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STUDY OF BIO BASED COMPOSITES FOR STRUCTURAL APPLICATION

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ABSTRACT

The quest for sustainable materials in building construction has generated growing interest in the use of bio-based materials for structural purposes. This review paper reviews the mechanical performance of structural members fabricated from bio-based materials such as natural fibres, bio-based polymers, and engineered wood products. Major mechanical properties like tensile, compressive, and flexural strength, as well as durability against environmental stressors, are reviewed to determine their viability for load-bearing purposes.

The article also addresses influences on mechanical behavior, such as moisture absorption, temperature sensitivity, and manufacturing methods. Comparative analysis is presented for the performance of bio-based materials compared to traditional materials such as steel and concrete, highlighting both their advantages and disadvantages. Improvements in bio-based composites, such as hybridization and nanotechnology, are discussed for their ability to enhance mechanical strength.

Moreover, sustainability parameters, including life cycle assessment and end-of-life biodegradability, are assessed to highlight the environmental advantages of bio-based structural members. The paper ends with future research directions, calling for innovation in bio-based material technology to fulfill structural requirements and facilitate the construction industry's transition toward greener practices. This review is intended to give engineers and researchers a basic understanding to incorporate bio-based materials into sustainable structural designs.

Keyword : - Bio-based materials, Mechanical performance, Sustainable construction, Structural applications, Natural fibre composite

INTRODUCTION

Structural members in building construction are the basic elements that constitute the skeleton of buildings, bridges, and other structures, conferring stability, strength, and durability. Such elements, intended to carry and transmit loads, are categorized according to their function, shape, and material. Major structural members are beams, columns, trusses, slabs, and foundations, each serving a particular purpose in the transmission of forces within a structure. Beams are flat members that resist bending and shear forces, distributing loads to columns or walls. Columns, being vertical members, are intended to resist compressive loads, carrying the weight above. Trusses, made of triangular components, are lightweight but strong frameworks often employed in roof structures. Slabs, generally of reinforced concrete, create smooth horizontal surfaces, like ceilings and floors, that transfer loads to beams or walls. Material selection for these members—like steel, concrete, wood, or composite materials—is based on considerations such as load-carrying needs, exposure conditions, and economy [17], [89], [100]. Materials technology and advancement have improved structural member design to result in stronger, more efficient structures. Structural elements have to be properly designed to guarantee stability, safety, and durability in every form of building construction.

Sustainable and bio-based materials are revolutionizing construction by minimizing environmental footprint and maximizing resource efficiency. In contrast to traditional materials, bio-based materials like bamboo, hemp, mycelium, and recycled wood are produced from renewable resources, reducing the dependence on fossil fuels and lowering carbon emissions during their lifecycle [101], [196], [43]. Sustainable materials tend to have less energy-intensive production processes, thus becoming an environmentally friendly option that helps lower overall greenhouse gas emissions.

The construction industry, known for its significant resource consumption and waste generation, benefits immensely from these materials, as they are typically biodegradable or recyclable, reducing landfill use and promoting a circular economy. Bio-based materials, such as hempcrete and cross-laminated timber, offer excellent insulation properties, improving building energy efficiency and reducing operational energy costs [116], [181], [63], [93]. In addition, these materials promote healthier indoor spaces since they are often free of harmful chemicals embedded in synthetic alternatives. Bio-based material use also promotes biodiversity and has the potential to generate employment in agricultural and forestry industries, generating sustainable economic development [114], [211], [220]. As climate change deepens, sustainable and bio-based materials offer a critical avenue through which the construction sector can drive environmental objectives, reduce carbon footprints, and develop resilient, sustainable infrastructure to the benefit of future generations.

Recent developments in bio-based materials for structural use target enhanced mechanical performance and durability. Hybrid composites of natural fibres with synthetic or bio-based polymers are a major innovation, providing greater strength, lower moisture sensitivity, and better thermal stability. Nanotechnology also transforms bio-based materials by the addition of nanocellulose, graphene, and other nanoparticles, greatly enhancing tensile strength, elasticity, and resistance to environmental degradation. These innovations overcome shortcomings of bio-based materials, including their inherent variability and sensitivity to environmental conditions, making their integration into contemporary structural design and encouraging green construction a real possibility.

