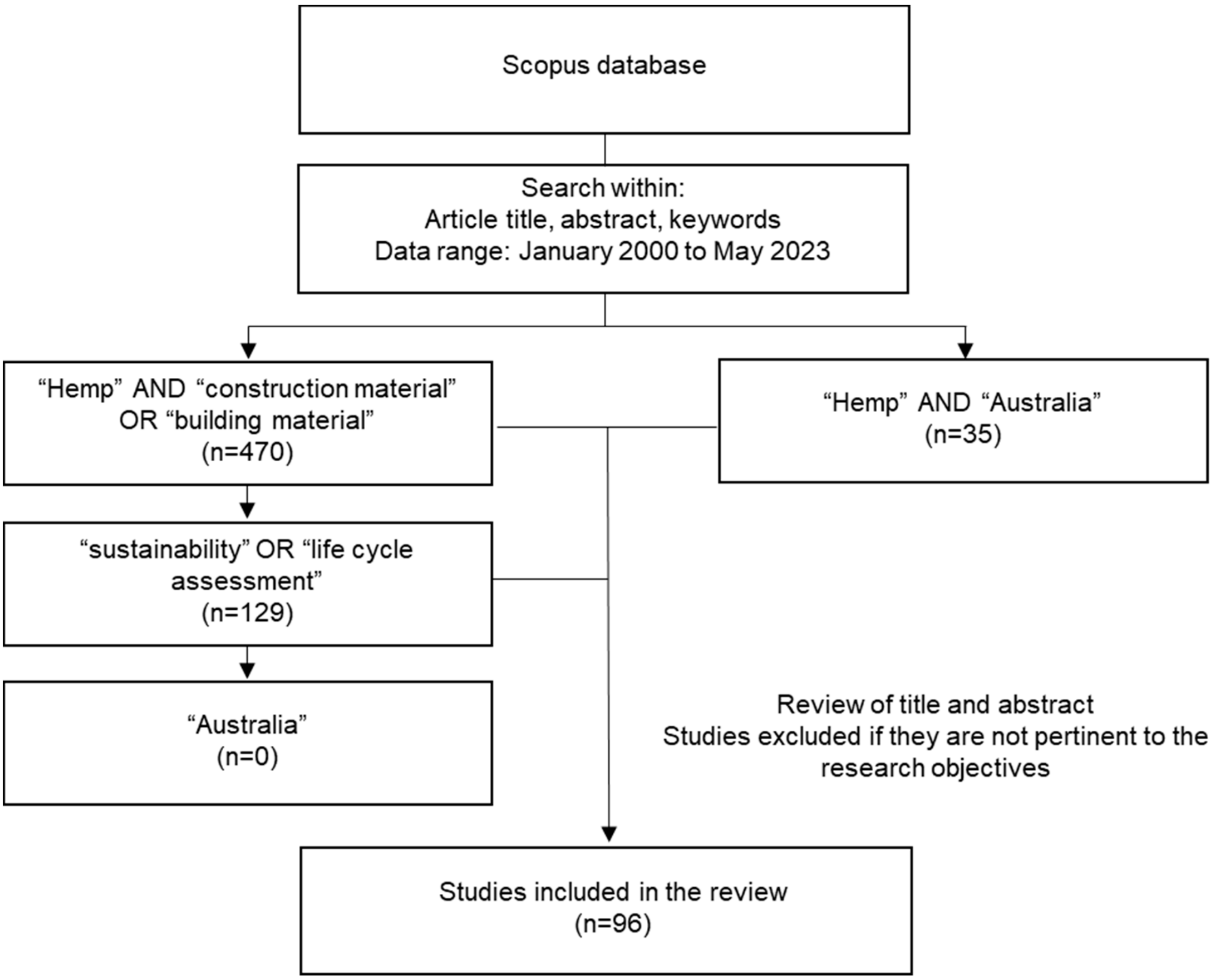

Figure 1. Flowchart of the review methodology.

Figure 2 shows the publication years of the studies retrieved according to the keywords used in the searches. Of the 505 studies obtained in total, 77% were published in the last decade, which highlights the growing interest in this topic globally and in Australia.

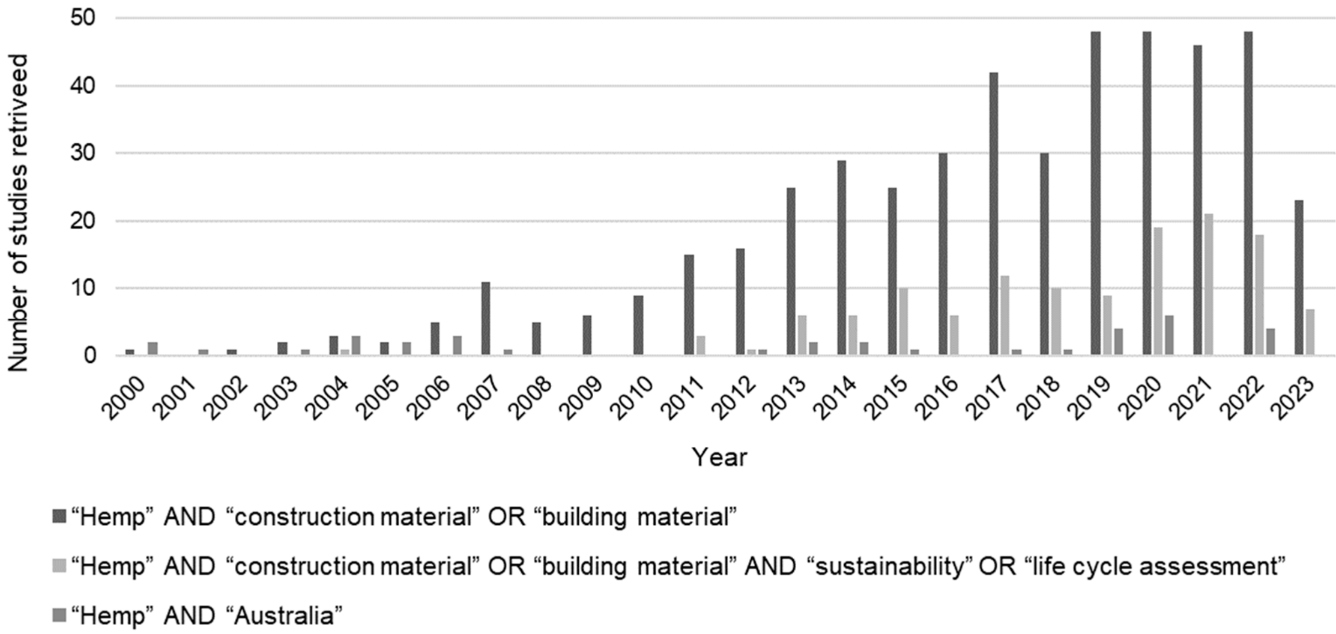

Figure 2. Time distribution and number of studies retrieved according to the keywords used in the search.

4. Industrial Hemp

4.1. Global Hemp Industry

Hemp, an annual herbaceous high-yielding crop native to central Asia [55], has been grown in an ample range of geographical zones and climatic conditions for centuries [56]. In contrast to other hemp varieties with a high content of psychoactive compounds (delta-9 tetrahydrocannabinol—THC), industrial hemp contains minimal quantities of THC and traditionally has been cultivated for fibre, seeds and medicine [57,58].

Hemp is one of the first fibre crops [59], as well as the main cash crop until the 19th century [60]. The introduction of cotton and synthetic fibres, and the prohibition of hemp in many countries due to its association with biotypes containing a high content of THC, led to a rapid decline in industrial hemp cultivation [61]. In the 1970s, the European Union (EU) reintroduced the legal cultivation of hemp varieties with a psychotropic content lower than 0.3% [62]. Along with legislative support, the EU has encouraged its hemp industry through economic aid for hemp growers and processors [63], generating renewed interest in this crop from various countries and industries [64]. Over the 1990s, the research and development of industrial hemp contributed to changes in the perception of this controversial plant [65].

