Bio-Based Materials for Construction: A Global Review of Sustainable Infrastructure Practices

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Abstract- The construction industry is a major contributor to global carbon emissions, resource depletion, and waste generation, driving the search for more sustainable material alternatives. Bio-based materials have emerged as a promising pathway toward low-carbon, circular, and resource-efficient infrastructure, offering the potential to replace or complement conventional materials such as cement, steel, and plastics. This global review synthesizes current knowledge on the role of bio-based materials in sustainable construction, examining their applications, benefits, challenges, and emerging trends across diverse regional contexts. This categorizes bio-based materials into key groups, including engineered timber, bamboo, hempcrete, agricultural residue-based products, mycelium composites, and biopolymers. Findings reveal that timber innovations such as cross-laminated timber (CLT) are reshaping urban skylines in Europe and North America, while bamboo and agricultural residues play a critical role in affordable housing across Asia, Africa, and Latin America. These materials demonstrate substantial environmental advantages, including carbon sequestration, biodegradability, and reduced embodied energy, alongside economic and social benefits such as job creation in local supply chains and improved housing affordability. However, the widespread adoption of bio-based construction materials faces persistent challenges. Technical barriers include durability, fire resistance, and performance standardization, while policy and regulatory frameworks often lag behind material innovations. Economic competitiveness with conventional materials and limited expertise among professionals further restrict uptake. Despite these challenges, emerging trends such as digital integration (BIM, digital twins), hybrid construction approaches, and advanced bio-composites indicate a rapidly evolving field with strong potential for scaling. This concludes that bio-based materials hold significant promise for advancing sustainable infrastructure, but their success depends on multidisciplinary collaboration, supportive policy environments, and context-specific research. By fostering global knowledge exchange and aligning innovation with local needs, bio-based materials can become a cornerstone of sustainable construction practices worldwide.

Index Terms- Bio-Based Materials, Sustainable Construction, Green Infrastructure, Renewable Resources, Lifecycle Assessment, Environmental Impact, Carbon Footprint Reduction, Energy Efficiency, Circular Economy, Material Innovation, Building Performance, Sustainable Design

I. INTRODUCTION

The construction industry plays a pivotal role in global economic development but remains one of the largest contributors to environmental degradation. Conventional construction materials such as cement, steel, and plastics, while essential to modern infrastructure, have significant ecological footprints (Nath *et al*., 2018; Gálvez-Martos *et al*., 2018). Cement production alone accounts for approximately 7–8% of global carbon dioxide emissions, primarily due to the energy-intensive calcination process. Steel, although highly durable and recyclable, generates considerable emissions during extraction and manufacturing, while plastics used in insulation, piping, and composites are linked to fossil fuel dependency and long-term waste management issues (Chilana *et al*., 2016; Correia *et al*., 2016). Together, these materials contribute to rising greenhouse gas emissions, resource depletion, and waste accumulation, exacerbating climate change and environmental instability.

The urgent need to mitigate these impacts has fueled a rising demand for sustainable alternatives in global infrastructure development. Governments, industries, and international organizations increasingly recognize the importance of adopting materials that minimize embodied carbon, reduce life cycle costs, and promote circular economy principles (Giesekam *et al*., 2016; Akbarnezhad and Xiao, 2017). Global initiatives such as the Paris Agreement, the United Nations Sustainable Development Goals (SDGs), and regional green building certification systems have accelerated the search for construction solutions that align with climate action targets. Within this context, bio-based construction materials have gained prominence as renewable, low-carbon, and locally adaptable alternatives capable of addressing both environmental and socio-economic challenges (Lokesh *et al*., 2018; Varho *et al*., 2018).