Although structural members play a critical role in construction, most attention has gone to traditional materials such as steel and concrete, with less investigation of bio-based products. Biomaterials such as bamboo, hemp, and cross-laminated timber have high environmental and energy efficiency benefits. Despite this, however, there is still a gap in the knowledge of their performance, durability, and working into structural designs. Assessing bio-based materials as potential substitutes for structural elements is essential for promoting sustainable building practices and limiting the environmental footprint of the construction industry. Resolving these challenges can promote greater use of sustainable materials, supporting more sustainable and resilient infrastructure construction.

The aims of this review are developed to tackle particular knowledge gaps in the application of bio-based materials for structural purposes. Some of the important areas are assessing their mechanical behavior—tensile, compressive, and flexural strength—and durability under a range of environmental conditions. The review presents the challenges such as moisture absorption, sensitivity to temperature, and mechanical constraints while looking at innovation in hybridization and nanotechnology to improve performance. Methods of incorporating bio-based materials into contemporary construction are explored, with an emphasis on production processes and comparison to traditional materials. These goals intend to inform engineers and researchers how to overcome hurdles to adoption to facilitate the construction industry's transition to sustainable processes.

OVERVIEW OF BIO-BASED MATERIALS IN STRUCTURAL APPLICATIONS:

Bio-based materials are materials obtained from renewable biological resources, including plants, animals, and microorganisms. Unlike conventional materials, which tend to be based on fossil fuels, bio-based materials utilize naturally occurring biological processes and raw materials, which encourage sustainability. Bio-based materials may consist of bio-polymers, natural fibres, bio-composites, and bio-chemicals, which are used in packaging, automotive, construction, and healthcare industries. The defining feature of bio-based materials is that they are either partially or completely produced from biological materials, which contributes to a decrease in greenhouse gas emissions as well as the use of non-renewable resources.

Bio-based materials are usually categorized into a number of different groups depending on their origin and structure. One of the broad categories is polymers, for example, polylactic acid (PLA), which comes from corn starch, and polyhydroxyalkanoates (PHAs), which are created by microorganisms. Another group is natural fibres, such as bamboo, jute, and flax, commonly applied in textiles and composite materials. Bio-composites also stand out, where natural fibres are infused in a bio-based or synthetic matrix for enhanced mechanical properties. Finally, bio-chemicals are chemicals that are made through biological processes like bio-ethanol and bio-diesel. This categorization enables industries and researchers to nominate certain bio-based materials for specific applications, eventually paving the way for the transition towards a more sustainable, circular economy.

Table 1 classifies bio-based materials into type, with examples, sources, and applications, to demonstrate the variety and potential of these renewable materials. Polymers such as PLA and PHA, made from corn or sugarcane, are applied in packaging and medical devices because they are biodegradable. Natural fibres such as bamboo and jute offer environmentally friendly alternatives for the textile and automotive interior industries. Bio-composites bring together natural fibres and polymers for strong construction and car applications. Bio-chemicals such as bio-ethanol are sustainable fuels. Other ranges such as bio-adhesives and bio-coatings demonstrate advances in bonding and protective coatings to facilitate the move towards greener industrial processes.

Table 1. Classification and applications of bio-based materials.

Category	Examples	Source	Applications
Polymers	PLA, PHA, Starch-based Plastics	Corn, sugarcane, microorganisms, Algae and Seaweed, Oil crop	Packaging, 3D printing, medical implants
Natural Fibres	Bamboo, Jute, Flax	Plants	Textiles, automotive interiors, furniture
Bio-Composites	Wood-plastic composites, Natural fibre-reinforced polymers	Wood fibres, hemp, flax	Construction, automotive parts, consumer goods
Bio-Chemicals	Bio-ethanol, Bio-diesel, Lactic acid	Corn, sugarcane, plant oils	Fuel, solvents, food preservatives
Bio-Adhesives	Soy-based adhesives, Casein glue	Soybeans, dairy proteins	Woodworking, construction, paper products
Bio-Coatings	Chitosan, Cellulose-based coatings	Crustacean shells, plant cell walls	Food packaging, paper coatings, medical wound dressings
Biodegradable Plastics	PBAT, PBS, PCL	Sugar, plant oils	Packaging, agricultural films, single-use items

