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Sustainable, Carbon-Neutral Construction Using Biobased Materials

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Abstract

The construction industry plays a significant role in global carbon emissions. This issue has led to a growing interest in sustainable, carbon-neutral building materials. This paper reviews the potential of biobased materials such as hempcrete, biochar-enhanced concrete, timber, clay, cork, etc. in lowering the environmental footprint of construction.

Hempcrete, a composite of hemp shiv, lime binder, and water, offers excellent insulation, thermal efficiency, and breathability. Its ability to absorb CO_2 during its life cycle makes it a carbon- negative material. However, it requires a structural frame due to its low mechanical strength. Biochar, derived from biomass through pyrolysis, is another sustainable material. It enhances concrete's mechanical strength, durability, and thermal performance while significantly reducing its carbon footprint. By using biochar in appropriate amounts, concrete can store CO_2, making it a more sustainable alternative to traditional cement-based construction.

A case study of a four-story CO_2-neutral residential building in Windau, Switzerland, demonstrates the successful application of these materials. Biochar-enhanced concrete, prefabricated timber structures filled with hempcrete, alongside with other biobased materials such as clay, cork, and straw are used for constructing this building. This innovative hybrid construction reduces carbon emissions and enhances energy efficiency. The building follows a plus-energy concept which means it generates more energy than it consumes through passive solar heating, smart ventilation, and intelligent energy management. The combination of high thermal mass materials and strategic design choices minimizes heating and cooling demands. Material reuse and sustainable energy solutions ensure a net-zero carbon emission over its 60-year lifespan. Additionally, the building's energy-efficient design significantly decreases energy costs for its residents.

Introduction

One of the most challenging environmental issues we face today is global warming, caused by greenhouse gas emissions such as carbon dioxide (CO_2). According to the Global Status Report for Buildings and Construction (Global Alliance for Buildings and Construction [GABC], 2022), the building sector is responsible for 39% of CO_2 emissions worldwide related to energy use and industrial processes. The energy crisis makes this problem even worse, as the increasing energy demand, especially from fossil fuels, leads to higher carbon emissions and faster depletion of natural resources (Mohasseb & Davoodi, 2024).

Carbon emissions from buildings occur not only during their operation, such as through heating, cooling, and lighting, but also throughout the entire lifetime of the building. This includes emissions from the extraction, production, transportation, and disposal of materials. The extraction of raw materials such as aggregates, limestone, and other natural resources also contributes significantly to environmental degradation and depletion of non-renewable resources. Due to the high consumption of energy-intensive materials such as concrete, brick, cement, steel, and glass, which require a large amount of energy to produce, there has been a growing interest in adopting low-carbon and sustainable alternatives to traditional construction materials (Mohasse, 2020; Mohasseb & Ghazanfari, 2021).

Exploring methods to improve environmentally friendly and bio-based building materials may be an important aspect of sustainable building with a limited impact on natural ecosystems. Biobased materials have emerged as a sustainable solution. They are made from natural resources like plants or biomass. They can grow naturally or be created through processes that use biomass. In other words, materials like wood, animal products, and paper are considered biobased. However, the term often refers to modern materials that are processed in more advanced ways.

There are few alternatives to traditional intensive energy construction materials, but hemp is a good and sustainable substitution for such materials. Hemp can be grown in small areas with minimal land usage, making it an efficient crop in terms of space efficiency. Moreover, hemp has a short growing cycle, typically it takes only about four months to reach maturity which allows rapid production. This makes it an ideal crop for construction, as it can be planted and harvested quickly to meet the demands of the industry (Malabadi et al., 2023; Baldini et al., 2018; Nath, 2022). Remarkably, hemp captures and stores more carbon dioxide than trees, making it a carbon-negative resource (Ip & Miller 2012). This characteristic helps mitigate greenhouse gas emissions more effectively than many other crops (Hoxha et al., 2020). Additionally, hemp requires less water, pesticides, and fertilizers, enhancing its sustainability as a building material (Malabadi et al., 2023) Hempcrete, also named hemp-lime concrete is a composite lightweight material composed of hemp shiv (the woody core of hemp), natural lime binder, and water (Bevan & Woolle, 2008). It is primarily used in constructing walls, floors, and roofs due to its excellent insulation properties, thermal efficiency, and breathability. However, hempcrete is not suitable for load-bearing applications because of its low mechanical strength and requires a supporting timber or steel frame for structural stability. Hempcrete can be cast in situ, sprayed, or used in precast forms such as bricks and panels, which speeds up construction and minimizes waste (Yadav & Saini, 2022). Another advantage of hempcrete is its ability to resist mold and degradation, even in external applications, when properly plastered with lime finishes (Bevan & Woolle, 2008). Additionally, hempcrete's low thermal conductivity and density make it an efficient insulator that can enhance energy savings in buildings (Amziane et al., 2013). Despite these advantages, its high- water absorption and retention capacity pose challenges to durability, requiring careful selection of binders and proper ventilation during curing (Yadav & Saini, 2022). However, studies have shown that higher levels of compaction during casting can significantly improve compressive strength up to 7.11 MPa (Nozahic et al., 2012). Water absorption and biodegradation can be reduced through different methods, such as chemical treatments including alkaline copper quaternary (ACQ) or copper-based preservatives, which help prevent the growth of fungi, mold, and bacteria. Additionally, applying coatings like epoxy-based or acrylate resins to hemp fibers can enhance their resistance to water absorption while also improving their mechanical properties and durability Lawan et al., 2018).