Bio-based materials encompass a wide range of products derived from biological resources such as plants, agricultural residues, and fungi (Kuppusamy *et al*., 2016; Gontard *et al*., 2018). Examples include engineered timber (e.g., cross-laminated timber), bamboo, hempcrete, straw bale, mycelium composites, and emerging biopolymers. These materials possess inherent advantages in terms of carbon sequestration, biodegradability, and low embodied energy, making them particularly relevant for climate change mitigation. Their use not only reduces reliance on resource-intensive materials but also supports rural economies and fosters community resilience by creating localized supply chains (Knickel *et al*., 2017; Velasquez, 2017). Moreover, bio-based materials align with contemporary sustainability strategies such as nature-based solutions and circular construction, underscoring their potential to redefine the future of infrastructure (Dammer *et al*., 2017; Xing *et al*., 2018).

The purpose of this, is to synthesize current knowledge on the adoption, performance, and challenges of bio-based materials in construction. While scattered studies have documented individual materials or regional applications, comprehensive evaluations of their role in sustainable infrastructure remain limited. This review therefore aims to provide a holistic perspective by examining the types of bio-based materials currently in use, assessing their environmental, economic, and social impacts, and identifying barriers to widespread implementation. In addition, this highlights emerging innovations and future directions that can accelerate their integration into mainstream construction practices.

To guide the review, several key research questions are posed: What categories of bio-based materials are most commonly applied in construction, and what are their performance characteristics? How are different regions adopting and adapting these materials in response to local environmental, economic, and cultural contexts? What benefits and challenges are associated with their use in infrastructure projects? What emerging trends, innovations, and policy frameworks are shaping the global trajectory of bio-based materials? And finally, what gaps remain in research and practice that must be addressed to scale up their adoption?

By addressing these questions, this review seeks to contribute to the global discourse on sustainable infrastructure, offering insights for policymakers, practitioners, and researchers. Bio-based materials, if effectively developed, standardized, and mainstreamed, have the potential to become a cornerstone of environmentally responsible and socially inclusive construction practices worldwide.

II. METHODOLOGY

The methodology for this global review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure rigor, transparency, and replicability. A structured search strategy was developed to identify relevant academic and grey literature on bio-based materials for construction and sustainable infrastructure. Searches were carried out in major databases including Scopus, Web of Science, ScienceDirect, and Google Scholar, covering publications from 2000 to 2025 to capture both early research on traditional materials such as bamboo and straw and recent advancements in engineered timber, mycelium, and biopolymers. The search strategy employed combinations of keywords and Boolean operators such as “bio-based materials,” “sustainable construction,” “green infrastructure,” "timber," "bamboo," "hempcrete," "mycelium composites," "biopolymers," and "circular economy in construction." Reference lists of selected papers were also screened to identify additional studies.

The selection process was conducted in multiple stages. Duplicates were removed, after which titles and abstracts were screened to assess relevance. Full-text screening was then applied using predetermined eligibility criteria. Studies were included if they addressed bio-based materials in construction or infrastructure and examined their environmental, economic, social, or technical performance. Both qualitative and quantitative studies were considered, including case studies, life cycle assessments, experimental research, and policy analyses. Excluded materials were those that focused solely on non-construction applications of bio-based products, studies unrelated to sustainability, publications not available in English, and articles lacking sufficient methodological detail.

Data extraction was performed systematically using a coding framework. Extracted information included publication year, geographic focus, type of bio-based material, application context, methodological approach, and reported outcomes related to sustainability and performance. Two reviewers independently conducted the extraction and screening process, and discrepancies were resolved by consensus to reduce the risk of bias.

Quality assessment of included studies was carried out using adapted appraisal tools, evaluating transparency of methodology, data robustness, and relevance of findings. Studies were categorized as high, medium, or low quality, which allowed for nuanced interpretation during synthesis. The review results were then organized thematically to capture categories of bio-based materials, regional adoption patterns, benefits, challenges, and emerging trends. A PRISMA flow diagram was used to illustrate the number of records identified, screened, excluded, and included at each stage of the review process. By employing this structured methodology, the review ensures that conclusions are evidence-based, globally representative, and aligned with best practices for systematic synthesis.