During the following years, other industrialised economies, including Canada in 1998, Australia in 2017 and, more recently, the USA in 2018, reauthorised and reintroduced hemp cultivation with low THC content as an agricultural commodity, marking a renaissance in the emerging global hemp market [57]. Almost 50 countries now grow hemp legally for commercial and/or scientific purposes [38,66]. Globally, it is estimated that the area under hemp cultivation for grain is 11,422 hectares (ha) and 74,307 ha for fibre in 2021, with an increase of 117% and 63% compared to the levels recorded in 2010, respectively [67].

Australian Hemp Industry

Cannabis sativa cultivation is not novel in Australia [66]. The plant landed in the country with the first European colonisers at the end of the 18th century, and it was sold legally for textile and medicinal use until the beginning of the 20th century, when it was classified as a noxious weed [68]. During the 1980s and 1990s, some states modified their legislation to allow hemp cultivation for research and/or commercialisation [44]. In the

1990s, a formal distinction between industrial hemp and biotypes with high psychotropic content was introduced.

Tasmania started the first hemp trials in 1991 [68]. New South Wales, South Australia and Victoria followed in 1995, Queensland in 1996 and Western Australia (WA) in 1997. Over time, trials have examined several varieties of industrial hemp under different regional conditions and have reported promising results regarding this profitable crop [69–71].

As of November 2017, hemp foods were legalised nationwide [44]. In 2020, around 100 licensed hemp growers cultivated an estimated 2000 hectares [72], with Tasmania contributing the largest share of planted area [73]. Most hemp crops are harvested for grain and only 3% are used for hurds and fibre, which are mainly produced in WA (80 ha) and Victoria (30 ha) (see Figure 3).

(**a**) (**b**) (**c**)

Figure 3. (**a**) Hemp plantation for hurds and fibre in WA; (**b**) hemp fibres bailed; (**c**) different non-structural hemp-based building materials manufactured in WA.

4.2. Industrial Applications of Hemp

Hemp is a multipurpose crop that produces three main components: fibre, seeds and phytochemical compounds [57]. Hemp can be used as a phytoremediator for soils contaminated by heavy metals [74,75]. Because all plant parts (stem, seeds, leaves and flowers) find application in a myriad of end-use products [38,58], hemp is considered a valuable alternative material for the circular economy transition of various industries [37,76,77].

Recent developments in the areas of breeding, morphology and pathology have augmented hemp production to meet the demand for new industries. Today, hemp is used in carbon sequestration, bioplastics [39], cosmetics [78], bioenergy [79], automobile [80] and construction industries [61]. Currently, the paper, textile, food and construction sectors are the dominant markets for industrial hemp [58]. It is estimated that this versatile crop can be used for over 25,000 different products [81].

4.2.1. Hemp Production and Processing

Industrial hemp belongs to genetically diverse plants, both in terms of morphological and chemical features [82]. For this reason, hemp has been able to adapt to almost every geographical and climatic condition, even in contaminated soils [75,76]. Hemp is a tall, high-yielding, summer annual crop with a relatively short cropping period, usually from 70 to 140 days [39,83]. Hemp's ideal cultivation temperature ranges between 15 and 27 °C, albeit it can tolerate temperatures outside this range [79].

Industrial hemp is frequently touted as an ecological [77] and low cost crop [58] despite the fact that in many regions, it requires intensive fertilisation [84] and irrigation to obtain optimal biomass [66]. Although, hemp fertilisation requirements can be smaller than other commercial grains, such as maize [64]. Similarly, hemp usually has less problems with regard to pests and diseases, and generally outgrows most weeds; therefore, it requires comparatively less pesticide and herbicide application, which can help to alleviate both environmental impacts and costs to some extent [38]. Nevertheless, the specific characteristics of the production and processing of this fast-growing crop depend on the component to be produced [85] and the local conditions.

4.2.2. Hemp Fibres

Hemp stalks contain two main parts: fibres and hurds. Typically, the hurds comprise 60 to 70% of the stem dry matter [59,86]. To separate the fibres from the hurds, the stems undergo a four-step process: retting, breaking, scutching and hackling [39]. The quality of the hemp fibre is affected by various factors such as the crop production method, environmental conditions, crop maturity at harvest and the retting process [87].

Hemp is one of the strongest plant-based fibres [38]. Additionally, compared to its synthetic counterparts, hemp exhibits greater hygroscopicity, thermal and aseptic properties, better UV defense and fewer allergenic effects. These characteristics have amplified the application of hemp fibres further than the traditional textile and paper production [58]. Nowadays, the automobile, bioplastic and construction sectors have replaced some synthetic fibres with hemp elements to manufacture composites and other bio-based products.

Hemp hurds, which are considered a by-product with little commercial value [88], are usually used for mulch and livestock beddings [58]. Since the 1990s, the construction sector has been using hemp hurds for the manufacturing of building materials, including hemp concrete and hemp concrete blocks [89], in a textbook example of industrial symbiosis, where wastes of the hemp fibre industry are used as raw products for other high-earning industries, such as construction, allowing the full utilisation and valorisation of biomass resources.

4.2.3. Hemp Seeds

Hemp seeds have a high nutritional value [90], typically containing 25–35% oil, 20–30% protein and 20–30% starch [39], along with a broad range of vitamins and minerals [38,91]. Because of its nutritional content, hemp grains are often regarded as a rich source of plant-based protein, gaining popularity as food for humans and animals [87]. The quality of the seeds is determined by the content of oil, fatty acids and protein, which can vary according to the cultivar [66]. The seed oil can be used for cooking or as a raw product for the cosmetic [92] and biofuel industries [57]. The residual grain cake is usually used as protein rich fodder.

Research in hemp breeding is fostering the development of dual-purpose hemp varieties: grain and fibre [56,83]. However, both seed and biomass productivity depends on the species grown under a particular regional climate and soil conditions [93]. Despite the increasing availability of dual purposes varieties, hemp growers mainly set their production systems for a single purpose [66].

4.2.4. Phytochemicals

There are more than 100 known bioactive compounds found in hemp inflorescences and many more that are still under investigation [82]. These compounds have applications in cosmetic and therapeutic industries [66]. The two most abundant and known hemp phytochemicals are THC, which produces a psychotropic effect, and cannabidiol (CBD), which is non-intoxicating [90] and can be used for the treatment of various medical conditions [57]. Nowadays, CBD is the main active ingredient for many innovative products for medicinal and non-medicinal purposes [38].

5. Hemp-Based Construction Materials

Recent advances in hemp components are widening their field of application in the construction sector [94,95]. As a result, there is an ample range of different materials formed by hemp fibres and hurds mixed with binders and other additives that, according to their composition, are used in different building applications and are mainly divided in hemp concretes and insulation mats [37,85].

5.1. Hemp Concretes

Hemp concrete is the most common bio-based material used in construction and one of the largest studied [96], with the majority of research conducted in Europe [89]. Only a few studies have investigated the characteristics of hemp hurds farmed under Australian conditions as aggregates for hemp concretes, which obtained similar results to the research conducted in Europe [97].

Hemp concrete, also known as 'hempcrete', is a mixture of hemp hurds, binder (usually lime) and water [89,98], requires the use of gloves and respiration equipment to work with lime, and is considered Category 3 organ systemic toxicity classification for single exposure [99]. Hempcrete exhibits good technical characteristics, presents an alternative to conventional materials and can help to improve the comfort of residents [100]. Nevertheless, its performance strictly depends on the characteristics of the hemp hurds, the type of binder and their proportions in the mixture.