TYPES OF BIO-BASED MATERIALS FOR STRUCTURAL USE

Natural fibres such as hemp, flax, and bamboo are becoming increasingly popular for use in their structural applications because they are strong, lightweight, and renewable. These fibres are either utilized as reinforcements in bio-composites or are used to improve the mechanical properties of building materials, automotive parts, and furniture pieces. Hemp with its tensile strength is best suited for tough, lightweight composites. Flax is utilized in insulation and panels and offers superior thermal and acoustic characteristics. The inherent stiffness and flexibility of bamboo are why it's widely used in structural frameworks and flooring. Its use decreases the reliance on man-made materials and encourages environmentally friendly, sustainable construction solutions.

contrasts two reinforced concrete beam configurations, one using natural fibre rebars and steel stirrups (a) and the other with steel rebars and natural fibre-reinforced polymer (NFRP) stirrups (b). Natural fibre rebars are the main reinforcing bars in configuration (a), supported by steel stirrups in terms of additional shear reinforcement. In configuration (b), the steel rebars are the primary reinforcement and the stirrups are NFRP, providing improved corrosion resistance and sustainability. Both designs investigate the integration of natural fibres in concrete structures, favouring environmentally friendly substitutes for conventional steel reinforcements, possibly enhancing durability and minimizing environmental footprint.

Hemp fibres have drawn interest for structural applications because of their mechanical properties, sustainability, and potential as green reinforcements in composites. Mwaikambo & Ansell report that alkali treatment enhances tensile strength of hemp fibres to be used in construction reinforcement materials. Kabir et al. also established the impact of chemical treatments, which include fibre structure enhancement, bonding, and durability in composites. Baghaei et al.worked on aligned hemp fibres for bio-composites, reporting increases in mechanical performance and resistance to moisture, which are essential for structural use. Together, these researches highlight the potential of hemp in minimizing environmental footprint with added structural advantages in construction use. Menna et al. investigated the reinforcement of masonry panels using hemp fibre composite grids with enhanced structural resistance and performance. Likewise, Donatelli et al. ested hemp's aging characteristics under several treatments, its applicability in the Mediterranean climate, where environmental resistance is a priority. In recent research, Di Sarno et al. examined hemp-fibre-reinforced concrete, lighting its toughness and sustainability as a replacement for conventional building materials.

Flax fibre is becoming more known as a useful material for building purposes owing to its durability, lightweight composition, and environmental friendliness. Goutianos et al. studied flax fibre fabrics as reinforcements in composite materials, indicating that they have the potential to contribute to increased structural stiffness. In a similar manner, Bodros et al. tested biopolymers reinforced with randomly dispersed flax fibres and determined that these composites can fulfill structural demands, particularly for lightweight applications. Carbon-flax hybrid composites were investigated by Fiore et al. indicating that flax can offer mechanical toughness and enhance the strength of carbon, leading to high-performance, sustainable materials. Yan et al. presented a critical review of flax composites, highlighting their structural potential based on favorable energy sorption and environmental advantages. Missing and Haag discussed flax fibre within composite reinforcements based on its biodegradable nature and favorable mechanical properties. Baley et al. critically reviewed the variability of flax fibre properties and concluded that although some inconsistencies were found, flax was still viable for composite reinforcement. Rahman also emphasized the mechanical and damping properties of flax composites, which can be used for vibration-resistant applications like automotive and construction industries. These studies in aggregate support flax as a sustainable, high-performance material for structural engineering.

Bamboo has emerged as a sustainable material for structural purposes because of its high strength-to-weight ratio, fast renewability, and flexibility. Research into the mechanical properties of bamboo emphasizes its potential for scaffolding because of its strong structural integrity Additional research has shown that bamboo is resistant to buckling as columns, indicating its suitability under compression in structural systems . Investigations into bamboo as a reinforcement material in concrete show that it can successfully reinforce concrete members, offering a lightweight, economical substitute for steel in certain applications Environmental and economic evaluations of the benefits of bamboo highlight its suitability as a green structural material with real advantages in sustainable building . Studies on lightly treated bamboo identify it as ready for direct application in structural uses [188], whereas engineered bamboo provides improved performance and stability, broadening its potential in structures Under tropical conditions, the durability of bamboo in wet conditions facilitates its use in building structures . Developing codes for bamboo design ensure its standardization in building . Bamboo composites are used more in the field of structural engineering, with progressively better durability over time .