Figure 1 shows how hempcrete interacts with CO_2 throughout its life cycle. First, hemp plant absorbs CO_2 from the air as it grows. When the hemp is processed into hempcrete blocks, some CO_2 is released. However, once the hempcrete is used in a wall, it absorbs more CO_2 over time through carbonation. (Arrigoni et al., 2017).

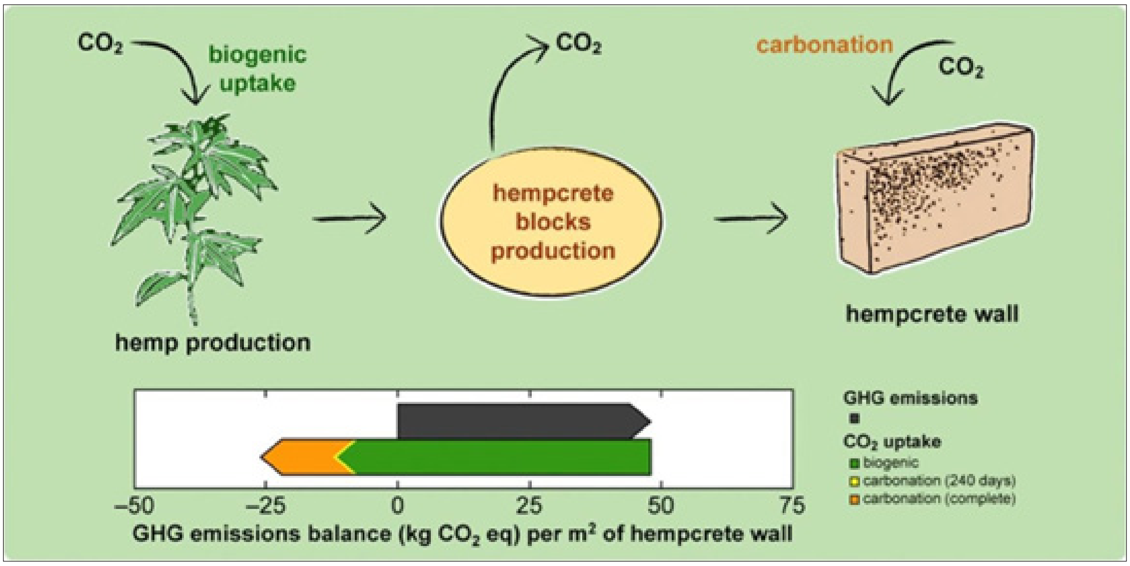


Figure 1: Hempcrete's Carbon Cycle (Arrigoni et al., 2017).

Another renewable material gaining attention in the construction industry is biochar. Biochar derived from biomass is a highly carbon-rich material. Biomass includes agricultural residues (such as crop waste and straw), forestry waste, municipal solid waste, food waste, and animal manure (Varjani et al., 2019). There are various thermochemical processes for producing biochar, including torrefaction, pyrolysis, flash carbonization, and hydrothermal carbonization. However, pyrolysis is the most widely used method (Bridgwater, 2012). It is a process that heats biomass in a low-oxygen environment and decomposes it into a carbon-rich substance. Adding biochar to concrete in optimal amounts (typically 1–2% by weight) enhances both compressive and flexural strength due to better hydration, internal curing, and crack resistance (Javed et al., 2022; Liu et al., 2022). Biochar has a porous nature due to high water loss during the dehydration process in the pyrolysis method. This characteristic helps create a denser microstructure, making the concrete less permeable, reducing shrinkage, and protecting it from sulfate and chloride attacks. This improves its long-term durability (Gupta et al., 2021). By partially replacing cement with biochar, biochar enhanced concrete becomes a more sustainable building material that supports global decarbonization goals and improves both structural strength and environmental performance.

