ACADEMIA
MATERIALS SCIENCE

Review Article
Published: 2024-11-27
https://doi.org/10.20935/AcadMatSci7369

Mainstreaming precast and block hempcrete—a carbon sequestering solution for the built environment

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Abstract

The International Residential Code (IRC) appendix, which offers guidance on acceptable building materials, was updated in 2023 to include hempcrete for the first time in its 2024 version. Hempcrete, a blend of hemp hurd, lime, and water, has emerged as a sustainable and carbon-negative building material with promising applications in the construction industry. This review article provides a comprehensive overview of hempcrete, starting with its historical roots and the basic science behind its composition. Hemp was used in Rome as far back as Julius Caesar's time and in the sixth century when France was still Gaul. Lime building construction dates to before its use in the pyramids and can be found in ancient Africa, Persia, Rome, and throughout many indigenous cultures. Exploring the role of lime in enhancing the material's properties, we delve into the reasons behind its inclusion in hempcrete formulations. Opportunities and challenges in the adoption of hempcrete are discussed, highlighting its potential to revolutionize the construction sector. The evolution of curing techniques for hempcrete, from traditional methods to modern innovations, is examined, offering insights into future advancements. We explain why the utility of hemp has historically been overshadowed by a false narcotics narrative and association. We codify hempcrete's performance to underscore its environmental benefits and economic viability. We explore how lime, CO_2, and structural components can increase commercial viability and create the scale necessary for the United Nations Intergovernmental Panel on Climate Change's (IPCC) call for nations to maintain the global temperature increase below 1.5°C and net zero by 2050 while tackling the global housing crisis. Thus, this article serves as a valuable resource for researchers, architects, and policymakers interested in advancing adoption of sustainable construction practices.

Keywords: *hempcrete, bio-based materials, sound insulation, environmentally friendly building material, construction material, hemp-lime, sustainable construction, carbon sequestration, energy efficiency, thermal/fire resistant*

Citation: Gibson P. Mainstreaming precast and block hempcrete—a carbon sequestering solution for the built environment. *Academia Materials Science* 2024;1. https://doi.org/10.20935/AcadMatSci7369

1. Introduction

Hempcrete, a composite material made from hemp hurd (the woody internal core of the hemp plant), lime (also known as limestone, CaCo3), and water (H_2O), has garnered significant attention in recent years as a sustainable and eco-friendly alternative to traditional building materials. This review aims to provide a comprehensive overview of hempcrete, focusing on its composition, properties, applications, and environmental impact. Numerous articles have been published on the history, environmental performance, and technical properties of hempcrete. However, mainstream and North American adoptions remain nascent. Building upon the existing literature, this paper presents a synthesis of recent research findings and explores the potential of hempcrete to revolutionize the North American construction industry.

The growing interest in hempcrete can be attributed to its unique combination of properties, making it an attractive building material. Hemp hurd, derived from the stalks of the hemp plant, is lightweight, strong, and biodegradable, making it an ideal sustainable alternative to traditional construction materials [1–5]. When combined with lime, a mineral binder, hemp hurd becomes a composite material having fire resistance, mold resistance, and excellent thermal and acoustic insulation properties [3, 4, 6].

One of the key advantages of hempcrete is its low environmental impact. Hemp plants absorb large amounts of carbon dioxide during their growth, making them carbon-neutral or even carbon-negative crops [7]. When hemp hurd is used in construction materials like hempcrete, it continues to sequester carbon dioxide, which helps to reduce the overall carbon footprint of buildings [8–10]. This carbon sequestration potential makes hempcrete an attractive option for sustainable construction practices.

Research into the mechanical properties of hempcrete has shown promising results. Studies have demonstrated that hempcrete exhibits good compressive strength, comparable to that of traditional concrete, making it suitable for load-bearing applications [2, 7, 11, 12]. Additionally, hempcrete has been found to have excellent thermal insulation properties, which can contribute to energy

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savings in buildings [11, 13–18]. These properties make hempcrete a versatile material that can be used in a wide range of construction applications.

In addition to its mechanical and thermal properties, hempcrete also offers advantages in terms of its fire resistance and durability. Hemp hurd is inherently fire-resistant, and when combined with lime, hempcrete becomes even more fire-resistant [3, 15]. This makes hempcrete a safe and durable building material that can withstand harsh environmental conditions.

The use of hempcrete is not limited to new construction projects; it can also be used in the renovation and retrofitting of existing buildings. The lightweight nature of hempcrete makes it easy to work with and can help reduce the overall weight of a structure, which is beneficial for older buildings that may not have been designed to support heavier materials [3, 16]. Additionally, the breathable nature of hempcrete allows moisture to escape, which can help prevent issues such as mold growth and dampness in older buildings [1, 14, 19, 20].

The adoption of hempcrete in the construction industry is also supported by its sustainability credentials. Hemp plants require minimal water and pesticides to grow, making them a more sustainable alternative to other crops used in construction materials [3, 4]. Additionally, hemp hurd is biodegradable, which means that at the end of its life cycle, hempcrete can be recycled or composted, further reducing its environmental impact.

Despite its many advantages, the widespread adoption of hempcrete faces some challenges. One of the main challenges is the availability of hemp hurd and lime, as well as the cost of these materials compared to traditional building materials. However, as the demand for sustainable construction materials grows, it is expected that the availability and cost of hemp hurd and lime will improve, making hempcrete a more viable option for builders and developers. According to the U.S. Department of Agriculture Farm Service Agency's 2023 report [21], the acres of land planted cannabis for CBD (cannabidiol) use are on the decline in 2023, whereas plantations of cannabis for fiber use have already experienced a 29% year-over-year increase from 2022 to 2023 [22].

Hempcrete's versatility extends beyond its use in buildings. It has also been explored as a material for manufacturing furniture, decorative items, and even automotive components. The lightweight nature of hempcrete makes it an attractive option for applications where weight is a concern, such as in the automotive industry, where reducing vehicle weight can improve fuel efficiency and reduce emissions [23]. Additionally, the biodegradability of hemp hurd makes hempcrete a sustainable choice for these applications, reducing the environmental impact of manufacturing processes.

Recent advancements in material science and engineering have led to the development of novel hempcrete formulations with enhanced properties. For example, researchers have explored the use of additives such as silica fume, fly ash, and recycled aggregates to improve the strength and durability of hempcrete [24, 25]. These additives have been found to enhance the mechanical properties of hempcrete, making it suitable for a wider range of construction applications.

In addition to its environmental benefits, hempcrete also offers economic advantages. The use of hemp hurd and lime in construction can create new opportunities for farmers and manufacturers, boosting local economies and providing sustainable sources of income. Furthermore, the long-term cost savings associated with hempcrete, such as reduced energy costs and maintenance requirements, can make it a cost-effective option for building owners and developers [17, 18].

The future of hempcrete looks promising, with ongoing research focused on further improving its properties and performance. Researchers are exploring new techniques for processing hemp hurd, such as enzyme treatments and fiber modifications, to enhance the compatibility between hemp hurd and lime binders [26, 27]. These advancements could lead to the development of even stronger and more durable hempcrete materials, further securing its position as a durable, long-lasting alternative to traditional building materials.

