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Sustainable Material Innovation Design for Building Construction: Exploring Bio-Based Alternatives

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Abstract. Modern architecture stands at the convergence of innovation and sustainability, urging a reevaluation of construction materials. This paper explores the transformative potential of biomaterials in reshaping the ecological and aesthetic landscape of the built environment. By scrutinizing conventional materials' limitations, we introduce bio-based alternatives. Examining bamboo, hemp concrete, mycelium composites, and Bio-plastics reveals their unique attributes and life cycle assessments. Comparative analyses demonstrate bio-based materials' superiority in terms of carbon footprint, energy consumption, and waste generation. The innovative design strategy of bio-based materials is proposed, and the possible problems in implementation are summarized and the corresponding solutions are put forward.

Keywords. Biomaterials, sustainable construction, architectural innovation

1. Introduction

The construction industry has historically relied on traditional materials such as concrete and steel, which have proven effective in building structures but have serious environmental consequences. The construction industry is a highly active sector all over the world [1]. It is responsible for a high rate of energy consumption, environmental impact, and resource depletion[2]. Buildings have a direct impact on the environment, ranging from the use of raw materials during construction, maintenance, and renovation to the emission of harmful substances throughout the building's life cycle[3]. Resource-intensive production processes, high energy consumption and the emissions associated with these materials have led to a growing focus on their long-term sustainability. As the international community recognizes the urgency of addressing climate change and resource depletion[4], there is an urgent need to reassess building practices and explore greener alternatives[5]. As the impact of traditional building materials on the environment increases, its shortcomings become more and more obvious. Buildings consume substantial amounts of available raw materials, especially non-renewable raw materials, and produce large amounts of waste during extraction, transformation, construction, and demolition[6]. The current trajectory of construction is not sustainable. In order to minimize the environmental impact of the industry, the use of sustainable building materials has become a major focus of research and development to achieve the

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goals of sustainable construction and minimize the impact on the environment, while maintaining structural integrity and performance[7].

This paper aims to address these challenges by investigating the potential of bio-based materials as sustainable alternatives in building construction. Bio-based materials from renewable resources such as bamboo, hemp, mycelium composites, and Bio-plastics offer a promising pathway to reduce carbon footprint, conserve resources and promote eco-friendly building practices. The main objective of this study is to explore the characteristics, advantages and feasibility of incorporating bio-based materials into construction projects. By doing so, we seek to contribute to the advancement of sustainable building practices and support the transition to a more resilient and environmentally conscious built environment.

2. Conventional building materials and bio-based materials

Traditional building materials, such as concrete and steel, have long been the backbone of the built environment. However, their widespread use comes with a series of serious environmental deficiencies. Carbon emissions are alleged as a major contributor to anthropogenic climate change[8]. Buildings worldwide consume 40% of energy and contribute 33% of carbon emissions[9]. In addition, the extraction and processing of raw materials such as aggregate and iron ore consumes limited resources and destroys ecosystems[10]. Energy-intensive manufacturing processes further exacerbate the environmental impact, resulting in a significant consumption of non-renewable energy sources. As the consequences of these practices become more apparent, the urgency of transitioning to more sustainable alternatives increases.

Bio-based materials, including bamboo, hemp, mycelium composites, and Bio-plastics, have brought a promising shift towards sustainable building practices. Some of these building materials have been used for centuries, only beginning to be replaced by concrete in the 20th[11]. These materials come from renewable resources and harness nature's regenerative potential. Bamboo, for example, has impressive tensile strength while being a rapidly renewable resource. Hempcrete consists of hemp fibers and lime-based binders with excellent insulating properties and low embodied energy. Mycelium composites grown from fungi exhibit extraordinary versatility and customization potential. Bio-plastics are derived from bio-sources and provide a moldable and biodegradable alternative to traditional plastics. Bio-based materials emphasize their renewable nature and have the potential to significantly reduce dependence on fossil fuels and non-renewable resources.

In addition, bio-based materials align with circular economy principles by facilitating a cradle-to-cradle design approach. Unlike traditional materials, which often end up as waste in landfills, bio-based materials can be biodegradable or recycled, closing the loop and minimizing environmental impact. By reducing the need for resource extraction and limiting production-related emissions, these materials provide a pathway for a more regenerative construction industry.