5.1.1. Thermal and Acoustic Insulation Properties

The high porosity of the hemp hurds provides low thermal conductivity to the hemp concrete, which translates to a high thermal insulation ability [89,101]. Lawrence, Fodde [102] compared the thermal performance of an experimental hemp concrete building against a timber framed building with walls insulated using mineral wool. The study reported that the external temperature variations for the hemp-derived building were significantly moderated internally compared to the performance of the wool-insulated building. Haik, Peled [86] investigated the thermal performance of test cells made with hemp concrete and cells produced with mineral-based materials (autoclaved aerated concrete, hollow concrete blocks and expanded polystyrene). The hemp concrete cells yielded better thermal performance compared to the cells made of conventional materials during summer. Yet, during winter, the cells made with autoclaved aerated concrete presented a slightly better thermal performance than the hemp-based cells. The high porosity of hemp hurds also has an impact on the acoustic properties of the hemp concrete [103]. Glé, Gourdon [104] concluded that hemp concretes made with lime binders and small hurd particles are good acoustic absorbents.

5.1.2. Hygroscopic Properties

Another characteristic of the hemp hurds is that they are made from different hydrophilic macromolecules, which translates to high hygroscopic behaviour [103]. Lawrence, Fodde [102] compared the humidity levels of the hemp concrete building with a mineral wool-insulated building. Their results showed that the internal relative humidity in the hemp-derived building is maintained at a remarkably stable level with respect to the analogous product. More recently, Asli, Brachelet [105] assessed the ability of hemp concrete to regulate indoor humidity conditions and suggested that it is a much better regulator than traditional materials, including cellular concrete, plaster and cement concrete. The high porosity of hemp hurds also has an impact on the acoustic properties of the hemp concrete [103].

5.1.3. Mechanical Properties

Hemp concrete is a lightweight material (dry density ranging from 250 to 400 kg/m^3) that shows low compressive strength [106]. Therefore, it is primarily used to construct non-load-bearing walls of timber-frame residential houses [37,96]. Despite the mechanical strength limitation, the use of hempcrete has rapidly spread over hundreds of low- and medium-rise buildings since the 1990s in a number of European countries, such as France, Great Britain, Germany and Italy [107,108], and lately is gaining popularity in Canada [89] and Australia [71].

5.2. Hemp-Based Insulation Mats

In construction, hemp fibres are used for manufacturing mats with good thermal and acoustic insulation properties [58]. Torres-Rivas, Palumbo [109] suggested that hemp-sourced insulation products can compete with their conventional counterparts in terms of thermal conductivity (around 0.040 W/m·K). Santoni, Bonfiglio [29] investigated ways to enhance the acoustic performance of hemp fibres through different chemical and mechanical processes. Their results showed that the sound absorption of hemp fibres can match the performance of traditional petroleum-based fibres after an alkaline treatment followed by combing processes.

6. Sustainability Implications of Hemp-Based Construction Materials

There is an increasing body of literature assessing the sustainability implications of hemp-based materials; however, this is still significantly lower than the number of publications evaluating their technical performance [95]. Most of the research has been conducted in European contexts and under climate zones different to Australia.

6.1. Hemp Concretes

6.1.1. Environmental Implications of Hemp Concretes

LCA-based studies have consistently reported hempcrete as a climate positive construction material, because the amount of CO_2 sequestered during plant growth and lime binder carbonation tends to be higher than the CO_2 released during the material manufacturing, transport and construction stages combined [36,110–114] (Table 1). It is worth mentioning that the production of lime and its application to neutralise Western Australia's acidic soil was found to increase the carbon footprint of crop production [115]. As such, hempcretes usually exert substantially lower embodied GHG emissions compared to traditional materials.

Table 1. Comparison of the life cycle CO_2 emissions of existing LCA studies on hemp concretes.

Location of the Study	Thermal Conductivity, W/m·K	U-Value, W/m^2·K	Carbon Footprint, kg CO_2-Equivalent	Reference
United Kingdom	0.057	0.19	−36.08	[111]
France	0.086	0.36	−1.6	[112]
Italy	0.067	0.27	−12.09	[110]
Latvia	0.075	0.18	−19.28	[113]
Canada	0.05–0.06	0.15	−15.27 to −8.92	[36]

Shang and Tariku [116] applied the LCA method to perform a comparative assessment of a residential hemp concrete building against a conventional split-insulated timber-frame building with the same thermal conductivity in Canada. The authors reported that the use of a hempcrete enclosure resulted in a reduction of embodied GHG emissions between 10 and 23%. Similarly, Di Capua, Paolotti [37] compared a hempcrete wall against a traditional wall with similar thermal insulation performance formed by perforated brick blocks with polystyrene insulation in Italy. The study concluded that the use of the hempcrete wall reduces CO_2-equivalent emissions by 86%.

In addition to measuring GHG emissions, some authors have assessed other environmental indicators associated with the life cycle of hemp concretes. LCA studies have shown that the farm stage, which serves as the primary stage of these materials, can exhibit higher impacts in terms of eutrophication, eco-toxicity [85], ozone layer depletion [117] and land use [37] compared to traditional materials.

6.1.2. Economic Implications of Hemp Concretes

The economic aspects of hemp concretes have received less attention. Agliata, Marino [54] compared the costs involved with the use of gypsum and hemp mixed with lime to be used as plasters during the refurbishment of an Italian house. The hemp plaster involved 37.5% more costs compared to the use of the gypsum-based plaster. Colli, Bataille [118] applied the eco-efficiency framework to assess the environmental and economic aspects of different insulation materials, including hemp concrete, cellulose, glass wool, polystyrene and polyurethane, throughout their life cycle. The study evaluated refurbishment scenarios for a family house in France, and found that in terms of environmental performance, the best scenario was the one using hempcrete, whereas the use of polyurethane showed the worst environmental performance. Conversely, hempcrete exhibited the worst economic performance due to its higher price, while polystyrene had the best cost performance. The eco-efficiency matrix resulted in a group of eco-efficient scenarios using different insulating materials that excluded hempcrete.

6.2. Hemp-Based Insulation Mats

6.2.1. Environmental Implications of Hemp-Based Insulation Mats

Compared to hemp concretes, the number of studies assessing the environmental aspects of hemp-based insulation materials across their life cycle is much smaller, but interestingly, they have reported similar results. Zampori, Dotelli [119] applied the LCA method to calculate the embodied CO_2 equivalent emissions of an insulation panel with a U-value of 0.2 $W/m^2{\cdot}K$, made by hemp fibres (85%) and polyester fibres (15%) in Italy. The study suggested that the hemp panel involved -4.28 kgCO_2-equivalent emissions. More recently, Hult and Karlsmo [120] conducted LCA and LCC assessments to compare a hemp-based insulation mat against glass wool in a one-storey house in Sweden. They reported that the GHG emissions associated to the hemp insulation were estimated to be 10% lower than the glass wool, with 20% higher costs than the latter.

6.2.2. Economic Implications of Hemp-Based Insulation Mats

The articles evaluated have consistently reported that hemp fibre insulation materials usually involve higher costs compared to their traditional counterparts [109]. Schulte, Lewandowski [33] indicated that traditional insulation materials, such as polystyrene and mineral wool, have a considerable cost advantage over hemp fibres in Germany. Similarly, Dickson and Pavía [34] investigated the cost performance (manufacturing cost and annual space heating cost) of a wide range of 21 insulation materials in Ireland. The study reported that rock wool, phenolic foam and glass mineral wool are cheaper options than hemp-based solutions.