This comprehensive review aims at the in-depth exploration of hempcrete, beginning with its historical roots and evolution to its modern-day applications. The discussion begins with an investigation into hemp's sorted legal trails and extends to the properties of hempcrete—emphasizing its remarkable strength, thermal insulation capabilities, and resistance to mold and fire—while meticulously analyzing its environmental impact, highlighting its carbon-negative properties and potential to mitigate climate change. It describes the manufacturing process of hempcrete, detailing the blending and curing of its constituents to create a sustainable and durable building material. The review critically assesses the challenges and limitations hindering the widespread adoption of hempcrete. Despite the challenges, it concludes on an optimistic note offering a glimpse into the promising future outlook of hempcrete in revolutionizing the construction industry. It emphasizes the need for further research and development in sustainable building materials with hempcrete serving as a beacon of innovation and sustainability. This article aspires to be an indispensable guide for researchers, architects, and policymakers seeking to embrace sustainable construction methodologies. An example of this is the five-million-dollar grant pilot project between Florida A&M and the U.S. Department of Agriculture [28], which utilized industrial hemp for carbon sequestration by supporting farmers in growing and selling hemp as a climate-smart crop. **Figure 1** outlines the research review organization.

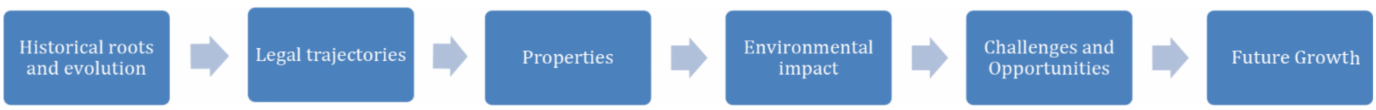

Figure 1 • Review roadmap.

2. A brief history

Why was hemp illegal?

In the late 1800s, hemp was the third highest-produced agricultural crop in the USA. In 2023, it fell to number 83 in the USA for commercial agricultural production [29, 30]. There has been almost a century's break in innovation with hempcrete as a building material. The plant that hemp hurd is derived from is commonly known as cannabis (*Cannabis sativa*). Hemp hurd is derived from the male cannabis sativa plant, which can wildly grow up to 30 feet tall [31]. Its industrial uses number in the thousands and include, but are not limited to, paper, linen fabrics, ropes, fuel, plastics, animal feed, and building materials such as hempcrete. The female plant that grows more like a bush is the intoxicant marijuana. Taxonomies aside, hemp is wildly dissimilar to its female counterpart; however, propaganda against hemp was pushed across America beginning in the 1910s and continuing through the 1930s. Harry Anslinger was the head of the Federal Bureau of Narcotics for four presidential administrations and was responsible for many of the taxes and laws. According to Deitch [29], Anslinger was instrumental in designing and executing the conflation of the male and female cannabis plants that led to the 1937 Marijuana Tax Act, the first of many laws making all forms of cannabis illegal.

After seven years of resisting Anslinger's attempts to criminalize marijuana, suddenly and without explanation the Treasury Department reversed its position and supported his proposal in the form of H.R. 6385, which came to be known as the Marijuana Tax Act. The reversal officially came on April 14, 1937, while Congress was involved in preparing and debating the budget; it was presented as a revenue-enhancing proposal. It required manufacturers, importers, dealers, and users of marijuana to register with the federal government and pay an occupational tax. It also required a considerable amount of paperwork (designed to discourage people) and imposed a $1-an-ounce tax on transfers to registered persons, and $100-per-ounce tax on transfers to non-registered persons. That was exorbitant, considering that at the time marijuana cigarettes could be bought for 25 cents at one of New York City's many tea houses or an ounce of marijuana could be bought on the streets for a couple of dollars [29].

Deitch [29] uncovered major lobbyists and industrial families from the 1910s to the 1980s, including the Du Ponts and Rockefellers with an agenda to slow the nascent but growing hemp industry. Deitch asserts that "the new law was the final blow that ended this country's cultivation and use of that plant. At the time, America was still producing many products from hemp and hemp oil—including paints and varnishes, lubricants, linoleum, soap and other" [29]. While Du Pont's agenda can be directly linked to competition via the development and patenting of nylon in 1938 (which would replace hemp as the most utilized fiber for ropes, clothing, and other goods), Deitch missed the largest financial contributors to the increase in propaganda and expulsion of hemp from the American industrial market. Representatives from the Brick Masonry lobby, which began in 1934 with a major agenda of positioning hemp alongside marijuana in propaganda aimed at the public, prompted the 1937 legislation. The Treasury Department's reversal seemed to be "without explanation." However, the steel, brick, and petrochemical lobby played a critical role in hemp's American and global industrial demise and yet have had the most to gain from it. "But what was good for Rockefeller, Mellon, and DuPont was good for Hearst and Anslinger. The petrochemical companies took over hemp's former markets, starting us all on the road to petroleum dependency" [29]. The critical funding and support, which can be seen from the major construction, petrochemical, and paint lobbyists, cannot and should not be ignored as powerful opponents ensure hemp's demise—later to be legally categorized alongside Schedule 1 heroin. The Agriculture Improvement Act of 2018, known as the 2018 Farm Bill, included provisions to enable farmers to commercially cultivate and sell industrial hemp in the USA, expanding on the provisions of the 2014 Farm Bill. In 2018, many of these laws had a termination date, creating an opportunity for innovation in material science to reemerge.

2.1. Massive growth

According to the European Commission [21], hemp cultivation has increased in the European Union from just over 20,000 hectares in 2015 to over 33,000 hectares by 2022. The EU's agriculture and rural development [32] acknowledges that "Hemp cultivation contributes to the European Green Deal Objectives." Due to these advances in 2024, hemp was added to the International Residential Code (IRC) appendix for non-load-bearing walls and wall infills as a viable building material [33, 34].

Hemp has been a valuable resource for various civilizations throughout history, and its use in construction dates back thousands of years. Ancient civilizations, such as those in China, Egypt, and Mesopotamia, utilized hemp hurd for a variety of purposes, including textiles, ropes, and construction materials. The use of hemp-based materials in construction continued through the Middle Ages and into the early modern period, where it was commonly used for building homes, some bridges, and even some ships due to its strength and durability [5, 35]. **Figure 2b** depicts the height and density of hemp as the source material for hempcrete as well as the phenotypically and genetically different female plant in **Figure 2a** which is used for cannabis.

In recent times, the modern resurgence of hempcrete can be traced back to the early 20th century in Europe, where it was used as an insulating material in construction. However, it was not until the late 20th century that hempcrete gained widespread attention as a sustainable building material. Recently, various projects have showcased the potential of hempcrete as a viable building material for modern construction, sparking interest and further research into its properties and applications [32, 36–39].

Figure 2 • Eight-week-old hemp plants: (a) female hemp plant and (b) male hemp plant. Reproduced with permission from Kumeroa et al. [40].