Some of the major trends in bio-based construction materials are the increasing use of hemp, flax, and bamboo for their mechanical properties, sustainability, and environmental friendliness. Hemp's alkali and chemical treatments increase its tensile strength, durability, and resistance to moisture, making hemp a perfect candidate for composites and concrete reinforcement. Flax fibers exhibit very good structural stiffness, vibration damping, and biodegradability, commonly applied in lightweight applications and hybrid composites. The high strength-to-weight ratio, fast renewability, and engineered configurations of bamboo widen its structural uses, particularly under humid conditions. Complications arise from material property variability, while innovations in treatments, hybridization, and standardization are enhancing performance and scaling up adoption.

Wood and engineered wood products:

Wood and wood-based products are multi-purpose bio-based materials that find extensive applications in structural use because of their renewability, low carbon intensity, and high mechanical properties. Conventional wood, harvested in a sustainable manner, offers structural members like beams, columns, and trusses, which are characterized by high strength-to-weight ratio and inherent aesthetic value. Engineered wood products, such as cross-laminated timber (CLT), glued laminated timber (glulam), and laminated veneer lumber (LVL), provide greater uniformity, stability, and performance by merging layers of wood bonded together with adhesives. Th
ese innovations overcome the shortcomings of natural wood, such as warping and inconsistency, allowing them to be used in larger, more sophisticated structures.

Wood and engineered wood are beneficial to sustainable construction through carbon sequestration, minimizing dependence on energy-consuming materials such as steel and concrete, and optimizing the use of resources. Treatments and fabrication methods are further innovated to maximize durability and resistance to weathering, which make these materials vital to sustainable and resilient structural forms. Table 2 compares the benefits of engineered wood to solid wood.

Engineered wood has superior strength-to-weight ratios, increased dimensional stability, consistent fire resistance, and optimized resource usage. It allows longer spans, as opposed to solid wood, whose performance is hampered by inherent flaws, tendency to warp, quick collapse during fires, and limited dimensions.

Table 2. Comparison of engineered wood vs. solid wood: key properties and advantages.

Property	Engineered Wood	Solid Wood
Strength-to-Weight Ratio	Higher (e.g., CLT, glulam)	Lower (grain, knots limit strength)
Dimensional Stability	High	Susceptible to warping
Fire Resistance	Predictable charring	May crack and fail rapidly
Sustainability	Highly efficient use	Limited by tree size
Span Capabilities	Long spans (e.g., glulam)	Limited by tree length

shows a wooden building structural framework, demonstrating the application of engineered wood components in different structural functions. It shows floor panels and beams that carry horizontal loads, with truss chords strengthening the roof structure. The figure also labels tension elements and compression elements in the framework, which are parts that carry tensile (pulling) and compressive (pushing) forces, respectively. This design illustrates how engineered wood elements can be employed to develop a strong, load-carrying structure, leveraging the inherent strength of wood to carry vertical and lateral loads in an efficient, sustainable way in construction.

ENVIRONMENTAL AND ECONOMIC ADVANTAGES:

The utilization of bio-based materials for structural purposes presents substantial environmental and economic benefits, making them a sustainable solution compared to traditional materials. Obtained from renewable sources like wood, bamboo, and crop by-products, bio-based materials lower dependence on fossil fuels, decrease greenhouse gas emissions, and support sustainable agriculture and forestry practices. Bio-based materials help create healthier ecosystems by limiting pollution and waste while enhancing biodiversity. Their reduced carbon footprint and renewability help reinforce global efforts against climate change, making them part of environmentally sustainable construction practices.

