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Trends and Challenges of Implementing Innovative Bio-Based Construction Materials for Green Infrastructure

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Abstract, *The construction industry is one of the sectors that has a significant impact on environmental damage due to high energy consumption, exploitation of natural resources, and carbon emissions. In response to these challenges, this study aims to analyze the potential for implementing sustainable construction materials to support the development of green infrastructure. Using qualitative methods through literature studies, documentation, observation, and in-depth interviews, this study evaluates the advantages, challenges, and economic and environmental impacts of various innovative materials, such as foam glass, green wall systems, bamboo composites, eco-cement, and mycelium-based blocks. The results show that these materials are able to reduce carbon emissions, increase building energy efficiency, and offer long-term cost savings. Mycelium-based blocks, in particular, are recorded as the most effective material in reducing construction costs by up to 25% and CO_2 emissions by 250 kg per project. However, the implementation of sustainable materials in Indonesia still faces obstacles such as cost, material availability, and technical regulations. Therefore, synergy is needed between the government, academics, and industry in encouraging research, preparing technical standards, and public awareness campaigns to expand the adoption of environmentally friendly materials in the national construction sector.*

Keywords: *Eco-Friendly Construction, Green Infrastructure, Sustainable Materials*

1. INTRODUCTION

The modern construction industry is faced with a fundamental dilemma, namely balancing the pace of infrastructure development with responsibility for environmental sustainability . The building sector, both directly and indirectly, is one of the main contributors to annual environmental damage, thus encouraging the need to find more environmentally friendly methods (Sumerli & Wulan (2024) .

Umar, Khamidi, & Tukur (2012) stated that sustainable development requires a paradigm shift in the way we design and build . One of the main pillars of this change is the selection of the right materials.

The environmental impact of the construction sector is massive and well documented . Buildings are responsible for the use of approximately 40% of the total natural resources extracted in industrialized countries (Pulselli et. al., 2007) . In addition to natural resources, energy consumption is also significant, with buildings using almost 70% of the total electricity generated globally .

Clean water consumption is also a concern, with the construction sector consuming around 12% of the total drinking water supply (Wang et. al., 2010) .

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The development of the construction sector currently contributes greatly to environmental degradation. Various construction activities, from the extraction of building materials to the construction process, significantly contribute to carbon emissions, exploitation of natural resources, and environmental pollution (Umar et al., 2012). In addition, the large need for space in urban areas encourages the acceleration of building construction that often ignores the principle of sustainability. Consequently, the quality of the city environment is decreasing, accompanied by increasing air pollution, construction waste, and high energy consumption.

In response to these problems, the concept of *green building* began to be developed as an effort to present environmentally friendly and energy efficient buildings. The application of sustainable construction materials is one of the main pillars in green building design. These materials not only aim to reduce environmental impacts, but also increase the comfort, health, and efficiency of buildings in the long term (Sumerli & Wulan, 2024). This is in line with the goals of sustainable development which prioritize the balance between development needs and environmental preservation.

Various studies have shown that the use of innovative materials, such as recycled concrete, bamboo composite, foam glass, and mycelium-based blocks, can significantly reduce carbon emissions, while minimizing dependence on conventional materials that are environmentally damaging (Hu et al., 2021). In addition, environmentally friendly materials have the potential to increase the energy efficiency of buildings through characteristics such as good thermal insulation and the ability to absorb air moisture.

In various developed countries such as Japan, Germany, and China, various green material innovations have been applied in large construction projects, including the utilization of eco-cement from industrial waste and municipal waste (Hu et al., 2021). An example of the application of this concept in the Asian region can be found in the K11 MUSEA project in Hong Kong which applies a green facade and living wall system, thereby improving urban air quality and reducing the temperature of the surrounding environment.

In Indonesia, efforts towards sustainable development still face various challenges, one of which is the limitations in the adoption of environmentally friendly materials. Cost constraints, material availability, and regulations are quite dominant inhibiting factors (Sumerli & Wulan, 2024). In fact, the application of this innovative material not only provides environmental benefits but also long-term economic benefits by reducing building operational and maintenance costs.

A study conducted by Umar et al. (2012) also highlighted the importance of selecting materials that take into account the life cycle of the material, starting from the raw material extraction process to the building demolition stage. The use of materials that are easily recycled, do not produce hazardous waste, and have high durability are key factors in realizing environmentally friendly buildings.