3. Selection and performance of bio-based materials

A key aspect of exploring bio-based alternatives is understanding the unique properties and benefits that each material brings. Known for its rapid growth and superior tensile strength, bamboo offers a sustainable solution for structural components. Its inherent flexibility and elasticity make it ideal for a range of applications, from beams to floors. Architect PT Bambu has built a green school out of bamboo in Bali, Indonesia, demonstrating the versatility and strength of bamboo in architectural applications. Hemp concrete is made from hemp fibers combined with a lime binder, providing an environmentally friendly solution for insulation needs. Its porous structure regulates moisture and thermal conductivity, contributing to energy-efficient buildings. "Hemponair" in Switzerland is a private residence that uses hemp concrete as its walls. The mycelium composite originates from fungal growth and exhibits extraordinary versatility in form and function. In Brooklyn, New York, architect David Benjamin (founder of The Living Architecture Studio) has created "Mushroom Farm", an innovative architectural project that demonstrates the use of mycelium composites as a sustainable bio-based building material. These materials can be molded into a variety of shapes, providing opportunities for intricate details and innovative designs. Bio-plastics from organic sources have plasticity similar to conventional plastics while being biodegradable, thus solving the common challenge of plastic waste.

The adoption of any building material depends on its mechanical properties and durability. Extensive analysis of the mechanical properties of bio-based materials is essential to ensure their suitability for a wide range of structural elements. Bamboo's high-strength-to-weight ratio and excellent flexibility contribute to its load-bearing capacity. Although the density of hemp concrete is lower than that of conventional concrete, it exhibits remarkable insulating properties and long-term durability. Mycelium composites have inherent strength and adaptability, allowing them to withstand a wide range of loads and conditions. The mechanical properties of Bio-plastics vary by composition, offering a range of possibilities for design and function.

The performance of biobased materials on key indicators is also compared, and the performance of biobased materials is scored based on the common sense and typical characteristics of these materials as well as empirical data. The performance of biobased materials in terms of tensile strength, insulation properties, environmental impact, life cycle assessment, energy consumption, resource consumption, carbon footprint, and contained energy was compared and each material was assigned a score for each attribute on a scale of 1 to 10, with higher scores indicating better performance. See figure 1 to 4.

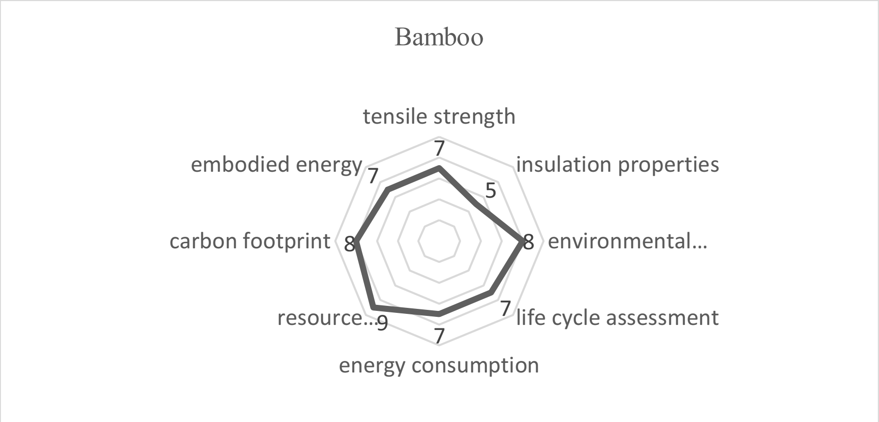

Figure 1. Bamboo fraction.