7. Future Directions: Application of Sustainability Assessment Tools for Hemp-Based Construction Materials in Australia

As alluded to in the Section 1, Life Cycle Sustainability Assessment (LCSA) tools can be used to assess the performance of construction materials and identify the key factors affecting the TBL aspects of infrastructure projects. Hence, LCSA can assist in addressing adoption barriers for hemp-based construction materials, such as a lack of understanding of their environmental advantages, potential higher costs, potential higher use of labor and implications for the occupational health and safety of workers [43,44].

Except for an increasing number of LCA studies and a still limited number of LCCs for hemp-based construction materials, researchers have not yet utilised Social Life Cycle Assessment (SLCA) for determining their social implications. In a country such as Australia, where the hemp industry is still in its infancy but has tremendous potential in building applications, the use of TBL assessment tools is important to discern the strategies for designing hemp-based materials that are environmentally friendly, cost-competitive and improve social wellbeing.

An eco-efficiency framework has been used for assessing the environmental and economic aspects of sustainability using LCA and LCC, which can provide a basis for the adoption of environmentally friendly and cost-effective hemp-based materials [121]. The eco-efficiency framework, however, does not contemplate the social dimension of sustainability. This characteristic has been considered a weakness of this approach, as cost-competitive and environmentally friendly technologies could result in negative social consequences, such as job losses, human rights and poor working conditions [122].

Kloepffer [123] introduced a life cycle method that integrates the three dimensions of sustainability through the following scheme for a LCSA: LCSA = LCA + LCC + SLCA. Janjua, Sarker [14] has successfully implemented this framework for selecting sustainable building(s) for WA. Similarly, a LCSA approach that integrates the TBL objectives could assist in the decision-making for selecting hemp-based construction materials with the highest sustainability score.

Another important aspect of the LCA of plant-based products is that their environmental impacts vary across regions due to differences in the soil and climatic conditions. For example, the carbon footprints of biodiesel production were 37 kg CO_2 eq and 115 kg CO_2 equivalent for WA and South Africa, respectively [124]. Therefore, hemp production in the semi-arid climate of WA could markedly be different to its production in other parts of the world.

Figure 4 shows the future direction of the hemp-based research focusing on the construction materials (e.g., plaster board), where the social, economic and environmental data of pre-, on- and post- farm data will be converted into social, economic and environmental indicators, which will then be integrated into a single sustainability score for comparison with the competing products.

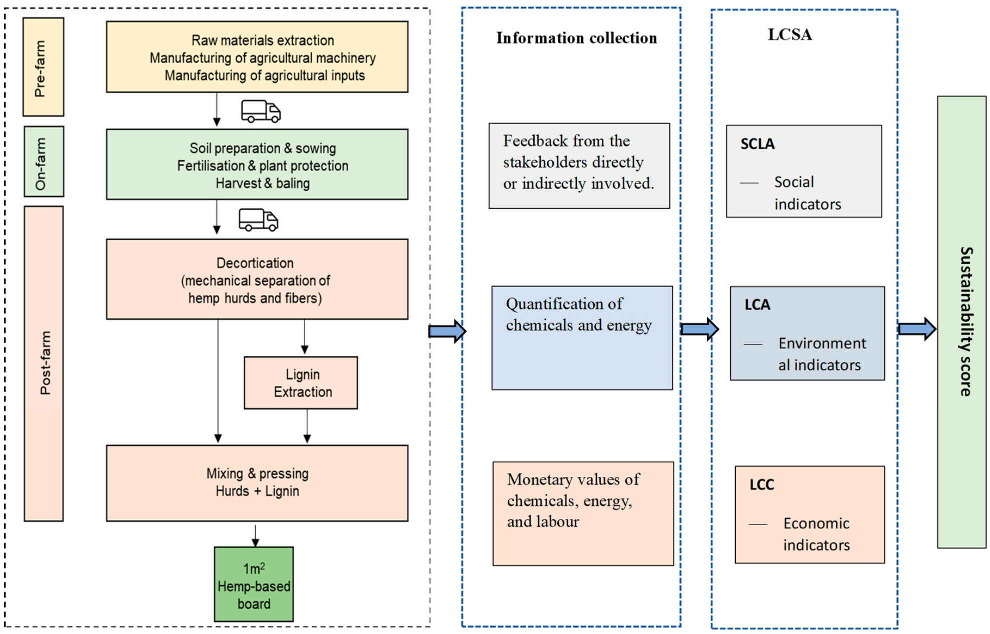

Figure 4. Future direction in hemp-based production research.

8. Conclusions

Progressively, the environmental impacts associated with construction materials are gaining attention as their contribution to the whole-life cycle burdens of the global construction sector is increasing, and Australia is no exception. As such, there is growing interest in the substitution of conventional construction materials with sustainable alternatives, such as bio-based materials. Among a myriad of plants with the potential to form construction materials, industrial hemp presents a promising solution because of its ability to sequester CO_2 through plant development, its fast growth, the reduced level of agricultural input requirements and its good technical features.

The reviewed literature showed that hemp-based construction materials, including hemp concretes and insulation mats, exhibit good thermal and acoustic insulation performance compared to conventional mineral-based alternatives. Hemp concretes, however, present low mechanical strength, which can be a limitation to the scalability of these products as structural components. This review also found that research on the sustainability implications of hemp-based materials is still limited and has mainly focused on assessing the environmental pillar, with an emphasis on GHG emissions across their life cycle and little consideration for economic and social dimensions. The results show that the use of hemp-based materials can help to alleviate the environmental impacts of the Australian construction sector and assist in achieving climate targets. However, they can involve higher costs. While these alternatives are not currently widespread in the country, a region-specific LCSA approach is needed to evaluate and understand the environmental, economic and social implications of their potential production and use in Australia, which can further assist in addressing adoption barriers.

Author Contributions: Conceptualisation, D.R.-A., M.J. and W.B.; writing—original draft preparation, D.R.-A.; writing—review and editing, D.R.-A., M.J. and W.B.; supervision, M.J. and W.B.; funding acquisition, M.J. and W.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by MIRRECO®, Food, Fibre and Land International Group and Curtin University through the Curtin HDR PhD scholarship (CF2206030041).

Data Availability Statement: Not applicable.

Acknowledgments: The authors gratefully acknowledge David Campbell and Daniel Taylor from the Margaret River Hemp Co. for their contribution concerning the description of hemp production and processing in WA, and Daniel Patterson from the Arcforms Architectural Design Studio, for his contributions during the review phase regarding the design and construction materials and practices. The authors greatly acknowledge Richard Evans, Robert Edkins and Warrick Fort for reviewing and editing the report.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Chen, Z.-S.; Martínez, L.; Chang, J.-P.; Wang, X.-J.; Xionge, S.-H.; Chin, K.-S. Sustainable building material selection: A QFD- and ELECTRE III-embedded hybrid MCGDM approach with consensus building. *Eng. Appl. Artif. Intell.* **2019**, *85*, 783–807.
2. Tunji-Olayeni, P.; Omuh, I.; Afolabi, A.; Ojelabi, R.; Eshofonie, E. Effects of construction activities on the planetary boundaries. *J. Phys. Conf. Ser.* **2019**, *1299*, 012005.
3. Tunji-Olayeni, P.; Omuh, I.; Afolabi, A.; Ojelabi, R.; Eshofonie, E. Climate change mitigation and adaptation strategies for construction activities within planetary boundaries: Limitations of developing countries. *J. Phys. Conf. Ser.* **2019**, *1299*, 012006. [CrossRef]
4. Goel, A.; Ganesh, L.; Kaur, A. Sustainability integration in the management of construction projects: A morphological analysis of over two decades' research literature. *J. Clean. Prod.* **2019**, *236*, 117676.
5. Marinova, S.; Deetman, S.; van der Voet, E.; Daioglou, V. Global construction materials database and stock analysis of residential buildings between 1970–2050. *J. Clean. Prod.* **2020**, *247*, 119146.
6. UNEP. *2021 Global Status Report for Buildings and Construction: Towards a Zero-Emission Efficient and Resilient Buildings and Construction Sector*; United Nations Environment Programme: Nairobi, Kenya, 2021.