In line with this, Sumerli & Wulan's (2024) research confirms that various innovative materials have advantages in terms of cost efficiency and carbon emission reduction. The study shows that mycelium-based blocks, for example, are able to provide a reduction in construction costs of up to 25% and a reduction in CO_2 emissions of 250 kg per project, superior to conventional materials such as ordinary concrete or reclaimed wood. Therefore, this research is important to explore more deeply the potential of sustainable construction materials, especially in the context of green infrastructure projects in Indonesia. Through literature studies and case study analysis of projects that have implemented environmentally friendly materials, it is expected to obtain a more comprehensive understanding of the advantages, challenges, and prospects of implementing this innovative material in the national construction sector.

Theoretical basis

Jones and Brancart (2020) stated that mycelium-based composites are an innovative class of materials that utilize fungal root networks, known as mycelium, as natural adhesives. These materials are made by growing certain fungal species on organic waste substrates, such as sawdust, rice husks, or other plant residues. During the growth process, the dense network of mycelial hyphae binds the substrate particles together, forming a solid, lightweight composite material without the need for additional heat, pressure, or synthetic adhesives. This biological manufacturing process makes mycelium composites a fully biodegradable and sustainable alternative to conventional materials. From an engineering perspective, the mechanical properties of mycelium composites are highly dependent on several key variables, including the type of fungal species used, the composition and particle size of the substrate, and the final density of the product. In general, these materials exhibit compressive strengths comparable to expanded polystyrene (EPS) foam and can be tailored for non-structural to semi-structural applications. Their flexural strength and modulus of elasticity are also significantly affected by growth conditions and post-process treatments, such as dehydration or hot pressing, which can increase the density and strength of the internal bonds.

In addition to its mechanical properties, Jones and Brancart (2020) stated that mycelium composites exhibit excellent thermal and acoustic properties, making them promising candidates for building insulation applications. The porous microstructure of the interlocking

hyphal network effectively traps air, providing low thermal conductivity. This porous characteristic also contributes to significant sound absorption capabilities across a wide range of frequencies, which can help reduce indoor noise.

One of the most important properties of a material for construction applications is its fire resistance. Mycelium composites naturally exhibit good levels of fire resistance due to the chitin content in the mushroom cell walls and their dense composite structure. When exposed to fire, the material tends to form a char layer on its surface, which acts as a barrier to slow the spread of fire and further heat release. This property makes it safer than some polymer-based insulation materials that can melt and release toxic fumes.

Sustainable Development in the Construction Sector

The concept of sustainable development in the construction sector aims to minimize the negative impacts of development activities on the environment. According to Umar et al. (2012), the global construction industry is responsible for around 40% of natural resource use, 70% of energy consumption, and produces 45-65% of waste in landfills. Therefore, the application of *green building principles* that utilize environmentally friendly materials is a strategic step in an effort to reduce the rate of environmental damage due to construction activities.

Sustainable Construction Materials

Sustainable construction materials are materials that are selected and produced by considering the environmental impact throughout their life cycle, starting from raw material extraction, production process, use to recycling or disposal stages (Sumerli & Wulan, 2024). These materials are designed to reduce carbon emissions, minimize waste, and reuse available resources. In other words, sustainable materials not only provide structural functions but also play a role in maintaining ecosystem balance.

The main purpose of using these materials is to significantly reduce carbon emissions associated with construction activities. For example, the use of recycled concrete and reclaimed wood has been shown to reduce the demand for new natural resources, while diverting waste from landfills. This dual benefit is in line with the principles of the circular economy , which encourages more efficient and sustainable use of resources in a closed cycle.

Ultimately, sustainable materials play a crucial role in the development of green infrastructure , a concept that emphasizes the integration of natural systems into the urban environment to support ecological balance. As such, the function of these materials goes beyond mere structural elements; materials such as mycelium-based composites also contribute

to other functional aspects such as thermal insulation and humidity regulation, which in turn improves the overall performance of the building.

Types of Eco-Friendly Materials

Various types of sustainable construction materials have been widely developed, such as foam glass, green wall systems, bamboo composites, and eco-cement. Foam glass, for example, is a lightweight insulation material made from recycled glass that has good fire resistance, soundproofing, and heat insulation capabilities (Hu et al., 2021). In addition, materials such as mycelium-based composites based on mushrooms have proven effective as environmentally friendly, lightweight building materials that can absorb air humidity.

Foam Glass in Construction

Foam glass is one of the superior insulation materials made from glass waste. This material is non-flammable, resistant to moisture, and lightweight. In Europe, foam glass has been widely used as lightweight concrete aggregate and wall insulation in energy-efficient buildings (Hu et al., 2021). The main advantages of foam glass lie in its fire resistance and its ability to maintain room temperature efficiently, thereby reducing cooling and heating energy consumption.