3. Manufacturing process

The manufacturing process of hempcrete involves several key steps, beginning with extracting and processing hemp hurd. Hemp hurd is typically obtained from the stalks of the hemp plant, which are harvested and processed to extract the fibers. The fibers are then cleaned and separated to remove any impurities, ensuring that they are ready for use in the production of hempcrete [6, 27]. **Figure 3** presents a process flow chart mapping the process of taking hemp from agricultural crop to home building block.

Once the hemp fibers are prepared, they are mixed with a lime-based binder to create the hempcrete mixture. The lime binder, usually in the form of hydrated lime or lime putty, acts as a binding agent that holds the hemp fibers together and provides strength to the final product [2, 24, 36]. The mixing process is crucial to ensure that the hemp fibers are evenly distributed throughout the mixture, ensuring uniform properties in the final product [24, 41].

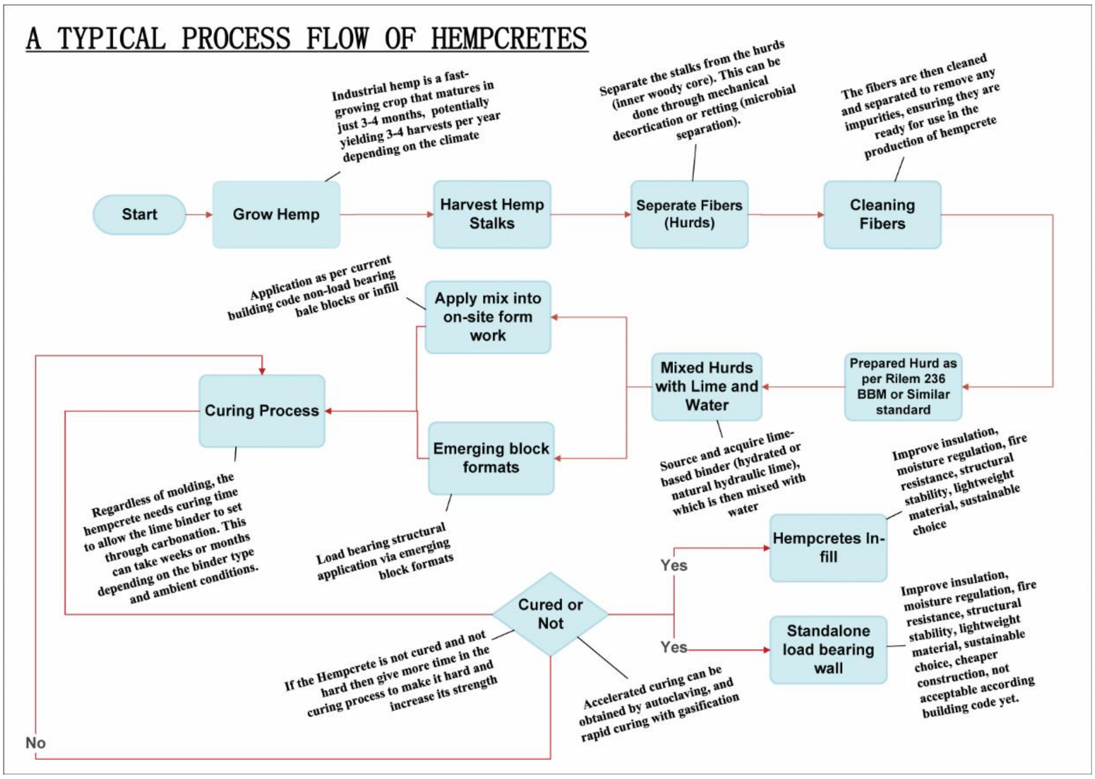

Figure 3 • A schematic flow chart depicting various steps in the hempcrete production process.

After the hempcrete mixture is prepared, it is placed into molds or formwork to give it the desired shape and size as shown in **Figure 4**. The mixture is then compacted to remove any air pockets and ensure that the hemp fibers are well bonded with the lime binder. The compaction process is typically done using hand tools or mechanical equipment, depending on the scale of the project [36].

Figure 4 • Manually clamped and externally vibrated individual hempcrete block mold prototype. Reproduced with permission from ClimatBloc [42].

Once the hempcrete mixture is compacted, it undergoes an ambient curing process utilizing trace CO_2 in the air to allow the lime binder to harden and strengthen the material. The curing process is critical to the performance of hempcrete, as it allows the lime binder to undergo a chemical reaction known as carbonation, where carbon dioxide from the air reacts with the lime to form calcium carbonate, which strengthens the material [9, 10, 20, 42, 43].

The curing temperature and time are crucial factors that affect the strength and durability of hempcrete. The temperature should be controlled to ensure that the lime binder cures properly without causing any thermal stress to the hemp fibers. Typically, the curing process can last 28–45 days if carried out in ambient conditions. However, it can vary depending on the specific formulation of the hempcrete mixture and the environmental conditions [43].

The properties of hemp hurd to be used in hempcrete have been standardized via Rilem 236 BBM [44], and binders in hempcrete have seen improvements resulting in hempcrete being accepted as an optimal infill material as per the 2024 IRC appendix [45]. The code specifies in situ application, and despite advances in the field, few examples of non-ambient-cured, plant-manufactured hempcrete blocks exist. The ultimate goal of research in this area is manufacturing a ready-to-use load-bearing building unit delivered to a site in a pre-cured state—one that would be included in the IRC. Buildings in 2023 have made major breakthroughs to "identify a link between the mechanics of bio-based materials and their hygroscopic behavior," but more research is needed to develop a standard in off-site curing of hempcrete blocks [46]. Such research should focus on controlling the relative humidity and the temperature of the curing environment and validating the optimal CO_2 concentration of the curing environment to enable thorough calcination of the hydrated lime to calcium carbonate.

In addition to the basic manufacturing process, there are several variations and innovations in the production of hempcrete. Some researchers have explored the use of additives such as silica fume, fly ash, or metakaolin to enhance the properties of hempcrete, such as its strength and durability [24, 25, 43, 47]. These additives can improve the overall performance of hempcrete and expand its potential applications in construction.

Another area of innovation in the manufacturing process of hempcrete is the use of different curing techniques. Traditional curing methods involve air curing, where the hempcrete mixture is left to cure in ambient conditions. However, researchers have also investigated the use of accelerated curing techniques, such as steam curing or autoclaving, to reduce the curing time and improve the efficiency of the manufacturing process [48–50].

The manufacturing process of hempcrete is a multifaceted process that requires careful attention to detail and quality control. From the extraction and processing of hemp fibers to the mixing with lime binder and curing techniques, each step plays a crucial role in determining the quality and performance of the final product. As research into sustainable building materials continues to advance, further innovations and improvements in the manufacturing process of hempcrete are expected, leading to a more sustainable and eco-friendly construction industry. A more recent trend is to make hemp blocks that can be commercially produced and transported [37, 39, 51]. The development of these innovative hemp blocks represents a significant step toward more sustainable building practices. As the construction industry increasingly prioritizes environmental considerations, the use of hemp blocks is expected to become more widespread, offering a viable and eco-friendly alternative to common building materials. Ongoing research and development in this area are likely to lead to further improvements in the performance and versatility of hemp blocks, making them a key component of future sustainable construction practices.