Despite the challenges, several buildings worldwide have been constructed using biobased and sustainable materials by those committed to reducing CO_2 emissions and energy consumption. This paper focuses on a building in Europe constructed with hempcrete, biochar, and other bio- based materials to review their role in sustainability and lower energy consumption.

Sustainable Building Innovations in Windaus, Switzerland

As mentioned, hempcrete has become important in the construction sector in reducing carbon emissions and energy consumption. One notable example of its application can be found in Windau, Switzerland (Openly (n.d.)). This 4-story building includes 19 apartments, Fig. 2, with a total area of 2200 m², making it the first CO_2-neutral multi-family home in the region.

Materials and Methods

This innovative hybrid construction includes 100% recycled steel, prefabricated timber elements, and biobased materials. Concrete use is kept to minimum, and when necessary, biochar-enhanced concrete is used to minimize environmental impact. In summary, the biobased materials used in this building include timber, hemp, clay, biochar, cork, and straw.

(a) Construction Progress

(b) Completed Building (Openly (n.d.)).

Figure 2: 4-story CO_2-neutral multi-family building in Windau, Switzerland

In this building, there are no load-bearing interior walls, which allows greater adaptability and flexibility in interior spaces. The exterior walls are constructed by using timber frame structures filled with hempcrete (hemp-lime concrete) and covered with hemp blocks, Fig. 3. According to openly AG (Openly (n.d.)), 1500 m² of timber-frame walls were prefabricated and infilled with hempcrete, using a mobile mixing plant in just 30 days. The load-bearing system is shown in Fig. 4.

(a) Filling timber frames with hempcrete

(b) Hemp blocks (Openly (n.d.)).

Figure 3: Hempcrete

As shown in Fig. 5, the ceiling consists of a prefabricated timber hollow-box system filled with clay and reinforced with reused steel girders for load-bearing support. The hollow box ceiling has a total height of 382 mm, consisting of a 3-layer spruce panel on the top (42 mm) and bottom (60 mm), with a 280 mm hollow core filled with 140 mm of clay fill. In total, 400,000 kg of clay fill is used throughout the building's ceilings and walls, helping to improve indoor air quality and regulate humidity levels. Ribbed beams (140 × 280 mm) are hooked into reused double-T steel girders (280 mm static height) for structural reinforcement. It is worth noting that this project has initiated the largest steel beam reuse in Switzerland which makes this building even more environmentally friendly. The flooring, positioned above the hollow-box ceiling, is made of ash wood parquet, which provides durability, warmth, and a natural appearance. As a renewable material, ash wood supports the project's sustainability goals by storing carbon and reducing environmental impact.