7. Rakhshan, K.; Morel, J.-C.; Alaka, H.; Charef, R. Components reuse in the building sector—A systematic review. *Waste Manag. Res. J. Sustain. Circ. Econ.* **2020**, *38*, 347–370.
8. Yu, M.; Wiedmann, T.; Crawford, R.; Tait, C. The carbon footprint of Australia's construction sector. *Procedia Eng.* **2017**, *180*, 211–220.
9. Pickin, J.; Wardle, C.; O'Farrell, K.; Stovell, L.; Nyunt, P.; Guazzo, S.; Lin, Y.; Caggiati-Shortell, G.; Chakma, P.; Edwards, C.; et al. *National Waste Report 2022*; Department of Climate Change, Energy, the Environment and Water: Canberra, Australia, 2023.
10. zu Ermgassen, S.O.; Drewniok, M.P.; Bull, J.W.; Walker, C.M.C.; Mancini, M.; Ryan-Collins, J.; Serrenho, A.C. A home for all within planetary boundaries: Pathways for meeting England's housing needs without transgressing national climate and biodiversity goals. *Ecol. Econ.* **2022**, *201*, 107562.
11. WCED. *Our Common Future*; World Commission on Environment and Development: Ottawa, ON, Canada, 1987.
12. Wu, L.; Huang, K.; Ridoutt, B.G.; Yu, Y.; Chen, Y. A planetary boundary-based environmental footprint family: From impacts to boundaries. *Sci. Total. Environ.* **2021**, *785*, 147383.
13. Lei, H.; Li, L.; Yang, W.; Bian, Y.; Li, C.-Q. An analytical review on application of life cycle assessment in circular economy for built environment. *J. Build. Eng.* **2021**, *44*, 103374.
14. Janjua, S.Y.; Sarker, P.K.; Biswas, W.K. A Review of Residential Buildings' Sustainability Performance Using a Life Cycle Assessment Approach. *J. Sustain. Res.* **2019**, *1*, 1–29.
15. Klöpffer, W. Life-Cycle based methods for sustainable product development. *Int. J. Life Cycle Assess.* **2003**, *8*, 157–159. [CrossRef]
16. Lawania, K.; Biswas, W.K. Application of life cycle assessment approach to deliver low carbon houses at regional level in Western Australia. *Int. J. Life Cycle Assess.* **2017**, *23*, 204–224.
17. Mah, C.M.; Fujiwara, T.; Ho, C.S. Life cycle assessment and life cycle costing toward eco-efficiency concrete waste management in Malaysia. *J. Clean. Prod.* **2018**, *172*, 3415–3427.
18. Filho, M.V.A.P.M.; da Costa, B.B.F.; Najjar, M.; Figueiredo, K.V.; de Mendonça, M.B.; Haddad, A.N. Sustainability Assessment of a Low-Income Building: A BIM-LCSA-FAHP-Based Analysis. *Buildings* **2022**, *12*, 181.
19. Cabeza, L.F.; Rincón, L.; Vilariño, V.; Pérez, G.; Castell, A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renew. Sustain. Energy Rev.* **2014**, *29*, 394–416.
20. Schmidt, M.; Crawford, R.H.; Warren-Myers, G. Quantifying Australia's life cycle greenhouse gas emissions for new homes. *Energy Build.* **2020**, *224*, 110287.
21. Sicignano, E.; Di Ruocco, G.; Melella, R. Mitigation Strategies for Reduction of Embodied Energy and Carbon, in the Construction Systems of Contemporary Quality Architecture. *Sustainability* **2019**, *11*, 3806. [CrossRef]
22. Chel, A.; Kaushik, G. Renewable energy technologies for sustainable development of energy efficient building. *Alex. Eng. J.* **2018**, *57*, 655–669.
23. Röck, M.; Saade, M.R.M.; Balouktsi, M.; Rasmussen, F.N.; Birgisdottir, H.; Frischknecht, R.; Habert, G.; Lützkendorf, T.; Passer, A. Embodied GHG emissions of buildings—The hidden challenge for effective climate change mitigation. *Appl. Energy* **2020**, *258*, 114107.
24. Robati, M.; Daly, D.; Kokogiannakis, G. A method of uncertainty analysis for whole-life embodied carbon emissions (CO_2-e) of building materials of a net-zero energy building in Australia. *J. Clean. Prod.* **2019**, *225*, 541–553. [CrossRef]
25. Asdrubali, F.; Ballarini, I.; Corrado, V.; Evangelisti, L.; Grazieschi, G.; Guattari, C. Energy and environmental payback times for an NZEB retrofit. *Build. Environ.* **2019**, *147*, 461–472. [CrossRef]
26. Kristjansdottir, T.F.; Heeren, N.; Andresen, I.; Brattebø, H. Comparative emission analysis of low-energy and zero-emission buildings. *Build. Res. Inf.* **2018**, *46*, 367–382. [CrossRef]
27. Al-Atesh, E.A.; Rahmawati, Y.; Zawawi, N.A.W.A.; Utomo, C. A decision-making model for supporting selection of green building materials. *Int. J. Constr. Manag.* **2021**, *23*, 922–933. [CrossRef]
28. Sahlol, D.G.; Elbeltagi, E.; Elzoughiby, M.; Elrahman, M.A. Sustainable building materials assessment and selection using system dynamics. *J. Build. Eng.* **2021**, *35*, 101978. [CrossRef]
29. Santoni, A.; Bonfiglio, P.; Fausti, P.; Marescotti, C.; Mazzanti, V.; Mollica, F.; Pompoli, F. Improving the sound absorption performance of sustainable thermal insulation materials: Natural hemp fibres. *Appl. Acoust.* **2019**, *150*, 279–289. [CrossRef]
30. Ximenes, F.A.; Grant, T. Quantifying the greenhouse benefits of the use of wood products in two popular house designs in Sydney, Australia. *Int. J. Life Cycle Assess.* **2013**, *18*, 891–908.
31. Jayalath, A.; Navaratnam, S.; Ngo, T.; Mendis, P.; Hewson, N.; Aye, L. Life cycle performance of Cross Laminated Timber mid-rise residential buildings in Australia. *Energy Build.* **2020**, *223*, 110091. [CrossRef]
32. Krueger, K.; Stoker, A.; Gaustad, G. "Alternative" materials in the green building and construction sector: Examples, barriers, and environmental analysis. *Smart Sustain. Built Environ.* **2019**, *8*, 270–291. [CrossRef]
33. Schulte, M.; Lewandowski, I.; Pude, R.; Wagner, M. Comparative life cycle assessment of bio-based insulation materials: Environmental and economic performances. *GCB Bioenergy* **2021**, *13*, 979–998. [CrossRef]
34. Dickson, T.; Pavía, S. Energy performance, environmental impact and cost of a range of insulation materials. *Renew. Sustain. Energy Rev.* **2021**, *140*, 110752. [CrossRef]
35. Churkina, G.; Organschi, A.; Reyer, C.P.O.; Ruff, A.; Vinke, K.; Liu, Z.; Reck, B.K.; Graedel, T.E.; Schellnhuber, H.J. Buildings as a global carbon sink. *Nat. Sustain.* **2020**, *3*, 269–276. [CrossRef]