4. Properties and performance

Manufactured construction materials from hemp hurd can have varied distinct properties and performance ranging from mechanical properties, thermal conductivity, acoustic insulation, fire resistance, energy efficiency, durability, moisture regulation, aesthetics and design flexibility, cost-effectiveness, regulatory compliance, structural stability, resistance to pests and mold, health and safety, and environmental impacts and sustainability. **Figure 5** provides an outline of metrics of performance for hempcrete.

Figure 5 • Process and performance attributes.

4.1. Mechanical properties

Like any other construction material, the mechanical properties, including compressive strength, tensile strength, and flexural strength, are critical for structural integrity. These characteristics vary based on factors like fiber content, curing method, and fiber quality, with compressive strength typically ranging from 0.1 to about 5 MPa [36, 43]. However, recent studies have shown that the addition of nanocellulose fibers can significantly improve the mechanical properties of hempcrete and thus enhance compressive strengths. Their tensile and flexural strength can be enhanced with the addition of fibers like steel or polypropylene. These fibers improve its resistance to tension and bending forces, making it suitable for a variety of construction applications. Research by Niyati Shah et al. [52] demonstrated that the incorporation of recycled carbon fibers into hempcrete could improve its flexural strength up to 30%, highlighting the potential for further enhancement of its mechanical properties [52].

4.2. Thermal conductivity

With a thermal conductivity ranging from 0.06 to 0.13 W/mK, hempcrete provides excellent thermal insulation compared to traditional concrete. This property helps in reducing energy consumption for heating and cooling, contributing to energy efficiency in buildings. Aerogel nanoparticles can be used as additives in hempcrete to further improve its thermal conductivity, achieving values as low as 0.05 W/mK [11, 14, 27, 43, 53].

Although the thermal conductivity of hempcrete is slightly higher than that of conventional ones, hempcrete's thermal insulating properties can still be considered good and increase in efficiency when considering aerosols and nanoparticles [14, 43].

This energy efficiency is due to its superior thermal insulation properties. Buildings constructed with hempcrete require less energy for heating and cooling, resulting in lower energy costs over time. Recent studies have focused on optimizing the thermal properties of hempcrete, with the use of phase change materials (PCMs) as additives showing the potential for further enhancing its energy efficiency [17, 18, 54].

4.3. Acoustic insulation

Hempcrete's acoustic insulation properties are advantageous for creating comfortable indoor environments. Its sound insolation coefficient of 0.2–0.4 makes it an effective material for reducing noise pollution in buildings according to the sound index for airborne sound. Walls made of hemp concrete demonstrate similar sound insulation with a coefficient of 0.2–0.4 compared to those made of porous concrete with a coefficient of 0.25–0.6 [55, 56]. **Figure 6** outlines absorption applications and best uses [55].

The noise reduction coefficient (NRC) of porous concrete has been calculated with a value of 1900 Hz rather than 2 kHz. Kinnane et al.'s [55] study highlighted the wall's role in sound insulation. Factors such as porosity and density have a lesser impact on the acoustic insulation of hempcrete than its chemical composition, and hempcrete made with lime-pozzolana binders exhibited better acoustic insulation than those with more hydraulic components—unfinished hempcrete walls were found to absorb 40–50% of the incoming sound with NRC values of 0.4 and 0.2 for unfinished and finished hempcrete, respectively [55]. The average NRC value of the hempcrete (0.3) can be considered a good acoustic performance, meaning that 70% of the sound can be reflected, leaving 30% transmitted.

4.4. Fire resistance

Hempcrete's natural fire resistance is a key advantage. It meets or exceeds fire resistance requirements for building materials, ensuring safety and durability in construction [20, 36]. Recent studies that investigated the use of intumescent coatings on hempcrete to further enhance its resistance to higher temperatures have shown promising results [56, 57]. ClimatBloc, a hempcrete block, had a flame spread and smoke development index of 0 and passed all noncombustibility, air leakage, and shrinkage assessments [39].

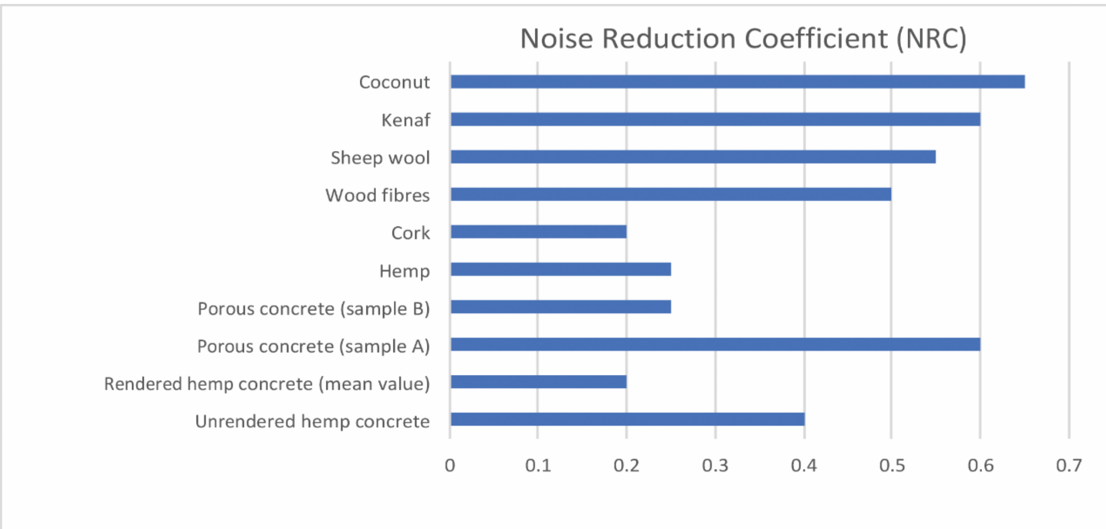

Figure 6 • Sound insulation values of commonly available biomaterials [55].

4.5. Durability

Its durability is comparable to that of traditional building materials. Properly constructed hempcrete structures can withstand harsh environmental conditions and have a long life span [1, 58]. Studies have shown that the addition of alkali-activated binders can improve the durability of hempcrete, increasing its resistance to chemical and physical degradation [54, 58, 59].

4.6. Moisture regulation and resistance to mold growth

Hempcrete's breathable nature allows moisture to escape, reducing the risk of mold growth and dampness in buildings. This property contributes to healthier indoor environments. Viitanen and Ojanen [60] proposed a model to estimate the mold growth index (MGI), which varied from 0 to 6, with each value representing a mold growth level observed. The mold index method by Viitanen et al. was published as a standard but later replaced by an alternative method. *R* range data are consistent in both methods.

Recent research has focused on improving the moisture regulation properties of hempcrete through the development of hydrophobic coatings and treatments showing promise in enhancing its moisture resistance [14, 53, 61]. Hempcrete's *R* value ranges from 3 to 5 per square inch with a mean of R40. The opportunity to build without a vapor barrier increases the moisture safety of the hemp structure. Hempcrete's ability to dampen variations in indoor humidity by absorbing and desorbing moisture in air provides moisture buffering to the indoor climate [14, 53].