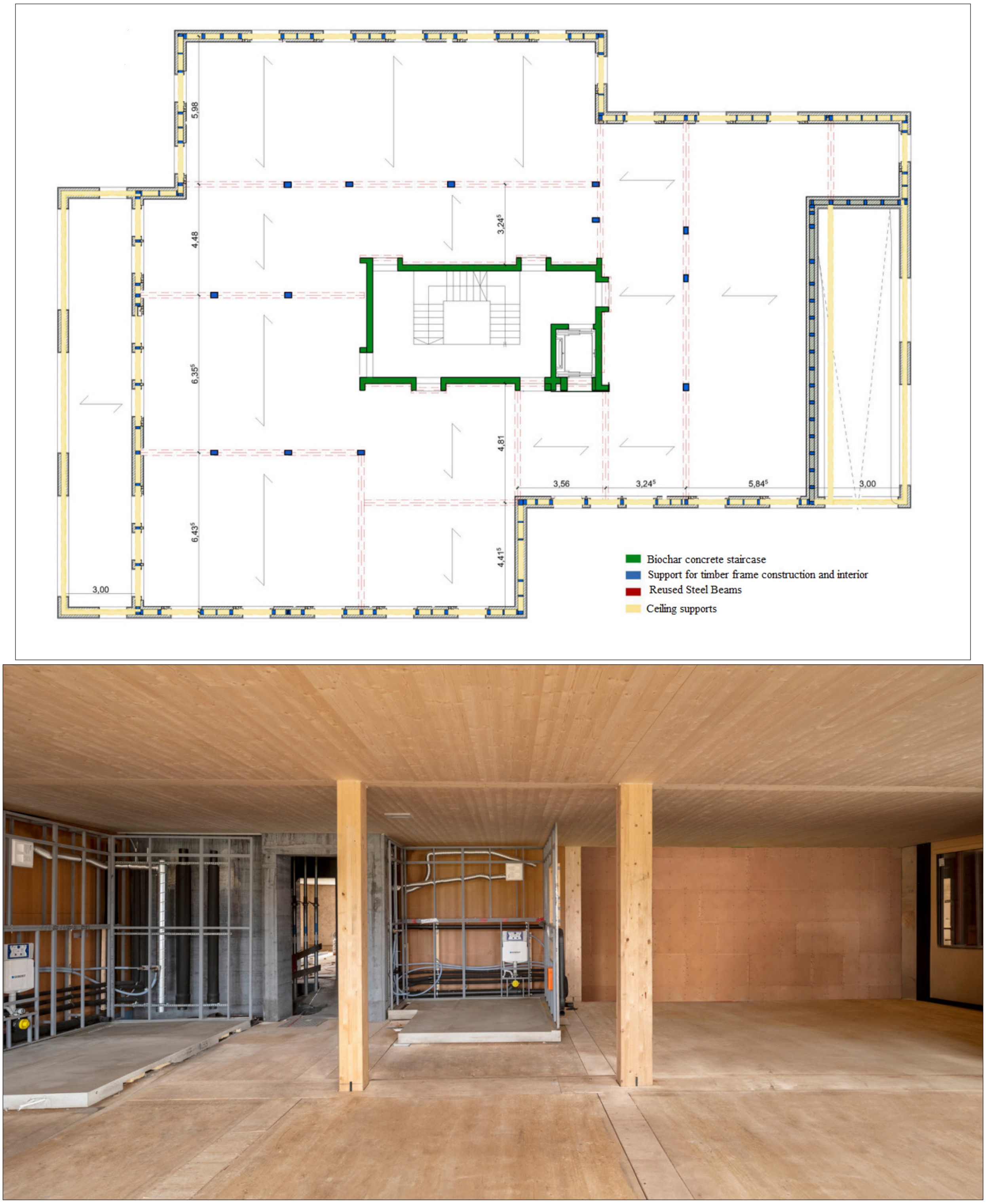
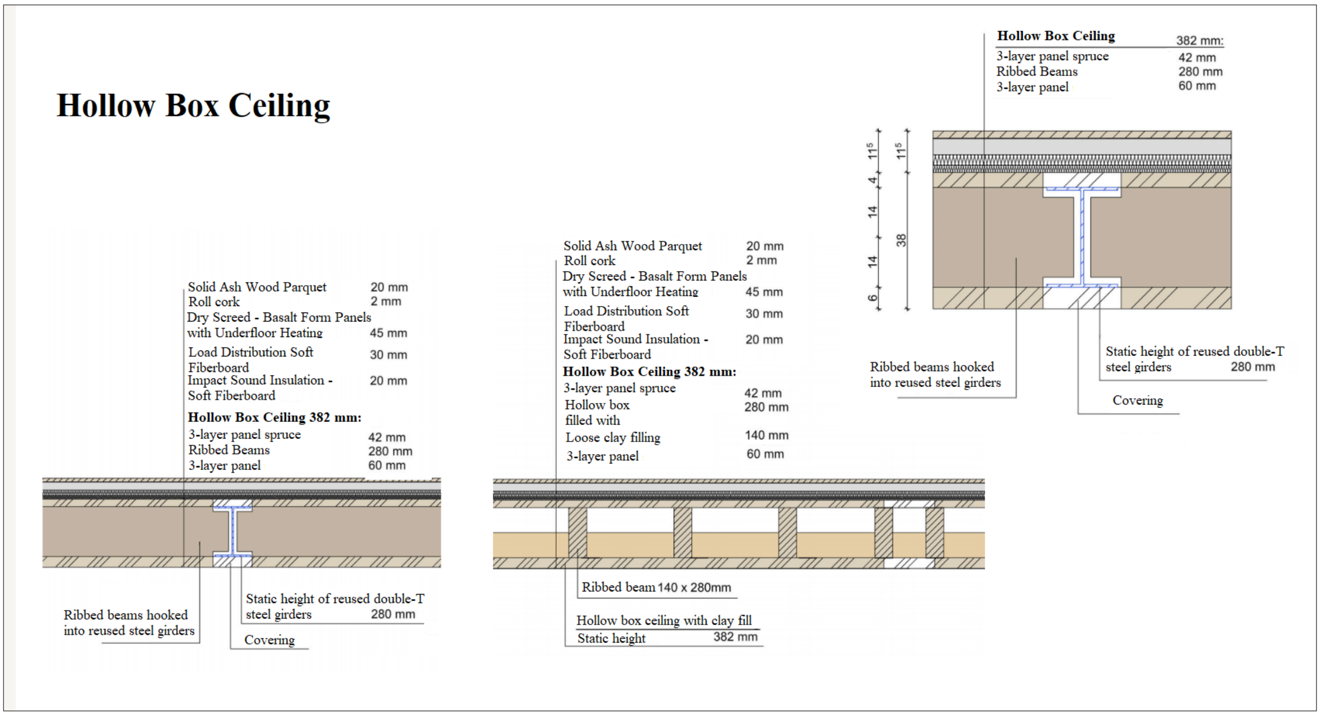


Figure 4: The load-bearing structure of the building (Openly (n.d.)).