Economically, bio-based materials offer several advantages, such as lower material and production energy costs. Due to their frequently lower weight in comparison with conventional materials, transportation as well as assembly is easier, which additionally leads to lower energy consumption and costs. Additionally, bio-based materials have the ability to generate regional economies through local demand for renewable resources, promoting green job creation, and sustainable production and processing industries. The compatibility of bio-based materials with environmentally friendly building standards, including LEED and BREEAM, maximizes property value and marketability, making them more likely to be used in the building sector. Research highlights the revolutionary impact of bio-based materials, although obstacles remain. Research, for example, by Pawelzik et al. has proven that bio-based materials tend to have lower carbon profiles and less fossil fuel use. Yet, inconsistencies in Life Cycle Assessment (LCA) methods make quantification of these advantages challenging, necessitating standardized procedures to provide sound evaluations. For instance, Krasny et al. contrasted a bio-based house with a traditional concrete building and found significant environmental advantages such as lower emissions and energy consumption in the bio-based house. In spite of these benefits, economic viability frequently also depends on local factors, such as access to and price of indigenous renewable resources, which may be problematic in some regions.

The incorporation of bio-based materials into circular economy systems makes them more sustainable. Spierling et al. highlighted the necessity for enhanced recycling and biodegradation processes to ensure maximum environmental impact reduction of bio-based materials. Le et al. also pointed out that although circular bio-based building materials can minimize waste and environmental damage, their limited use in actual applications underscores the necessity for more holistic assessments and practical implementation plans. Also, although bio-based composites and panels may provide reduced emissions in production, higher costs for transportation and processing can be incurred if the materials are not locally sourced This highlights the need for localized supply chains to improve both environmental and economic sustainability.

Policy incentives and technological advancements are important to overcome these challenges. AliAkbari et al. have contended that strong government policies in terms of subsidies, incentives, and research grants are necessary to make bio-based materials economically viable. Breakthroughs in material science, like hybrid composites and nanotechnology, can enhance the cost-effectiveness and functionality of bio-based alternatives, making them more suitable for widespread use in the construction industry. In conclusion, bio-based materials have great potential to revolutionize structural applications through significant environmental and economic advantages. Overcoming challenges in cost, lifecycle analysis, and recycling will be the determining factor in realizing their full potential, guaranteeing their contribution to a sustainable future.

CHALLENGES IN ADOPTION AND IMPLEMENTATION:

Implementing bio-based materials for structural applications is fraught with many challenges, restraining their mass adoption despite their huge environmental advantages. These include economic, regulatory, performance, and perception barriers that need to be overcome in order to upscale their adoption effectively. One of the biggest economic challenges is the initial expense of bio-based materials, which tends to exceed their long-term financial and environmental rewards. Such large projects, especially, are hit hard by these costs, according to Dace et al. [56]. Limited subsidies and financial incentives compound the problem further, rendering bio-based alternatives uncompetitive with traditional materials such as steel and concrete. Additionally, supply chain limitations prevent scalability due to the dependence of many bio-based materials on region-specific resources. This dependency raises transportation costs and increases vulnerability to shortages, particularly in areas with inconsistent agricultural outputs or insufficient processing infrastructure.

Regulatory issues also strongly hamper adoption. As noted by Zerari et al. [216], regulatory frameworks for the construction industry are adapted to traditional materials, and thus certification processes for bio-based counterparts are more complicated and expensive. The absence of standardized performance metrics for evaluation of structural performance further exacerbates the issue. Lacking regular benchmarks, as emphasized by Dams et al. [57], bio-based materials are unable to command the confidence of engineers and constructors, particularly for load-bearing purposes. Such regulatory loopholes cause delays in approvals and stifle innovation in the development and use of materials. Performance issues, especially durability and maintenance, are still another major obstacle. Bio-based materials are generally viewed as less durable compared to their traditional counterparts, necessitating increased replacement and maintenance. This awareness, reported by Yang et al. [211] and Hairon Azhar et al. [85], breeds concern among stakeholders and confines their usage in long-term structural construction works. Although innovations such as hybrid composites and nanotechnology are enhancing performance, general awareness and confidence in these technologies are not yet available.