Hempcrete's natural resistance to pests and mold is an important advantage for maintaining indoor air quality and reducing the need for chemical treatments. Recent research has focused on enhancing this property with the development of natural additives and treatments showing promise in improving hempcrete's resistance to pests and mold [60–62].

4.7. Aesthetics and design flexibility

Hempcrete offers architects and builders flexibility in design due to its moldability and ease of use. Its natural appearance and texture add aesthetic value to buildings. Studies have explored the use of natural pigments and dyes to enhance the aesthetic appeal of hempcrete, offering a wide range of design possibilities [8, 16, 36]. **Figure 7** shows an example of a 4000-square-foot single family home aesthetically built using hempcrete. The home features two bedrooms, two office suites, a studio, a den, 2.5 bathrooms, and panoramic views. There is also a greenhouse on site to harvest food.

It is worth noting that the home features a curved wall highlighting the design flexibility of hempcrete construction, as depicted in **Figure 8**.

4.8. Cost-effectiveness

While the initial costs of hempcrete may be higher than traditional materials, its long-term cost savings in terms of energy efficiency, labor, and maintenance make it a cost-effective choice for building owners. Recent cost-benefit analyses have shown that the use of hempcrete can lead to significant savings over the life cycle of a building, making it a financially viable option [1, 8, 13, 36, 43]. In traditional exterior walls, the assembly comprises cladding, strapping, weather-resistant barrier (WRB) membrane, sheathing, studs, insulation, vapor barrier, and gypsum board. On the other hand, hempcrete requires none of these materials and trades, but only needs the addition of plaster in the interior and exterior walls. Having fewer trades involved during construction can lead to faster production and increased savings for developments.

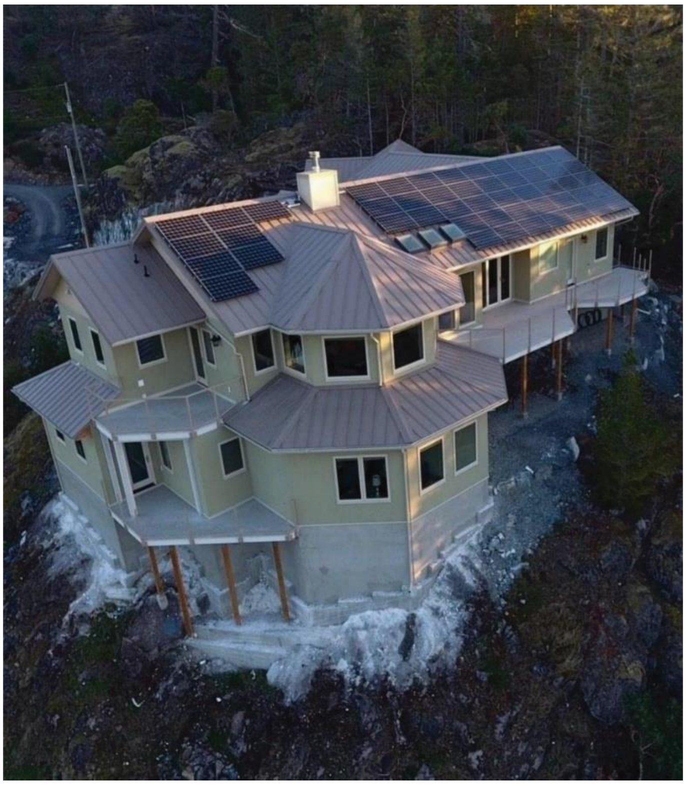

Figure 7 • Serial view of the Harmless Home, a hempcrete-built residence in British Columbia, Canada. Reproduced with permission from Keinonen [39].

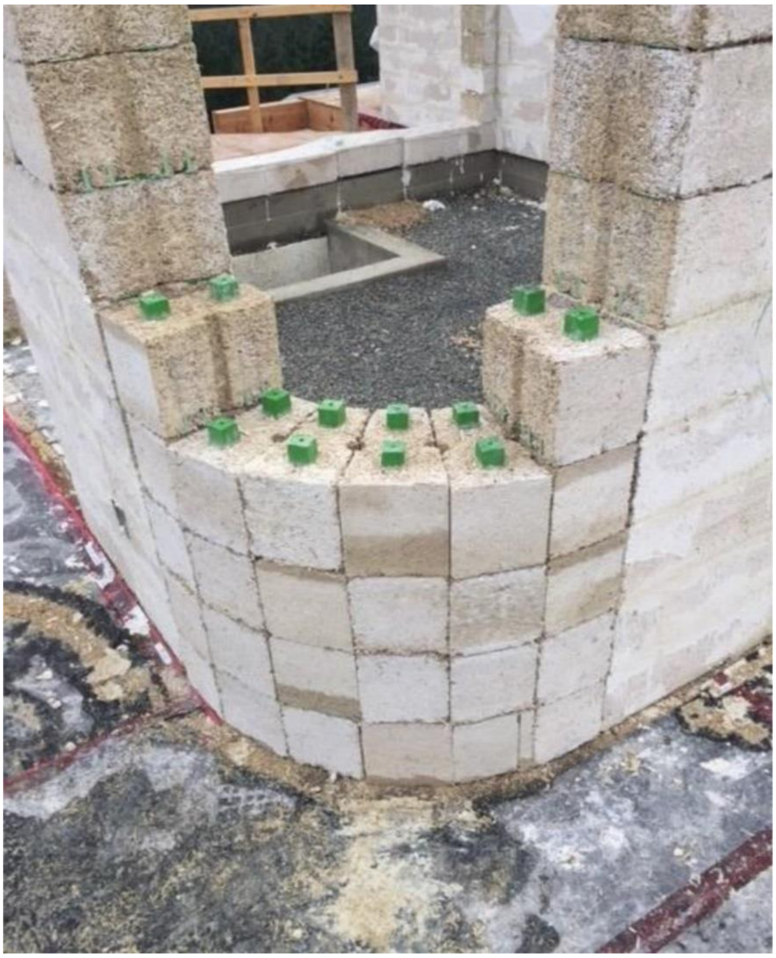

Figure 8 • Capability of hempcrete for curved wall to enhance esthetic appeal. Reproduced with permission from Keinonen [39].

4.9. Building code and regulatory compliance

Though hempcrete complies with precast standards, it has not achieved mainstream adoptions as a structural material per North American building codes or international guidelines. Organizations like the International Code Council (ICC) [34] have developed standards for testing and evaluating hempcrete materials, ensuring their quality and performance in construction projects. Appendix BL of the 2024 International Residential Code without Energy (IRC) continues to define hempcrete as a nonstructural building material. Developing various standardized testing methods to ensure hempcrete's compliance with regulatory requirements would be beneficial. Code compliance is a crucial step for the usability and acceptability of a product in the market, as funds are aligned with approvals.

4.10. Structural stability

Properly designed and constructed hempcrete structures demonstrate excellent structural stability. Its ability to resist various forces and maintain integrity over time is comparable to traditional material. Research has shown that the use of fiber-reinforced hempcrete can further enhance its structural stability, making it suitable for a wide range of construction applications [12, 63].