36. Heidari, M.D.; Lawrence, M.; Blanchet, P.; Amor, B. Regionalised Life Cycle Assessment of Bio-Based Materials in Construction; the Case of Hemp Shiv Treated with Sol-Gel Coatings. *Materials* **2019**, *12*, 2987. [CrossRef]
37. Di Capua, S.E.; Paolotti, L.; Moretti, E.; Rocchi, L.; Boggia, A. Evaluation of the Environmental Sustainability of Hemp as a Building Material, through Life Cycle Assessment. *Environ. Clim. Technol.* **2021**, *25*, 1215–1228. [CrossRef]
38. Zhao, X.; Wei, X.; Guo, Y.; Qiu, C.; Long, S.; Wang, Y.; Qiu, H. Industrial Hemp—An Old but Versatile Bast Fiber Crop. *J. Nat. Fibers* **2022**, *19*, 6269–6282. [CrossRef]
39. Ahmed, A.T.M.F.; Islam, Z.; Mahmud, S.; Sarker, E.; Islam, R. Hemp as a potential raw material toward a sustainable world: A review. *Heliyon* **2022**, *8*, e08753. [CrossRef] [PubMed]
40. Ntimugura, F.; Vinai, R.; Harper, A.B.; Walker, P. Environmental performance of miscanthus-lime lightweight concrete using life cycle assessment: Application in external wall assemblies. *Sustain. Mater. Technol.* **2021**, *28*, e00253. [CrossRef]
41. Mouton, L.; Allacker, K.; Röck, M. Bio-based building material solutions for environmental benefits over conventional construction products–Life cycle assessment of regenerative design strategies (1/2). *Energy Build.* **2023**, *282*, 112767. [CrossRef]
42. Figueiredo, K.; Pierott, R.; Hammad, A.W.; Haddad, A. Sustainable material choice for construction projects: A Life Cycle Sustainability Assessment framework based on BIM and Fuzzy-AHP. *Build. Environ.* **2021**, *196*, 107805. [CrossRef]
43. Soonsawad, N.; Martinez, R.M.; Schandl, H. Material demand, and environmental and climate implications of Australia's building stock: Current status and outlook to 2060. *Resour. Conserv. Recycl.* **2022**, *180*, 106143. [CrossRef]
44. Davidson, M.; Reed, S.; Oosthuizen, J.; O'donnell, G.; Gaur, P.; Cross, M.; Dennis, G. Occupational health and safety in cannabis production: An Australian perspective. *Int. J. Occup. Environ. Health* **2018**, *24*, 75–85. [CrossRef] [PubMed]
45. Acheampong, A.O.; Dzator, J.; Amponsah, M. Analyzing the role of economic globalization in achieving carbon neutrality in Australia. *Int. J. Sustain. Dev. World Ecol.* **2022**, *29*, 559–578. [CrossRef]
46. DCCEEW. Australia's Emissions Projections. 2022. Available online: https://www.dcceew.gov.au/climate-change/publications/australias-emissions-projections-2022 (accessed on 10 March 2023).
47. Lu, Y.; Karunasena, G.; Liu, C. Issues in compliance with low-carbon requirements in the Australian residential building industry. In Proceedings of the 45th Australasian Universities Building Education Association (AUBEA) Conference, Sydney, Australia, 23–25 November 2022.
48. Allen, C.; Oldfield, P.; Teh, S.H.; Wiedmann, T.; Langdon, S.; Yu, M.; Yang, J. Modelling ambitious climate mitigation pathways for Australia's built environment. *Sustain. Cities Soc.* **2022**, *77*, 103554. [CrossRef]
49. Allen, C.; Oldfield, P.; Teh, S.H.; Wiedmann, T.; Langdon, S.; Yu, M.; Yang, J. The embodied carbon of mass timber and concrete buildings in Australia: An uncertainty analysis. *Build. Environ.* **2022**, *214*, 108944.
50. Islam, H.; Jollands, M.; Setunge, S. Life cycle assessment and life cycle cost implication of residential buildings—A review. *Renew. Sustain. Energy Rev.* **2015**, *42*, 129–140. [CrossRef]
51. Curmi, L.; Weththasinghe, K.K.; Tariq, M.A.U.R. Global Policy Review on Embodied Flows: Recommendations for Australian Construction Sector. *Sustainability* **2022**, *14*, 14628. [CrossRef]
52. Vickers, J.; Warmerdam, S.; Mitchell, S.; Sullivan, N. *Embodied Carbon & Embodied Energy in Australia's Buildings*; Green Building Council of Australia (GBCA): Barangaroo, NSW, Australia, 2021; p. 75.
53. Skillington, K.; Crawford, R.H.; Warren-Myers, G.; Davidson, K. A review of existing policy for reducing embodied energy and greenhouse gas emissions of buildings. *Energy Policy* **2022**, *168*, 112920. [CrossRef]
54. Agliata, R.; Marino, A.; Mollo, L.; Pariso, P. Historic Building Energy Audit and Retrofit Simulation with Hemp-Lime Plaster—A Case Study. *Sustainability* **2020**, *12*, 4620. [CrossRef]
55. Islam, M.M.; Rengel, Z.; Storer, P.; Siddique, K.H.M.; Solaiman, Z.M. Industrial Hemp (*Cannabis sativa* L.) Varieties and Seed Pre-Treatments Affect Seed Germination and Early Growth of Seedlings. *Agronomy* **2021**, *12*, 6. [CrossRef]
56. Salentijn, E.M.J.; Zhang, Q.; Amaducci, S.; Yang, M.; Trindade, L.M. New developments in fiber hemp (*Cannabis sativa* L.) breeding. *Ind. Crop. Prod.* **2015**, *68*, 32–41. [CrossRef]
57. Schluttenhofer, C.; Yuan, L. Challenges towards Revitalizing Hemp: A Multifaceted Crop. *Trends Plant Sci.* **2017**, *22*, 917–929. [CrossRef]
58. Crini, G.; Lichtfouse, E.; Chanet, G.; Morin-Crini, N. Applications of hemp in textiles, paper industry, insulation and building materials, horticulture, animal nutrition, food and beverages, nutraceuticals, cosmetics and hygiene, medicine, agrochemistry, energy production and environment: A review. *Environ. Chem. Lett.* **2020**, *18*, 1451–1476. [CrossRef]
59. Struik, P.C.; Amaducci, S.; Bullard, M.J.; Stutterheim, N.C.; Venturi, G.; Cromack, H.T.H. Agronomy of fibre hemp (*Cannabis sativa* L.) in Europe. *Ind. Crop. Prod.* **2000**, *11*, 107–118. [CrossRef]
60. Zatta, A.; Monti, A.; Venturi, G. Eighty Years of Studies on Industrial Hemp in the Po Valley (1930—2010). *J. Nat. Fibers* **2012**, *9*, 180–196. [CrossRef]
61. Campiglia, E.; Gobbi, L.; Marucci, A.; Rapa, M.; Ruggieri, R.; Vinci, G. Hemp Seed Production: Environmental Impacts of *Cannabis Sativa* L. Agronomic Practices by Life Cycle Assessment (LCA) and Carbon Footprint Methodologies. *Sustainability* **2020**, *12*, 6570. [CrossRef]
62. Piluzza, G.; Delogu, G.; Cabras, A.; Marceddu, S.; Bullitta, S. Differentiation between fiber and drug types of hemp (Cannabis sativa L.) from a collection of wild and domesticated accessions. *Genet. Resour. Crop. Evol.* **2013**, *60*, 2331–2342. [CrossRef]
63. Vantreese, V.L. Hemp support: Evolution in EU regulation. *J. Ind. Hemp* **2002**, *7*, 17–31. [CrossRef]
64. Fike, J. Industrial Hemp: Renewed Opportunities for an Ancient Crop. *Crit. Rev. Plant Sci.* **2016**, *35*, 406–424. [CrossRef]