2.1 Theoretical Background

The search for sustainable construction solutions has led to increased interest in bio-based materials, which draw upon renewable biological resources as alternatives to conventional, resource-intensive materials such as cement, steel, and plastics. These materials not only reduce environmental impacts but also align with global climate targets and sustainable development goals (Gomez-Echeverri, 2018; Scherer *et al*., 2018). Understanding their definitions, classifications, underlying sustainability principles, and the global policy frameworks that support their adoption provides a foundation for evaluating their role in sustainable infrastructure.

Bio-based construction materials can be broadly defined as building products derived wholly or partly from biological resources such as plants, agricultural residues, or fungi. Unlike synthetic or mineral-based materials, bio-based products are renewable, often biodegradable, and possess lower embodied energy. They may serve structural, thermal, or aesthetic purposes, depending on their properties and applications.

Several categories of bio-based materials dominate the construction sector. Timber and engineered wood products, such as cross-laminated timber (CLT) and glued laminated timber (glulam), are increasingly used in mid-rise and high-rise construction, offering both strength and aesthetic appeal. Bamboo, known for its high tensile strength and rapid growth rate, is widely employed in Asia and Africa for scaffolding, housing, and decorative applications, with modern engineered bamboo products gaining traction in structural uses. Hempcrete, a mixture of hemp fibers, lime, and water, provides lightweight, insulating, and carbon-sequestering wall materials that combine thermal efficiency with sustainability (Cherney and Small, 2016; Florentin *et al*., 2017). Agricultural residue-based materials such as straw bales, rice husk ash concrete, and coconut coir composites offer locally available and low-cost alternatives for insulation and masonry. Mycelium composites, grown from fungal networks, represent a novel class of materials with potential for insulation and lightweight structures due to their biodegradability and tunable properties. Bioplastics derived from starch, cellulose, or other renewable sources provide emerging substitutes for petroleum-based plastics in cladding, piping, and insulation. Together, these materials reflect a diverse spectrum of renewable options capable of addressing different technical and regional needs.

The adoption of bio-based materials is strongly underpinned by key sustainability principles that guide their development and application. Central among these is the principle of the circular economy, which emphasizes extending the lifecycle of resources, minimizing waste, and reintegrating materials into productive use at the end of their service life. Bio-based construction materials often lend themselves naturally to circularity due to their biodegradability and recyclability (Clark *et al*., 2016; Kopnina, 2018). For instance, timber and bamboo can be reused, repurposed, or composted, while agricultural residues that would otherwise contribute to waste streams can be transformed into building materials.

Carbon sequestration is another critical principle. Many bio-based materials actively store atmospheric carbon dioxide absorbed during plant growth, effectively functioning as carbon sinks throughout their lifecycle. Engineered timber, hempcrete, and straw bale construction are particularly notable in this regard, as they not only offset emissions from conventional materials but can also result in buildings with net-negative embodied carbon. The durability of materials such as CLT enhances the permanence of carbon storage, contributing to long-term climate mitigation (Woodard and Milner, 2016; Hafner and Schäfer, 2018).

Resource efficiency further underscores the sustainability of bio-based materials. Conventional construction materials are highly energy- and resource-intensive, whereas bio-based alternatives typically require less processing and utilize renewable feedstocks. Materials like bamboo and hemp grow rapidly with relatively low inputs of water, land, and fertilizer, making them resource-efficient choices. Agricultural by-products such as rice husks and coconut coir embody the principle of valorizing waste, reducing pressure on virgin resource extraction. These attributes collectively position bio-based materials as essential components of sustainable construction strategies.

The promotion of bio-based materials in construction has been reinforced by a growing number of global and regional policy frameworks (Nattrass *et al*., 2016; Mengal *et al*., 2018). International climate agreements, particularly the Paris Agreement, have created pressure for the construction sector to decarbonize, encouraging innovation in low-carbon materials. The United Nations Sustainable Development Goals (SDGs), especially Goal 11 (Sustainable Cities and Communities) and Goal 12 (Responsible Consumption and Production), provide a normative framework that emphasizes resource-efficient and environmentally responsible infrastructure development.