Green Wall Systems and Their Benefits

Green wall systems or plant walls are an innovative method in supporting the concept of green buildings. This system not only provides aesthetic value, but is also able to lower the ambient air temperature, filter air pollution, and reduce the *urban heat island effect* (Hu et al., 2021). Several studies in urban areas of Asia have stated that the application of green walls can increase thermal comfort and absorb pollutants that are harmful to human health.

Eco-Cement as an Alternative Material

Eco-cement is a type of cement produced using industrial waste, combustion ash, and sewage sludge as the main raw materials. The advantage of eco-cement lies in its ability to reduce CO_2 emissions during the production process, while reducing dependence on conventional mining materials such as limestone (Hu et al., 2021). In addition, eco-cement-based concrete products have physical characteristics that are relatively equivalent to ordinary concrete, but with a lower environmental impact.

Economic Benefits of Innovative Materials

The use of innovative environmentally friendly materials not only provides ecological benefits but also economic ones. Sumerli & Wulan (2024) noted that mycelium-based blocks

can provide construction cost savings of up to 25% and reduce carbon emissions by up to 250 kg per project. In addition, materials such as bamboo composites offer advantages in terms of aesthetics, durability, and production efficiency, making them a competitive alternative material in the green construction market.

Challenges of Sustainable Materials Implementation

Despite its various advantages, the implementation of environmentally friendly materials in the Indonesian construction sector still faces a number of obstacles. Cost factors, technical regulations, and limited supply and availability in the market are the main obstacles (Sumerli & Wulan, 2024). Therefore, policy support, further research, and educational campaigns are needed for industry players and the wider community to increase the adoption of environmentally friendly materials more widely.

2. RESEARCH METHODS

Research Design

This study uses **a qualitative method** to analyze the application of environmentally friendly materials in the field of construction and sustainable infrastructure development. This method was chosen because it is able to explore the meaning, perceptions, and experiences of construction industry players related to the use of innovative materials that support environmental sustainability (Hu et al., 2021).

As expressed by Umar et al. (2012), the qualitative approach provides space for exploration of the social, technical, and environmental aspects of the application of sustainable materials, which can be measured not only quantitatively but also through narrative and contextual understanding.

Data source

The data in this study were obtained from two types of sources:

a. Primary data in the form of case studies of green building projects that have implemented environmentally friendly materials such as foam glass, green wall systems, and eco-cement.
b. Secondary data were obtained from scientific literature, journal articles, conference proceedings, and previous study reports related to sustainable construction material innovation (Sumerli & Wulan, 2024).

Data collection technique

The data collection techniques used in this research are:

1. Documentation study of project reports, scientific publications, and sustainable construction project documentation.
2. In-depth interviews with construction industry practitioners (architects, engineers, and project managers) who are directly involved in the implementation of environmentally friendly materials.
3. Participatory observation of the implementation of material use in the field to see the application process directly, as suggested by Hu et al. (2021).

Data analysis

The data obtained were analyzed using **thematic analysis** . Interview and documentation data were coded and categorized to identify key themes related to perceptions, benefits, barriers, and opportunities for implementing sustainable materials (Umar et al., 2012). Furthermore, the findings were compared with the results of previous studies to obtain data triangulation and ensure the validity of the findings.

Data Validity

Data validity is guaranteed through:

a. Source triangulation , by comparing data from interviews, observations, and documentation.
b. Peer debriefing, by asking for input from academics and practitioners regarding the interim results of the research.
c. Audit trail **,** in the form of documentation of the research process that can be traced back to check the consistency of the analysis.

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4. ANALYSIS AND DISCUSSION

Analysis of the Need for Sustainable Material Application in the Construction Sector

The construction sector globally contributes a significant proportion to environmental degradation due to high energy consumption, use of natural resources, and waste production

(Umar et al., 2012). This condition is exacerbated in urban areas with rapid population growth, which increases the need for building space without considering sustainability aspects. Therefore, the transition to the use of environmentally friendly materials is an urgent need in an effort to reduce carbon emissions and environmental pollution.

Potential of Environmentally Friendly Materials for Green Infrastructure

Based on the results of a literature study conducted by Sumerli & Wulan (2024), several types of environmentally friendly materials such as recycled concrete, bamboo composites, reclaimed wood, and mycelium-based blocks have been proven to reduce environmental impacts and offer construction cost efficiency of up to 25%. In addition, these materials have good thermal insulation capabilities, are weather resistant, and are easily recycled, thus supporting the principle of *a circular economy* in the construction sector.

Advantages of Foam Glass as Building Insulation Material

Foam glass is a building insulation material made from recycled glass that has high resistance to fire, humidity, and excellent heat and sound insulation capabilities (Hu et al., 2021). In addition to its technical advantages, foam glass also plays an important role in reducing the need for natural materials such as stone and sand for concrete aggregates, which have contributed to the destruction of river and hill ecosystems due to mining activities.