65. Phipps, B.; Schluttenhofer, C. Perspectives of industrial hemp cultivation. In *Industrial Hemp: Food and Nutraceutical Applications*; Pojicć, M., Tiwari, B.K., Eds.; Elsevier Science & Technology: San Diego, CA, USA, 2022; pp. 1–36.
66. Burton, R.A.; Andres, M.; Cole, M.; Cowley, J.M.; Augustin, M.A. Industrial hemp seed: From the field to value-added food ingredients. *J. Cannabis Res.* **2022**, *4*, 1–13. [CrossRef]
67. FAOSTAT. (Ed.) *Food and Agriculture Data*; FAOSTAT: Rome, Italy, 2023.
68. Montoya, D. *Hemp as Fibre and Food? Regulatory Developments and Current Issues*; NSW Parliamentary Research Service: Sydney, NSW, Australia, 2016.
69. Cole, C.; Zurbo, B. Industrial hemp—A new crop for NSW. *Primefacts* **2008**, *801*, 1–6.
70. Cooper, J.; Unkovich, M.; O'Leary, G. The growth and development of industrial hemp (*Cannabis sativa*) in central western New South Wales. In Proceedings of the 11th Australian Agronomy Conference, Geelong, VIC, Australia, 2–6 February 2003.
71. Clarke, D. Hemp, hemp masonry and hempcrete: Inside the budding regenerative materials industry. *Sanctuary Mod. Green Homes* **2018**, *43*, 76–80.
72. Dal Santo, P. *Australian Industrial Hemp Industry: Pesticide Review and Evaluation Program*; AgriFutures Australia: Wagga Wagga, Australia, 2022.
73. Jefferies, S. *Australian Industrial Hemp Strategic RD&E Plan (2022–2027)*; AgriFutures Australia: Wagga Wagga, Australia, 2022; p. 25.
74. Placido, D.F.; Lee, C.C. Potential of Industrial Hemp for Phytoremediation of Heavy Metals. *Plants* **2022**, *11*, 595. [CrossRef] [PubMed]
75. Linger, P.; Müssig, J.; Fischer, H.; Kobert, J. Industrial hemp (*Cannabis sativa* L.) growing on heavy metal contaminated soil: Fibre quality and phytoremediation potential. *Ind. Crop. Prod.* **2002**, *16*, 33–42. [CrossRef]
76. Wu, Y.; Trejo, H.X.; Chen, G.; Li, S. Phytoremediation of contaminants of emerging concern from soil with industrial hemp (*Cannabis sativa* L.): A review. *Environ. Dev. Sustain.* **2021**, *23*, 14405–14435. [CrossRef]
77. Sorrentino, G. Introduction to emerging industrial applications of cannabis (*Cannabis sativa* L.). *Rend. Lince-Sci. Fis. Nat.* **2021**, *32*, 233–243. [CrossRef]
78. Mark, T.B.; Shepherd, J.; Olson, D.W.; Snell, W.; Proper, S.; Thornsbury, S. *Economic Viability of Industrial Hemp in the United States: A Review of State Pilot Programs*; Economic Research Service: Washington, DC, USA, 2020.
79. Parvez, A.M.; Lewis, J.D.; Afzal, M.T. Potential of industrial hemp (Cannabis sativa L.) for bioenergy production in Canada: Status, challenges and outlook. Renew. *Sustain. Energy Rev.* **2021**, *141*, 110784. [CrossRef]
80. Mansor, M.R.; Salit, M.S.; Zainudin, E.S.; Aziz, N.A.; Ariff, H. Life Cycle Assessment of Natural Fiber Polymer Composites. In *Agricultural Biomass Based Potential Materials*; Springer Science and Business Media LLC.: Berlin/Heidelberg, Germany, 2015; pp. 121–141.
81. Gutierrez-Moscardo, O.; Canet, M.; Gomez-Caturla, J.; Lascano, D.; Fages, E.; Sanchez-Nacher, L. Sustainable materials with high insulation capacity obtained from wastes from hemp industry processed by wet-laid. *Text. Res. J.* **2022**, *92*, 1098–1112. [CrossRef]
82. Strzelczyk, M.; Lochynska, M.; Chudy, M. Systematics and Botanical Characteristics of Industrial Hemp *Cannabis Sativa* L. *J. Nat. Fibers* **2021**, *19*, 5804–5826. [CrossRef]
83. Humphries, T.; Florentine, S. Cultivation of low tetrahydrocannabinol (THC) *Cannabis sativa* L. cultivation in Victoria, Australia: Do we know enough? *Aust. J. Crop. Sci.* **2019**, *13*, 911–919. [CrossRef]
84. Deng, G.; Du, G.; Yang, Y.; Bao, Y.; Liu, F. Planting Density and Fertilization Evidently Influence the Fiber Yield of Hemp (*Cannabis sativa* L.). *Agronomy* **2019**, *9*, 368. [CrossRef]
85. Ingrao, C.; Giudice, A.L.; Bacenetti, J.; Tricase, C.; Dotelli, G.; Fiala, M.; Siracusa, V.; Mbohwa, C. Energy and environmental assessment of industrial hemp for building applications: A review. *Renew. Sustain. Energy Rev.* **2015**, *51*, 29–42. [CrossRef]
86. Haik, R.; Peled, A.; Meir, I. The thermal performance of lime hemp concrete (LHC) with alternative binders. *Energy Build.* **2020**, *210*, 109740. [CrossRef]
87. Rehman, M.; Fahad, S.; Du, G.; Cheng, X.; Yang, Y.; Tang, K.; Liu, L.; Liu, F.H.; Deng, G. Evaluation of hemp (*Cannabis sativa* L.) as an industrial crop: A review. *Environ. Sci. Pollut. Res.* **2021**, *28*, 52832–52843. [CrossRef]
88. Liu, S.; Ge, L.; Gao, S.; Zhuang, L.; Zhu, Z.; Wang, H. Activated carbon derived from bio-waste hemp hurd and retted hemp hurd for CO_2 adsorption. *Compos. Commun.* **2017**, *5*, 27–30. [CrossRef]
89. Barbhuiya, S.; Das, B.B. A comprehensive review on the use of hemp in concrete. *Constr. Build. Mater.* **2022**, *341*, 127857. [CrossRef]
90. Farinon, B.; Costantini, L.; Molinari, R.; Di Matteo, G.; Garzoli, S.; Ferri, S.; Ceccantoni, B.; Mannina, L.; Merendino, N. Effect of malting on nutritional and antioxidant properties of the seeds of two industrial hemp (*Cannabis sativa* L.) cultivars. *Food Chem.* **2022**, *370*, 131348. [CrossRef]
91. Ascrizzi, R.; Ceccarini, L.; Tavarini, S.; Flamini, G.; Angelini, L.G. Valorisation of hemp inflorescence after seed harvest: Cultivation site and harvest time influence agronomic characteristics and essential oil yield and composition. *Ind. Crop. Prod.* **2019**, *139*, 111541. [CrossRef]
92. Oomah, B.; Busson, M.; Godfrey, D.V.; Drover, J.C. Characteristics of hemp (*Cannabis sativa* L.) seed oil. *Food Chem.* **2002**, *76*, 33–43. [CrossRef]
93. Tang, K.; Struik, P.; Yin, X.; Thouminot, C.; Bjelková, M.; Stramkale, V.; Amaducci, S. Comparing hemp (*Cannabis sativa* L.) cultivars for dual-purpose production under contrasting environments. *Ind. Crop. Prod.* **2016**, *87*, 33–44. [CrossRef]