At the regional level, the European Union has been particularly proactive in promoting bio-based construction. Policies under the European Green Deal, the Circular Economy Action Plan, and initiatives such as Horizon Europe fund research and incentivize the use of renewable materials in buildings. The EU's Construction Products Regulation also emphasizes the need for environmental performance and resource efficiency in building materials, indirectly supporting bio-based alternatives. Certification systems such as Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), and Excellence in Design for Greater Efficiencies (EDGE) provide further regulatory and market-driven incentives by rewarding projects that incorporate bio-based materials. These systems integrate metrics for embodied carbon, material sourcing, and waste reduction, effectively creating a competitive advantage for projects that adopt renewable materials.

Globally, several countries have developed national strategies that promote bio-based construction (Bennich and Belyazid, 2017; Ladu and Quitzow, 2017). In North America, building codes in cities like Vancouver and states like Oregon now permit mass timber construction in high-rise applications, accelerating adoption. In Asia, China and India are scaling bamboo and agricultural residue-based building materials to meet affordable housing demands while reducing reliance on conventional cement and steel. In Africa and Latin America, development agencies and non-governmental organizations support the use of locally sourced bio-based materials in low-cost housing as part of broader sustainability and poverty reduction strategies.

Taken together, bio-based materials represent a diverse and rapidly evolving field within sustainable construction, strongly rooted in principles of circular economy, carbon sequestration, and resource efficiency. Their growing recognition in global policy and regulatory frameworks underscores their importance as tools for climate change mitigation and sustainable infrastructure development (Ladan, 2018; Upadhyaya *et al*., 2018). By integrating traditional knowledge with modern innovation, bio-based materials offer not only technical and environmental benefits but also economic and social opportunities, laying the foundation for their expanded role in global construction practices.

2.1 Types of Bio-Based Materials in Construction

The shift toward sustainable construction has brought bio-based materials into focus as viable alternatives to conventional materials as shown in figure 1 (Peñaloza *et al*., 2016; Horn *et al*., 2018). Their ability to combine structural performance, environmental benefits, and local availability makes them increasingly attractive for diverse infrastructure applications. Among the most significant categories are timber and engineered wood, bamboo, hemp and hempcrete, agricultural residue-based materials, and emerging innovations such as mycelium composites and biopolymers.

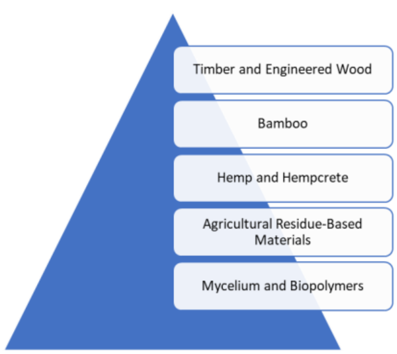

Figure 1: Types of Bio-Based Materials in Construction

Timber has long been used in construction, but technological advances have transformed it into a modern, high-performance material through engineered products. Cross-laminated timber (CLT) and glued laminated timber (glulam) are at the forefront of this innovation. CLT consists of layers of timber boards glued together at right angles, providing exceptional strength and dimensional stability, making it suitable for multi-story buildings. Glulam, created by bonding parallel layers of timber, offers flexibility in design and is widely applied in beams, columns, and curved structural elements.

Durability, once a limitation of timber, has been enhanced through treatments and engineering processes, allowing it to resist decay, fire, and pests more effectively. Timber also serves as a carbon sink, storing carbon dioxide absorbed during tree growth, and when used in large-scale projects, it can significantly reduce a building's embodied carbon. Timber skyscrapers in Europe, North America, and Asia exemplify its growing acceptance as a mainstream construction material.