Figure **9a** and **b**, in courtesy of an architectural suitability report by an architect and Engineering, Procurement, and Construction (EPC) firm [64], specifies a hemp-lime block and provides an example of interlocking, endoskeleton-type structural frame encased in hempcrete to enhance the overall structural strength of a ready-to-use block. This frame strengthens the hempcrete block and thus increases its vertical load-bearing compressive strength.

4.11. Health and safety

Hempcrete is a safe material for construction, posing minimal health risks to workers and occupants. Two major benefits of hempcrete are its natural composition and lack of toxic additives, which minimize chemical inputs across the built environment and contribute to a healthier built environment. Studies have shown that the use of hempcrete can improve indoor air quality, leading to better health outcomes for occupants [59, 65, 66].

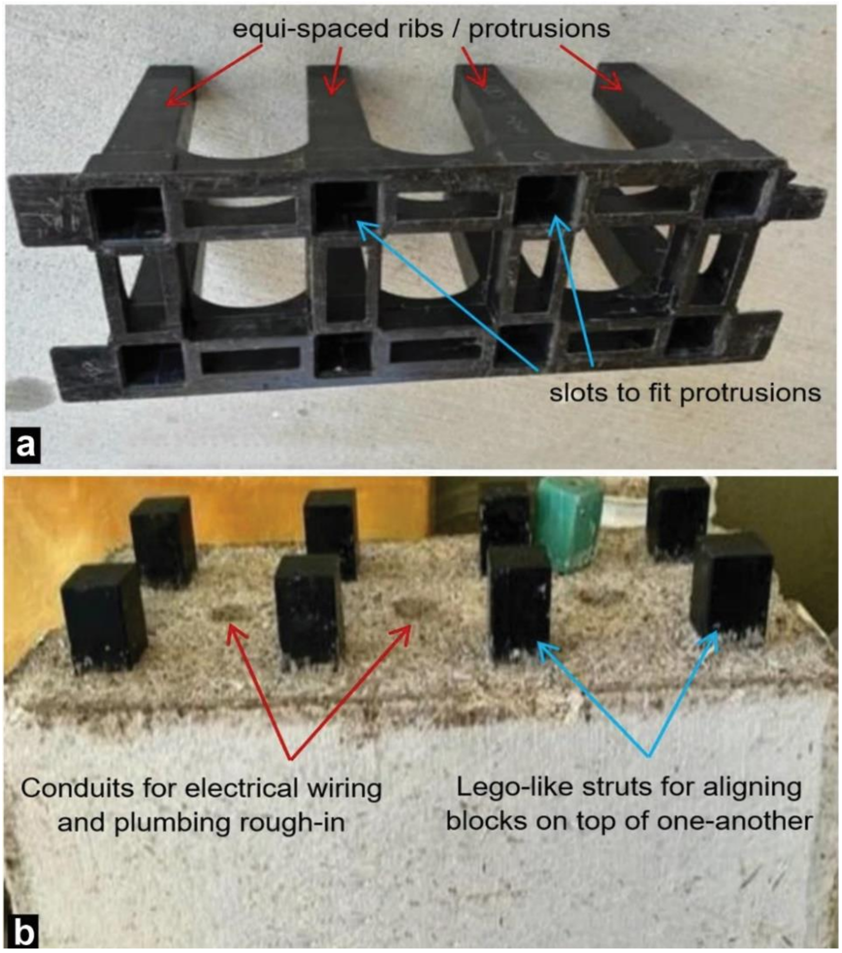

Figure 9 • (a) Thermosetting polymer skeleton and (b) compacted and cured hempcrete block. Reproduced with permission from Oberti [64].

5. Environmental impact and sustainability

Hemp is a highly sustainable crop known for its versatility and eco-friendly properties. It grows abundantly in various climates and soil types, and requires minimal water, pesticides, and fertilizers compared to other crops. Hemp is also a fast-growing plant with a harvest cycle of about four months and can yield up to four times more fiber per acre than trees. This rapid growth and high yield make hemp an environmentally friendly choice for agriculture and a sustainable source of raw material for various industries, including construction [6, 36].

Furthermore, hemp has a deep root system that helps improve soil health and structure. The deep roots of hemp plants can break up compacted soil, improve drainage, and reduce erosion, making it a beneficial crop for sustainable agriculture practices. Additionally, hemp has been found to positively impact biodiversity, providing habitat and food for a variety of insects and wildlife [6].

One of the key environmental benefits of hempcrete is its ability to sequester carbon dioxide (CO_2) from the atmosphere, further enhancing its sustainability. Global Warming Potential total (GWP total) is often negative for bio-based products that do not need a lot of processing, such as hemp, and therefore so-called cradle-to-gate emissions of hempcrete can be negative. During its growth, hemp absorbs CO_2 through photosynthesis, locking it into its fibers and biomass. This carbon sequestration can help offset greenhouse gas emissions and mitigate climate change [8–10]. Additionally, hemp plants have been found to have a high biomass production potential, meaning that they can produce large amounts of organic matter that can be used for bioenergy production or as a soil amendment. Use-stage carbon storage of hempcrete is distinct from carbon sequestration data during the growth of hemp and is indicated by the mean *R* value of 40. Carbon storage is not included in the carbon footprint but is reported as a positive climate impact outside the assessment boundary.

Hempcrete presents a compelling case for sustainable construction due to its significantly lower carbon footprint compared to traditional building materials. The production process of hempcrete involves mixing hemp shives, lime, and water, resulting in a material that sequesters carbon dioxide rather than emitting it. Research indicates that the production of conventional concrete is responsible for approximately 8% of global carbon dioxide emissions, making it a significant contributor to climate change [4, 7–9, 11]. In contrast, the production of hempcrete emits significantly less carbon dioxide and can even be carbon-negative over its lifetime due to the carbon sequestration properties of hemp. Carbon sequestration rates of hempcrete have been well documented [67].

Although various studies have found considerably different results regarding the overall greenhouse gas (GHG) emission, varying from −1.6 to −36.08 kg CO_2 eq./FU, it is interesting to note that in all the above mentioned studies, the overall outcome is a negative carbon emission, which indicates a positive impact on climate change due to carbon sequestration.

One of the key environmental benefits of hempcrete is its ability to sequester carbon dioxide. Hemp plants absorb carbon dioxide during their growth, and this carbon is stored in the hemp fibers. When hemp fibers are used in construction materials like hempcrete, they continue to sequester carbon dioxide, helping to offset the emissions associated with their production and use [4, 7]. Studies have shown that the use of hempcrete can lead to significant carbon savings over the life cycle of a building, making it a valuable tool for reducing greenhouse gas emissions [7, 10, 68]. The use of hemp fibers from agricultural waste streams for hempcrete production further enhances its sustainability, as it reduces waste and utilizes a renewable resource [5].

The thermal properties of hempcrete also contribute to its environmental sustainability. Hempcrete provides excellent thermal insulation, reducing the energy consumption required for heating and cooling buildings. This could lead to significant energy savings over the life cycle of a building, further reducing its environmental impact. Recent studies have explored the use of hempcrete in passive solar design, demonstrating its potential to further enhance energy efficiency in buildings [69].