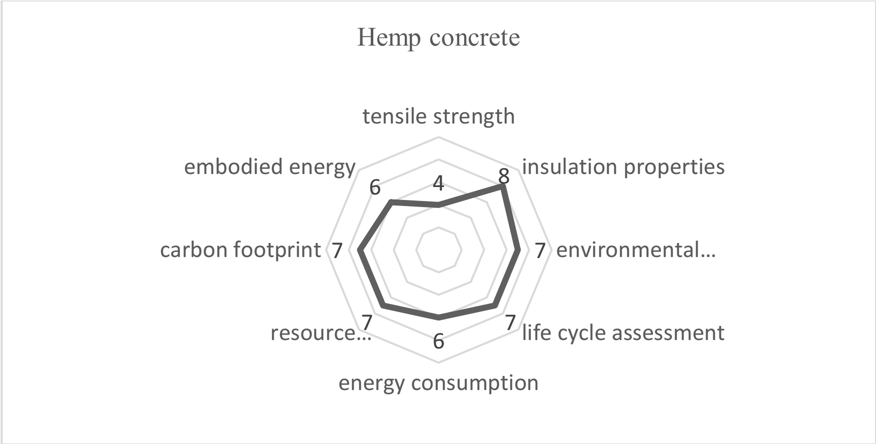

Figure 2. Hemp concrete fraction.

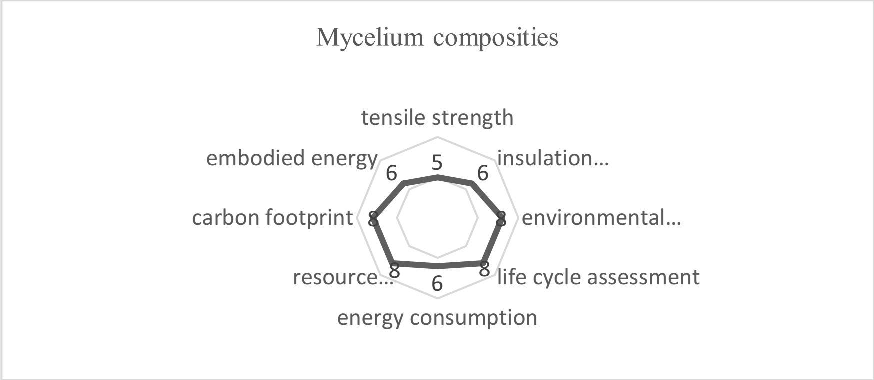

Figure 3. mycelium composites fraction.

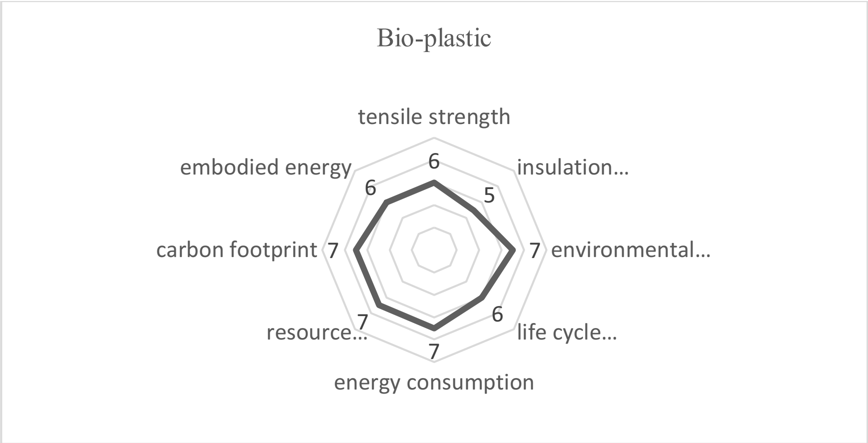

Figure 4. Bio-plastic fraction.

4. . Innovative design strategies

Biomaterials have unique intrinsic qualities that offer architects new possibilities to design flexible and uniquely attractive buildings. These materials, such as bamboo, hemp concrete, mycelial composites, and Bio-plastics, introduce a fresh departure from traditional building materials and promote innovation in architectural design. Here's how the intrinsic properties of biomaterials can enhance the flexibility and uniqueness of buildings:

4.1. Organic aesthetics, sustainability and visual appeals

Biomaterials are valued for their organic textures, patterns, and colors that resonate with nature. This organic aesthetic is not just an aesthetic choice; It is closely related to sustainability. Biomaterials enhance architectural design by creating a harmonious connection between the built environment and the surrounding natural landscape. This inner beauty adds a layer of visual interest and realism to the space. The use of biomaterials is often an environmentally conscious statement that aligns with the Sustainable Development Goals and resonates with occupants who value eco-friendly living.