Bamboo is another bio-based material recognized for its rapid renewability and exceptional mechanical properties. Its tensile strength rivals that of steel, and it can grow to maturity in just three to five years, making it one of the most resource-efficient materials (Altenburg and Pegels, 2017; George *et al*., 2018). Traditionally used in scaffolding and housing in Asia, bamboo is now being engineered into laminated boards and structural components suitable for modern construction.

Bamboo's adaptability is evident in its applications ranging from low-cost rural housing to contemporary architectural designs. Its hollow, lightweight structure makes it easy to transport and assemble, while engineered bamboo products extend its durability and resistance to environmental stressors. Bamboo also contributes to local economies, particularly in Asia, Africa, and Latin America, where it is cultivated extensively. Its role in both informal housing and high-end architecture highlights its versatility as a construction resource.

Hemp and its derivative, hempcrete, are increasingly recognized for their environmental and performance advantages. Hempcrete is a bio-composite made by mixing hemp shiv with lime and water, resulting in a lightweight material with excellent thermal insulation properties. While not a load-bearing material, hempcrete is commonly used as an infill for walls, offering breathability, moisture regulation, and fire resistance.

One of hempcrete's most notable attributes is its capacity for carbon storage. Hemp absorbs large amounts of carbon dioxide during its rapid growth cycle, and when combined with lime, the resulting material continues to sequester carbon over time through carbonation. This makes hempcrete one of the most climate-positive construction materials available. Its life cycle advantages extend to recyclability, low embodied energy, and alignment with circular economy principles. Although regulatory barriers and limited supply chains constrain its use in some regions, hempcrete is gaining momentum in Europe and North America as a sustainable alternative for residential and commercial construction.

Agricultural residues present another promising avenue for bio-based construction. Straw bale construction has a long history and remains relevant today as an affordable and effective insulation material. Straw bales provide high thermal resistance, are locally available, and can be incorporated into both traditional and modern wall systems (Aznabaev *et al*., 2916; Yin *et al*., 2018).

Rice husk ash concrete is another innovation, utilizing the silica-rich by-product of rice milling as a partial substitute for cement. This reduces reliance on energy-intensive clinker while enhancing durability and strength in concrete mixtures. Similarly, coconut coir composites, derived from coconut husk fibers, are being applied in insulation boards, panels, and reinforcement materials, particularly in tropical regions.

These residue-based materials exemplify circular economy principles by valorizing agricultural waste, reducing landfill burden, and creating new income streams for rural communities. Their scalability depends on local agricultural outputs, making them context-specific yet highly sustainable solutions.

Emerging innovations such as mycelium composites and biopolymers represent the frontier of bio-based construction materials. Mycelium, the root network of fungi, can be grown into molds to form lightweight, biodegradable composites with excellent insulating and fire-resistant properties. These materials are currently being explored for use in insulation panels, acoustic boards, and non-structural elements. Their low energy requirements for production and full biodegradability position them as strong candidates for circular construction systems.

Biopolymers, derived from renewable resources such as starch, cellulose, and lignin, provide another innovative pathway. They can be processed into cladding, insulation, piping, and even structural composites, offering a renewable alternative to petroleum-based plastics. Advances in nanotechnology and material science are enhancing the strength, durability, and thermal resistance of these biopolymers, opening the door for their scalability in mainstream construction.

While mycelium and biopolymers are still in early stages of development and face challenges in standardization and durability, their potential scalability is immense. With continued research, they could complement or even replace many conventional building products.

Collectively, these categories of bio-based materials illustrate the diversity and potential of renewable construction resources. Timber and bamboo are already demonstrating structural viability in large-scale projects, hempcrete and agricultural residues provide strong thermal and environmental performance, and innovations such as mycelium and biopolymers signal a future where construction materials are grown rather than extracted. Each material presents unique advantages and challenges, y*et al*l contribute to reducing environmental impacts and advancing sustainable infrastructure (Lounis and McAllister, 2016; Han *et al*., 2017).