In terms of end-of-life considerations, hempcrete is biodegradable and can be recycled or composted at the end of its life cycle. This reduces the amount of waste sent to landfills and contributes to a circular economy model. Additionally, the use of hempcrete in construction can help reduce the demand for conventional building materials that have a higher environmental impact, further contributing to sustainability.

6. Challenges, limitations, and the way forward

The adoption of hempcrete faces several challenges and limitations that hinder its widespread use in the construction industry. One primary challenge is the availability of raw materials, specifically high-quality hemp fibers. While hemp is a fast-growing crop that can be cultivated in various climates and soil types, there is a limited supply of hemp fibers suitable for construction-grade applications. Solutions to this challenge include promoting research and development efforts to enhance hemp cultivation techniques for improved fiber quality and yield. Additionally, establishing partnerships with farmers to ensure a consistent supply of high-quality hemp fibers can help mitigate supply chain issues.

Cost is another significant barrier to the widespread adoption of hempcrete. While hemp fibers are a renewable and sustainable resource, the processing and production of hempcrete can be more expensive than traditional building materials such as concrete. Factors contributing to the higher cost include the need for specialized equipment for processing hemp fibers and the relatively low demand for hempcrete compared to conventional building materials. To overcome this challenge, efforts should focus on optimizing manufacturing processes to reduce production costs. This could be achieved through the development of innovative processing techniques that increase the efficiency of hemp fiber extraction and lime production. Furthermore, increasing the scale of production and improving the availability of specialized equipment can help lower the overall cost of hempcrete.

Regulatory barriers also pose a challenge to the adoption of hempcrete. In some regions, building codes and regulations do not explicitly allow for the use of hempcrete in construction, leading to uncertainty and reluctance among builders and developers to use the material and to obtain approval from the regulatory authorities. To address this challenge, collaboration with regulatory authorities is essential to establish clear guidelines and standards for the use of hempcrete in construction. This could involve advocating for the development of building codes that recognize hempcrete as a viable construction material and conducting research to demonstrate its safety and performance. Additionally, providing educational resources to builders, developers, and regulatory agencies can help increase awareness and acceptance of hempcrete.

Another challenge is the perception of hempcrete as a niche or non-traditional building material. Despite its potential environmental benefits and unique properties, hempcrete is not yet widely accepted or understood within the construction industry. This lack of awareness and familiarity can lead to skepticism and reluctance among architects, engineers, and builders to use hempcrete in their projects. To change this perception, efforts should focus on increasing awareness of the benefits and potential applications of hempcrete. This could be achieved through targeted marketing campaigns, educational programs, and partnerships with architects and designers to showcase the versatility and aesthetic appeal of hempcrete in various construction projects. Additionally, highlighting the environmental benefits of hempcrete, such as its low carbon footprint and ability to sequester carbon dioxide, can help position it as a sustainable building material. Efforts should focus on educating architects, engineers, and builders about the benefits and applications of hempcrete. This could include providing case studies, technical specifications, and design guidelines that demonstrate the feasibility and performance of hempcrete in various construction projects. Additionally, collaborating with industry associations and professional organizations can help promote the use of hempcrete and encourage its adoption in mainstream construction practices.

The physical properties of hempcrete present both challenges and limitations. While hempcrete is known for its excellent thermal insulation properties, it may have lower compressive strength compared to traditional concrete [43, 63, 70, 71]. This limitation can restrict the use of hempcrete in certain structural applications where higher strength is required. To address this, research should focus on developing additives or reinforcement techniques that enhance the strength and durability of hempcrete, which could include incorporating natural or synthetic fibers into the mixture to improve its structural properties [52]. Additionally, conducting thorough testing and performance evaluations can help identify the optimal mix ratios and construction methods for maximizing the strength of hempcrete structures.

Traditional curing methods involve air curing, where the hempcrete mixture is left to cure in ambient conditions, which can take several weeks to cure. Temperature and relative humidity also play a critical role in the curing process. Successful hempcrete production is concentrated in the pre-manufactured block industry due to the lengthy curing time necessary for hempcrete infill.

Durability is another concern with hempcrete, particularly in terms of moisture resistance and long-term stability. If not built properly, hempcrete may be more susceptible to moisture damage and decay compared to conventional building materials, which can affect its longevity and performance in humid or wet environments. To improve the durability, research should focus on developing surface treatments or coatings to enhance its resistance to moisture and decay [72, 73]. This could involve using natural or eco-friendly materials that provide a protective barrier without compromising the sustainability of hempcrete. Additionally, conducting long-term durability studies in real-world conditions can help assess the performance of hempcrete over time and identify areas for improvement.

The fire resistance of hempcrete is also a topic of concern. While some studies have definitely shown that hempcrete can exhibit good fire resistance [15, 43, 57], further research is needed to understand its behavior in fire conditions and to develop strategies to enhance its fire resistance properties. To enhance its fire resistance properties, research should focus on developing additives or treatments that improve its fire performance. This can include incorporating fire-retardant materials into the mixture or applying coatings that enhance its resistance to high temperatures. Additionally, conducting fire tests and simulations could help evaluate the effectiveness of these treatments and ensure that hempcrete meets the necessary safety standards.

The limited availability of skilled labor and expertise in working with hempcrete is another challenge. The specialized knowledge and techniques required for the proper installation and construction of hempcrete structures may not be widely available, which can hinder its adoption in the construction industry. To address this, educational programs and training initiatives should be developed to educate construction professionals about the use and benefits of hempcrete. This could include workshops, seminars, and hands-on training sessions that provide practical experience with hempcrete construction techniques. Additionally, establishing certification programs for hempcrete installation could help ensure that skilled labor is available to meet the growing demand for hempcrete construction.

Transportation and logistics also pose challenges to the widespread use of hempcrete. Hemp fibers are often bulky and lightweight, which can increase transportation costs and carbon emissions associated with the material's distribution. Finding sustainable and cost-effective transportation solutions for hemp fibers is essential for reducing the environmental impact of hempcrete. To address this, efforts should focus on developing sustainable transportation solutions for hemp fibers. This could include using renewable energy sources for transportation or optimizing transportation routes to reduce carbon emissions. Additionally, promoting local sourcing of hemp fibers could help reduce transportation costs and minimize the environmental impact of hempcrete production.

The scalability of hempcrete production is another challenge that needs to be addressed. While small-scale production of hempcrete is feasible, scaling up production to meet the demands of large-scale construction projects can be challenging. To scale up production, investments should be made in research and development to improve the efficiency and productivity of the hempcrete manufacturing processes. This could involve developing automated production systems, optimizing material sourcing and logistics, and increasing the capacity of existing production facilities. Additionally, fostering collaboration and knowledge sharing among stakeholders can help accelerate the adoption of hempcrete and drive innovation in its production processes.

The variability of hemp fibers can pose challenges in achieving consistent quality and performance in hempcrete. Factors such as the age, growing conditions, and processing methods of the hemp plants can affect the quality of hemp fibers and their suitability for use in hempcrete. To address this, efforts should focus on developing standardized testing methods and quality control measures for hemp fibers. This could involve establishing guidelines for hemp cultivation, harvesting, and processing to ensure that fibers meet the necessary specifications for use in hempcrete. Additionally, conducting regular quality audits and inspections could help verify the consistency and reliability of hempcrete products.