Effectiveness of Green Wall System in Urban Environment

The application of the green wall system has been proven to reduce room temperature, improve air quality, and reduce the urban heat island effect in metropolitan areas (Hu et al., 2021). In addition to ecological benefits, this system also adds aesthetic value and psychological comfort to building occupants. The implementation of the green wall has been successfully implemented in the K11 MUSEA project in Hong Kong, which has made a significant contribution to improving the environmental quality around the downtown area.

The Role of Eco-Cement in Reducing Emissions in the Cement Industry

Eco-cement is an innovation in industrial solid waste-based materials developed to reduce carbon emissions from conventional cement production. A study by Hu et al. (2021) showed that eco-cement production can reduce the consumption of mining materials such as limestone and reduce the need for landfills for solid waste. In terms of performance, eco-cement-based concrete shows compressive strength equivalent to ordinary Portland concrete, making it an economical and environmentally friendly alternative.

Economic Impact of Innovative Materials in Infrastructure Projects

In addition to environmental benefits, innovative materials also offer positive economic impacts. Sumerli & Wulan (2024) noted that the use of mycelium-based blocks in 10 green

infrastructure projects was able to generate cost savings of up to 25% compared to conventional materials, while reducing CO_2 emissions by up to 250 kg per project. This condition proves that a relatively higher initial investment in sustainable materials can provide long-term benefits in the form of operational efficiency and building maintenance.

Barriers to Implementing Environmentally Friendly Materials in Indonesia

Despite having many advantages, the implementation of environmentally friendly materials in Indonesia still faces various challenges, including relatively higher material prices, limited distribution in areas outside large cities, and the absence of standard technical regulations (Sumerli & Wulan, 2024). This is reinforced by the results of a study by Umar et al. (2012) which stated that the weak awareness of construction industry players regarding sustainability is the main inhibiting factor in the implementation of *green materials* in developing countries.

The Role of Government Policy and Public Education

The government has a strategic role in encouraging the adoption of sustainable materials through the formulation of fiscal incentive policies, technical standards for environmentally friendly materials, and public education on the importance of green infrastructure (Umar et al., 2012). Without strong regulatory support and public awareness campaigns, the transition to sustainable construction will be difficult to achieve evenly across various regions in Indonesia.

Future Prospects for Sustainable Material Development

Looking at global trends and literature study results, the development of sustainable materials has bright prospects in the future. Innovations based on bio-material technology such as mycelium composites and bamboo composites are predicted to be the main solution to replace conventional materials that damage the environment (Sumerli & Wulan, 2024; Hu et al., 2021). In addition, collaboration between academics, industry, and government is expected to accelerate research and commercialization of these innovative materials in large-scale infrastructure projects in Indonesia.

5. CONCLUSION

Based on the analysis of the literature studies that have been conducted, the main conclusion that can be drawn is that innovative bio-based construction materials show a positive trend and transformative potential for the future of green infrastructure . The most significant finding is the outstanding performance of mycelium-based blocks, which consistently show the highest cost reduction and carbon emissions compared to other materials

studied . Bamboo composites also emerge as a superior material that offers a combination of structural strength, flexibility, and high aesthetic value .

The benefits of bio-based materials are not only limited to environmental aspects, but also include increased project efficiency, building durability, and stakeholder satisfaction . This study makes an important contribution by presenting a comprehensive comparative analysis between different types of sustainable materials . However, the journey towards mass adoption is still long and is faced with real and complex challenges . The main barrier consistently identified is the initial cost, which is considered high by developers . The lack of established regulatory standards is also a significant barrier, creating uncertainty for practitioners in the field .

Issues of raw material availability and production scalability for large projects also need to be addressed . Supply chains for these innovative materials are often not mature enough to support broad market demand . In addition, the lack of empirical data on the durability and long-term performance of these new materials is a source of doubt that needs to be answered through further research . Therefore, future research should prioritize longitudinal studies to test the durability of these materials under various conditions over long periods of time .

Developing more efficient and scalable manufacturing processes is also key to addressing cost and availability issues . Close collaboration between research institutions, industry, and government is crucial . This collaboration is needed to create a supportive ecosystem, through the development of standards, provision of incentives, and dissemination of knowledge . The integration of innovative sustainable materials is a vital step towards the advancement of green infrastructure . By continuing to emphasize their benefits and proactively seeking solutions to existing challenges, the construction industry can move towards a more sustainable future . This effort is in line with the global call for a greener, more resilient, and more hospitable built environment for future generations . Overall, the future of sustainable construction lies in intelligent material innovation and thoughtful implementation .

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