4.2. Customization, adaptability and formability

One of the main advantages of biomaterials is their versatility. They allow architects to customize the design according to the unique context of each project. Biomaterials are malleable and flexible during manufacturing and assembly, making them ideal for creating custom designs. Their adaptability simplifies the implementation of complex custom structures that are difficult to achieve with traditional materials.

4.3. Ecological and cultural significance

Biomaterials transcend their physical properties. They contribute to a deeper connection between the building and the environment. Embracing biophilic design principles, biomaterials emphasize the connection between humans and nature. Elements inspired by the natural world enhance the well-being and comfort of the occupants. In addition to ecology, biomaterials can also carry cultural significance through the use of indigenous materials that reflect local traditions. The integration of culture and environment into the architectural design results in buildings that represent the unique character of the region.

4.4. Tactile experiences and mixed material applications

Biomaterials provide a multi-sensory experience through their inherent texture and tactile properties. These qualities attract occupants and promote a deeper connection and interaction with the built environment. Spaces enriched with biological materials become more inviting and memorable. In addition, biomaterials seamlessly integrate with traditional materials, allowing architects to explore innovative hybrid solutions. This mixture of materials allows for structural integrity while achieving a unique aesthetic that balances tradition and innovation.

5. Implementation challenges and solutions

While bio-based materials hold great promise, they also present unique technical challenges during construction. The transition from traditional materials to bio-based alternatives may require adjustments to construction techniques, compatibility with existing systems, and careful material handling. Meeting these challenges is critical to ensuring seamless integration.

5.1. Strength and structure

Biomaterials often have different mechanical properties than traditional building materials such as concrete and steel. Ensuring that biomaterials meet the required strength and structural integrity standards is challenging.

Solution: Material characterization: Thorough characterization of the mechanical properties of biomaterials through testing, including tensile, compressive and bending strength. Mixing systems: Combining biological materials with conventional materials in a mixing system, taking advantage of their respective advantages. This approach can help achieve the desired structural properties while taking advantage of the advantages of biomaterials.

5.2. Durability

Biomaterials are prone to degradation, moisture absorption and biological attack, affecting their long-term durability.

Solution: Handling and protection: Apply appropriate treatments, coatings or sealants to enhance the resistance of biomaterials to environmental factors. Design considerations: Design load-bearing elements to minimize exposure to moisture and potential degradation sources, thereby extending the life of biomaterials.

5.3. Standards and specifications

Compared to traditional materials, biomaterials may lack established standards and specifications, leading to uncertainty in the design and approval process.

Solution: Conduct thorough research and testing to develop empirical data that can support the development of biomaterials design guidelines and standards. Work with regulators: Work with regulators to develop clear guidelines and specifications covering the use of biomaterials in load-bearing applications.

5.4. Construction techniques

The use of biomaterials may require specialized construction techniques that differ from traditional methods.

Solution: Conduct thorough research and testing to develop empirical data that can support the development of biomaterials design guidelines and standards. Work with regulators: Work with regulators to develop clear guidelines and specifications covering the use of biomaterials in load-bearing applications.

5.5. Dimensional change

Biomaterials, such as woody materials, also change in size due to changes in moisture content.

Solution: Proper drying and conditioning: Ensure that the biomaterial is properly dried and conditioned before being incorporated into the load-bearing element to minimize dimensional variation. Motion design: Incorporate design strategies that consider potential dimensional changes, such as allowing joints to be moved.

6. Conclusion

Through the lens of bio-based alternatives in building construction, a comprehensive exploration of sustainable material innovation begins. By delving into the environmental impacts, properties, challenges and practical applications of bio-based materials, a range of insights has been uncovered, revealing their potential to revolutionize the construction industry. Observe how these materials have the ability to reduce carbon emissions, conserve resources and improve the indoor environment, ultimately contributing to a more sustainable and resilient built environment.

It resonates deeply in the field of sustainable building practices. Bio-based materials provide a way to align buildings with ecological integrity and regenerative design principles. The feasibility of transitioning from traditional materials to bio-based alternatives without compromising structural integrity or design innovation was highlighted. Exploring bio-based alternatives is a positive step towards a more sustainable future, while ensuring the viability and longevity of the built infrastructure.

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