94. Salentijn, E.M.J.; Petit, J.; Trindade, L.M. The Complex Interactions Between Flowering Behavior and Fiber Quality in Hemp. *Front. Plant Sci.* **2019**, *10*, 614. [CrossRef]
95. Sáez-Pérez, M.; Brümmer, M.; Durán-Suárez, J. A review of the factors affecting the properties and performance of hemp aggregate concretes. *J. Build. Eng.* **2020**, *31*, 101323. [CrossRef]
96. Bumanis, G.; Korjakins, A.; Bajare, D. Environmental Benefit of Alternative Binders in Construction Industry: Life Cycle Assessment. *Environments* **2022**, *9*, 6. [CrossRef]
97. Delhomme, F.; Hajimohammadi, A.; Almeida, A.; Jiang, C.; Moreau, D.; Gan, Y.; Wang, X.; Castel, A. Physical properties of Australian hurd used as aggregate for hemp concrete. *Mater. Today Commun.* **2020**, *24*, 100986. [CrossRef]
98. Arehart, J.H.; Nelson, W.S.; Srubar, W.V., III. On the theoretical carbon storage and carbon sequestration potential of hempcrete. *J. Clean. Prod.* **2020**, *266*, 121846. [CrossRef]
99. Boral. *Boral Cement Safety Data Sheet*; Risk Management Technologies: Perth, Australia, 2015.
100. Benfratello, S.; Capitano, C.; Peri, G.; Rizzo, G.; Scaccianoce, G.; Sorrentino, G. Thermal and structural properties of a hemp–lime biocomposite. *Constr. Build. Mater.* **2013**, *48*, 745–754. [CrossRef]
101. Haik, R.; Meir, I.A.; Peled, A. Lime Hemp Concrete with Unfired Binders vs. Conventional Building Materials: A Comparative Assessment of Energy Requirements and CO_2 Emissions. *Energies* **2023**, *16*, 708. [CrossRef]
102. Lawrence, M.; Fodde, E.; Paine, K.; Walker, P. Hygrothermal Performance of an Experimental Hemp-Lime Building. *Key Eng. Mater.* **2012**, *517*, 413–421. [CrossRef]
103. Gourlay, E.; Glé, P.; Marceau, S.; Foy, C.; Moscardelli, S. Effect of water content on the acoustical and thermal properties of hemp concretes. *Constr. Build. Mater.* **2017**, *139*, 513–523. [CrossRef]
104. Glé, P.; Gourdon, E.; Arnaud, L. Acoustical properties of materials made of vegetable particles with several scales of porosity. *Appl. Acoust.* **2011**, *72*, 249–259. [CrossRef]
105. Asli, M.; Brachelet, F.; Sassine, E.; Antczak, E. Thermal and hygroscopic study of hemp concrete in real ambient conditions. *J. Build. Eng.* **2021**, *44*, 102612. [CrossRef]
106. Arnaud, L.; Gourlay, E. Experimental study of parameters influencing mechanical properties of hemp concretes. *Constr. Build. Mater.* **2012**, *28*, 50–56. [CrossRef]
107. Florentin, Y.; Pearlmutter, D.; Givoni, B.; Gal, E. A life-cycle energy and carbon analysis of hemp-lime bio-composite building materials. *Energy Build.* **2017**, *156*, 293–305. [CrossRef]
108. Stevulova, N.; Kidalova, L.; Junak, J.; Cigasova, J.; Terpakova, E. Effect of Hemp Shive Sizes on Mechanical Properties of Lightweight Fibrous Composites. *Procedia Eng.* **2012**, *42*, 496–500. [CrossRef]
109. Torres-Rivas, A.; Palumbo, M.; Haddad, A.; Cabeza, L.F.; Jiménez, L.; Boer, D. Multi-objective optimisation of bio-based thermal insulation materials in building envelopes considering condensation risk. *Appl. Energy* **2018**, *224*, 602–614. [CrossRef]
110. Jami, T.; Karade, S.R.; Singh, L.P. A review of the properties of hemp concrete for green building applications. *J. Clean. Prod.* **2019**, *239*, 117852. [CrossRef]
111. Arrigoni, A.; Pelosato, R.; Melià, P.; Ruggieri, G.; Sabbadini, S.; Dotelli, G. Life cycle assessment of natural building materials: The role of carbonation, mixture components and transport in the environmental impacts of hempcrete blocks. *J. Clean. Prod.* **2017**, *149*, 1051–1061. [CrossRef]
112. Ip, K.; Miller, A. Life cycle greenhouse gas emissions of hemp–lime wall constructions in the UK. *Resour. Conserv. Recycl.* **2012**, *69*, 1–9. [CrossRef]
113. Pretot, S.; Collet, F.; Garnier, C. Life cycle assessment of a hemp concrete wall: Impact of thickness and coating. *Build. Environ.* **2014**, *72*, 223–231. [CrossRef]
114. Sinka, M.; Van den Heede, P.; De Belie, N.; Bajare, D.; Sahmenko, G.; Korjakins, A. Comparative life cycle assessment of magnesium binders as an alternative for hemp concrete. *Resour. Conserv. Recycl.* **2018**, *133C*, 288–299. [CrossRef]
115. Barton, L.; Thamo, T.; Engelbrecht, D.; Biswas, W.K. Does growing grain legumes or applying lime cost effectively lower greenhouse gas emissions from wheat production in a semi-arid climate? *J. Clean. Prod.* **2014**, *83*, 194–203. [CrossRef]
116. Shang, Y.; Tariku, F. Hempcrete building performance in mild and cold climates: Integrated analysis of carbon footprint, energy, and indoor thermal and moisture buffering. *Build. Environ.* **2021**, *206*, 108377. [CrossRef]
117. Aversa, P.; Daniotti, B.; Dotelli, G.; Marzo, A.; Tripepi, C.; Sabbadini, S.; Lauriola, P.; Luprano, V.A.M. Thermo-hygrometric behavior of hempcrete walls for sustainable building construction in the Mediterranean area. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *296*, 012020. [CrossRef]
118. Colli, C.; Bataille, A.; Antczak, E. Investigating eco-efficiency procedure to compare refurbishment scenarios with different insulating materials. *Procedia CIRP* **2020**, *90*, 322–327. [CrossRef]
119. Zampori, L.; Dotelli, G.; Vernelli, V. Life Cycle Assessment of Hemp Cultivation and Use of Hemp-Based Thermal Insulator Materials in Buildings. *Environ. Sci. Technol.* **2013**, *47*, 7413–7420. [CrossRef]
120. Hult, M.; Karlsmo, S. Life Cycle Environmental and Cost Analysis of Building Insulated with Hemp Fibre Compared to Alternative Conventional Insulations—A Swedish Case Study. *J. Sustain. Arch. Civ. Eng.* **2022**, *30*, 106–120. [CrossRef]
121. França, W.T.; Barros, M.V.; Salvador, R.; de Francisco, A.C.; Moreira, M.T.; Piekarski, C.M. Integrating life cycle assessment and life cycle cost: A review of environmental-economic studies. *Int. J. Life Cycle Assess.* **2021**, *26*, 244–274. [CrossRef]
122. Brattebo, H. Toward a methods framework for eco-efficiency analysis? *J. Ind. Ecol.* **2005**, *9*, 9. [CrossRef]

123. Kloepffer, W. Life cycle sustainability assessment of products. *Int. J. Life Cycle Assess.* **2008**, *13*, 89–95. [CrossRef]
124. Biswas, W.K.; Barton, L.; Carter, D. Biodiesel Production in a Semiarid Environment: A Life Cycle Assessment Approach. *Environ. Sci. Technol.* **2011**, *45*, 3069–3074. [CrossRef]