The core staircase of the building is constructed from biochar-enhanced concrete reinforced with 100% recycled steel. Biochar is an innovative material that increases both structural integrity and sustainability. Mixing biochar into the concrete, improves thermal insulation, humidity regulation, and durability. Additionally, it stores carbon significantly. Each kilogram of biochar absorbs approximately 3 kg of atmospheric CO_2, making it a key material for reducing embodied carbon. Openly AG (Openly (n.d.)). set a record by laying 300 m³ of biochar concrete in just 14 hours per day and demonstrate the feasibility of large-scale applications of this material.



(a)

(b)

(C)

Figure 5: Ceiling Structure: (a) Ceiling section and details. (b) Timber hollow box (c) Timber hollow box filled with clay and reinforced with a reused steel beam (Openly (n.d.)).

This building follows a plus-energy concept, which means it generates more energy than it consumes. It operates with an air-source heat pump which is still efficient for this huge building through passive solar heating, intelligent energy management, and carefully chosen materials that enhance insulation and thermal efficiency.

To reach the passive solar heating goal, window areas are kept below 25%, which can balance natural lighting and energy conservation. The Compact design of this building also reduces the surface area exposed to heat loss. Cork and wood are used for insulation due to their excellent thermal resistance, breathability, and fire safety. These materials prevent unnecessary heat loss while maintaining a healthy indoor climate. Key materials such as hemp concrete, biochar-enhanced concrete, and clay play a crucial role in thermal mass storage, meaning they absorb heat during the day and release it slowly when temperatures drop. This reduces the need for additional heating. The hollow-box ceiling enhances this effect even more by storing up to 70% of its mass in ceilings, ensuring that warmth is evenly distributed.

The apartments are equipped with smart ventilation systems controlled by smart sensors. These sensors monitor the temperature, humidity, and CO_2 levels. When necessary, the system automatically opens ventilation slots near windows to allow natural air circulation.

Because of these design choices, the building requires less energy for heating and cooling than regular buildings. The result is significantly lower energy costs for residents, making it not just a sustainable choice, but an economical one as well.

Table 1 highlights the effectiveness of material choices and energy-plus strategies in achieving net- zero emissions. By using biobased materials, the building captures and locks away significant amounts of CO_2, making it an environmentally friendly structure.

Conclusion

The environmental challenges we face today demand urgent action, and the idea of CO_2-neutral buildings is no longer just a theory for the future but achievable today. The building in Windau, Switzerland, is a strong proof that it is possible to create structures that not only reduce their carbon footprint but neutralize it entirely. Through innovative and biobased materials combined with energy-efficient designs and sustainable solutions, this building demonstrates that we have the power to change the way we construct our world. It's a hopeful reminder that with the right material, creativity, and commitment, we can build a sustainable future and confront climate change.

By using materials such as hempcrete and biochar-enhanced concrete, the building captures and locks away CO_2, making it part of a carbon-negative cycle. Utilizing energy plus strategies ensures that the building generates more energy than it consumes, which reduces the environmental impacts of construction even more. Passive solar heating, intelligent energy management, and a compact design decrease the building's energy demand, while materials like cork, wood, and clay enhance insulation and thermal mass, minimizing heat loss and reducing the need for additional heating. The smart ventilation system helps maintain a healthy indoor environment, while the use of recycled steel and other sustainable building techniques contributes to the overall low environmental impact.

Table 1 demonstrates how these strategies, from material reuse to sustainable energy practices, effectively neutralize the building's CO_2 emissions, resulting in a net-zero carbon footprint over its 60-year lifespan. This project not only proves that it's possible to build with minimal environmental impact but sets a strong example for future sustainable architecture, where innovation in both materials and design can lead to buildings that support both our energy needs and the planet's health.

Table 1: CO_2 Reduction Over 60 Years

Category	CO_2 Reduction (t)
Material Reuse & Bionic Design	-120
Sustainable Energy Suppliers	-750
CO_2 stored in Building Materials	-750
Total CO_2 Emissions (60 years; 3 kg/m²) : Net Zero	

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