The long-term performance of hempcrete structures is still being studied. To improve our understanding of the material's durability and longevity, long-term monitoring and research should be conducted on hempcrete structures in real-world conditions. Understanding how hempcrete performs in real-world conditions and developing strategies to enhance its durability will be key to its widespread adoption. This could involve assessing the performance of hempcrete buildings over several years and evaluating their resistance to environmental factors such as moisture, temperature fluctuations, and structural loads. Additionally, developing predictive models and simulations could help forecast the long-term behavior of hempcrete structures and inform future design and construction practices.

While hempcrete offers significant potential as a sustainable and environmentally friendly building material, several challenges and limitations need to be addressed to facilitate its widespread adoption in the construction industry. By addressing these challenges through research, innovation, and collaboration, it is possible to unlock the full potential of hempcrete and realize its benefits for sustainable construction. Through continued efforts to improve raw material availability, reduce costs, address regulatory barriers, and enhance technical performance, hempcrete can become a mainstream construction material that contributes to a more sustainable built environment.

7. The future

Concrete is the most utilized material in the world after water. According to the carbon majority database between 2016 and 2022, 57 entities created 80% of all emissions. These entities exist in two industries: energy and construction, specifically concrete as a large polluter [74]. Performance-based standards and labeling to increase builder awareness are important regulatory steps alongside tax incentives. Future research must include a comparative assessment of hempcrete against traditional building materials to definitively determine environmental superiority and economic feasibility.

The future outlook for hempcrete is promising with ongoing research and development efforts focused on overcoming current challenges and unlocking its full potential as a sustainable building material. By leveraging technological innovation, supportive policies, and creative design solutions, hempcrete has the potential to transform the construction industry and contribute to a more sustainable and resilient built environment. In order for hempcrete to reach its full potential as a load-bearing structure and move beyond infill, more research must be conducted on increasing structural capacity, curing, admixtures, and production automation.

Technological advancements in hemp processing and lime production are expected to improve the efficiency and cost-effectiveness of hempcrete production, making it more competitive with traditional building materials. New applications of hempcrete, such as in prefabricated bricks and panels, modular construction, and 3D printing [62], are also likely to expand its use and accessibility in the construction industry.

One area of advancement lies in the optimization of manufacturing techniques to improve the consistency and quality of hempcrete. Researchers are exploring innovative methods such as pre-treatment of hemp fibers, optimized mixing processes, and advanced curing techniques to enhance the strength, durability, and overall performance of hempcrete [25, 36, 41, 52].

Moreover, advancements in additive manufacturing, also known as 3D printing, are opening up new possibilities for the application of hempcrete in construction. By using 3D printing technology, it is possible to create complex and customized structures with hempcrete, reducing material waste and construction time [62]. This innovative approach has the potential to revolutionize the construction industry, offering sustainable and cost-effective solutions for building construction.

In addition to technological advancements, the future of hempcrete is also influenced by regulatory and policy developments. As governments around the world increasingly prioritize sustainability and carbon reduction goals, there is a growing demand for eco-friendly building materials like hempcrete. Policymakers are exploring ways to incentivize the use of sustainable materials in construction through regulations, tax incentives, and green building certifications, which could further drive the adoption of hempcrete. Supportive policies and regulations that promote the use of sustainable building materials like hempcrete can definitely accelerate its adoption. Incentives for builders and developers to use hempcrete, such as tax credits, grants, and green building certifications, could help overcome cost barriers and encourage investment in sustainable construction practices. A label, similar to what is acceptable for food nutrition, outlining properties and environmental benefits of hempcrete is needed.

Architects and designers are also playing a key role in shaping the future of hempcrete by integrating it into innovative architectural designs. The natural texture and aesthetic appeal of hempcrete make it a versatile material for a wide range of applications from residential buildings to commercial structures. As architects continue to explore new ways to incorporate sustainable materials into their designs, hempcrete is expected to become a popular choice due to its environmental benefits and design flexibility.

Furthermore, the future of hempcrete is closely tied to the broader trends shaping the construction industry, such as the increasing focus on circular economy principles and the growing interest in bio-based materials. Hempcrete's biodegradability and ability to sequester carbon dioxide align with the principles of the circular economy, making it an attractive option for environmentally conscious builders. As the construction industry seeks to reduce its environmental impact and move toward more sustainable practices, hempcrete is likely to play a significant role in driving this transition.

Creative design solutions that incorporate hempcrete into innovative architectural designs can showcase its aesthetic appeal and functional benefits, further increasing its appeal to architects, builders, and homeowners. By highlighting the unique qualities of hempcrete, such as its thermal insulation properties, fire resistance, and carbon sequestration potential, stakeholders can be inspired to embrace hempcrete as a viable and sustainable building material. With continued research, innovation, and collaboration across the industry, hempcrete has the potential to revolutionize the construction industry and contribute to more sustainable and environmentally friendly built constructions.

8. Conclusions

Hempcrete, with its blend of hemp fibers and lime, possesses a myriad of promising qualities and applications. This innovative material is can lead to a sustainable revolution in the construction industry. Its unique combination of natural constituents not only offers superior thermal and acoustic insulation but also boasts excellent fire resistance and moisture regulation properties. Moreover, its carbon-negative footprint and ability to sequester carbon dioxide contribute significantly to reducing the environmental impact of construction. As technological advancements continue to enhance its manufacturing processes, and with increasing awareness and support for sustainable practices, hempcrete is positioned to play a pivotal role in shaping a greener and more sustainable future for construction. The growing clarity created by uncoupling hemp from the female plant marijuana along with decriminalization is increasing innovation in the building industry. Through collaboration among researchers, policymakers, architects, and investors, hempcrete can pave the way for a more resilient and eco-friendly built environment, offering a sustainable solution for generations to come.

Acknowledgments

The author thanks Oberto Oberti Architecture and Urban Design Inc., Code Project Enterprise Ltd. of Vancouver, Arno Keinonen, William (Mac) Radford, OBERCO, and ClimatBloc, LLC for providing copyright permissions for the images used in this review. The author also thanks Muhammad Haroon Qaiser, Pedram Nimreezi, and Robert N. Black, III Esq. for their counsel and editing of this review.

Funding

The author declares no financial support for the research, authorship, or publication of this article.

Author contributions

The author confirms sole responsibility for this work. The author approves of this work and takes responsibility for its integrity.

Conflict of interest

The author declares no conflict of interest.

Data availability statement

Data supporting these findings are available within the article, at https://doi.org/10.20935/AcadMatSci7369, or upon request.

Institutional review board statement

Not applicable.

Informed consent statement

Not applicable.

Additional information

Received: 2024-06-04

Accepted: 2024-09-20

Published: 2024-11-27

Academia Materials Science papers should be cited as *Academia Materials Science 2024*, ISSN 2997-2027, https://doi.org/10.20935/AcadMatSci7369. The journal's official abbreviation is *Acad. Mat. Sci.*

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