Public and industry attitudes also have a key role in restricting adoption. Misunderstandings regarding the reliability of bio-based materials, combined with a lack of knowledge regarding their environmental and economic advantages, deter their wider application. Educational programs aimed at industry experts and the general public are necessary to eliminate these misunderstandings and emphasize the benefits of bio-based materials. These efforts also tackle major challenges that inhibit their adoption and advancement, such as misconceptions among the public, economic hurdles, and logistical inefficiencies. Industry professionals and the public must be addressed through educational programs to eliminate knowledge gaps and misconceptions regarding bio-based materials. Awareness about their environmental and economic advantages can push their acceptance and demand, consistent with the study's aim of advancing green solutions.

Additionally, while digital fabrication technologies, as discussed by Bitting et al. [35], hold promise for enhancing bio-based material applications, their integration requires significant investment and specialized training. This need for new skills further slows the adoption process. To overcome these challenges, a multifaceted approach is required. Establishing clear and standardized performance metrics can enhance trust and facilitate regulatory approvals. Supportive policies, such as subsidies, tax incentives, and research support, are crucial in enhancing economic feasibility and stimulating innovation. Opening supply chain infrastructure and stimulating local production can lower cost and enhance accessibility. Supportive policies, like subsidies, tax incentives, and research support, are critical to overcoming the economic challenges of bio-based materials.

These actions enhance their affordability and drive innovation, directly influencing the feasibility and scalability of solutions presented in the study. Additionally, upgrading supply chain infrastructure and encouraging local manufacturing can lower costs and make the solutions more accessible, overcoming pragmatic obstacles to adoption on a mass scale. Through connecting these proposals to the opportunities and challenges in the study,

The sentences give practical routes toward fulfilling its purposes. They stress the necessity of a multifaceted strategy, combining education, policy, and infrastructure investment to speed the shift towards bio-based materials. Educational campaigns and coordinated efforts between industry players, policymakers, and researchers can transform attitudes and win acceptance. Through the elimination of these obstacles, bio-based materials can move from niche use to widespread construction practice, leading to a more sustainable and environmentally conscious construction sector. Such endeavors are essential in order to make the most out of bio-based materials in curbing climate change and ensuring sustainable development.

CONCLUSIONS

The application of bio-based materials in construction offers a promising transition towards sustainable construction, with immense environmental, economic, and social advantages. Made from renewable resources like bamboo, hemp, and engineered wood, these materials offer a green alternative to conventional construction materials such as steel and concrete. Although bio-based materials exhibit strengths in thermal insulation, lightness, and carbon sequestration, their effective implementation in structural applications hinges on the resolution of issues associated with mechanical variability, durability, and scalability.

Breakthroughs in material science, such as hybrid composites and nanotechnology, are overcoming many of the shortcomings of bio-based materials. Blending natural fibres with synthetic or bio-based polymers enhances their mechanical properties, including tensile strength, stiffness, and resistance to impact. These breakthroughs allow bio-based materials to be compatible with the performance requirements needed for load-bearing and high-stress applications, opening up greater possibilities for mainstream construction. In addition, integration with smart material systems and the application of advanced processing

technologies further improve the adaptability and robustness of bio-based structural elements.
From a green perspective, bio-based materials help to mitigate greenhouse gas emissions and support a circular economy. They have a reduced carbon footprint and are renewable, which aligns with global sustainability objectives, like those contained in the United Nations Sustainable Development Goals (sdgs). Life Cycle Assessments (lcas) show that the materials provide significant benefits compared to traditional materials when it comes to energy efficiency and end-of-life management, such as recycling and biodegradation. Standards for lcas and regulatory structures are, however, essential to provide uniform evaluation and quality assurance across applications.
The commercial scale-up of bio-based materials would need to overcome barriers such as prohibitive production costs, low infrastructure, and the demand for process techniques that are specialized. Policy-level measures that include fiscal incentives, research grants, and industry support are, therefore, critical to widespread penetration. Moreover, enhancing awareness and education among industry players can speed up the adoption of bio-based materials in construction processes.
In summary, bio-based materials have the potential to transform the construction sector by providing sustainable and robust alternatives to traditional materials. With ongoing research, innovation, and partnership among academia, industry, and government, these materials can transcend current limitations and become a keystone of green construction to make the world greener and resource-efficient in the future.

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