2.2 Global Adoption and Regional Practices

The adoption of bio-based construction materials has become a global movement, shaped by diverse policy frameworks, market dynamics, cultural traditions, and regional resource availability (Silva *et al*., 2017; Meyer, 2017). While Europe has embraced bio-based materials through strong policy initiatives, North America's trajectory has been driven largely by market innovation. Asia has leveraged both traditional practices and modern engineering, while Africa and Latin America showcase the role of local resources and indigenous knowledge in promoting affordable and sustainable building solutions. This regional diversity demonstrates the global momentum toward bio-based construction, even as adoption remains uneven across contexts.

Europe is at the forefront of bio-based material adoption, propelled by ambitious climate goals and circular economy policies. The European Green Deal and the Circular Economy Action Plan provide regulatory frameworks that encourage the use of renewable, low-carbon materials in construction. Countries such as Sweden, Finland, and Austria have pioneered large-scale timber buildings, facilitated by favorable building codes and subsidies. Cross-laminated timber (CLT) is widely used in multi-story construction, with projects like the Mjøstårnet tower in Norway and buildings in Vienna demonstrating the feasibility of timber skyscrapers.

Circular construction practices are particularly advanced in Europe, where bio-based materials are integrated into broader strategies for resource efficiency and waste reduction. For example, straw bale housing in France and hempcrete developments in the UK are gaining mainstream recognition. The EU's Horizon Europe program funds research on next-generation bio-based materials, including mycelium composites and bioplastics. By embedding sustainability into policy, Europe demonstrates how top-down governance can accelerate adoption while setting global benchmarks for bio-based innovation.

In North America, adoption of bio-based materials is largely driven by market forces, entrepreneurial innovation, and growing consumer demand for green buildings. Timber construction, particularly mass timber and CLT, has gained significant traction in the United States and Canada. Changes in building codes, such as the International Building Code (IBC) revisions in 2021, now permit tall timber structures up to 18 stories, paving the way for projects like the Ascent tower in Milwaukee, one of the tallest mass timber buildings in the world.

Sustainability certifications such as LEED (Leadership in Energy and Environmental Design) also play a central role by incentivizing bio-based material use in both residential and commercial projects. Hempcrete has gained momentum in states like Colorado and California, where regulatory barriers are easing and sustainable construction markets are expanding. Additionally, the growing focus on reducing embodied carbon in buildings has increased investment in agricultural residue-based composites and bio-insulation products (Akbarnezhad and Xiao, 2017; Almeida *et al*., 2018). Unlike Europe, where policy dominates, North America exemplifies how market demand and industry-led initiatives can scale bio-based construction materials.

Asia has a long history of using bio-based materials, particularly bamboo and agricultural residues, in construction. Bamboo, known as the "green steel," remains integral to housing and infrastructure in countries such as China, India, and Indonesia. Its rapid renewability and strength make it a preferred choice for both low-cost housing and modern architectural projects, such as the Bamboo Sports Hall in Thailand. Engineered bamboo products are also being developed to meet structural standards in urban projects.

Agricultural residues, including rice husk ash and straw, are widely utilized in rural housing and affordable construction. Rice husk ash concrete, for instance, has gained attention in India as a supplementary cementitious material that enhances durability while reducing emissions from cement production. In China, government policies supporting green building certification systems like Three Star encourage the integration of bio-based materials. Asia illustrates a hybrid adoption pattern, combining traditional practices with cutting-edge innovations that harness abundant regional resources.

In Africa, bio-based construction is closely linked to the urgent need for affordable and sustainable housing. Locally available materials such as timber, bamboo, and agricultural residues are widely used in informal and rural construction. Straw bale, mud-plaster composites, and coconut coir panels are employed as low-cost solutions that reduce reliance on expensive imported materials.

Development agencies and NGOs play a vital role in promoting bio-based materials as part of sustainable housing programs. For example, initiatives in Ethiopia and Kenya are experimenting with stabilized earth blocks and residue-based composites to address urban housing shortages. Although large-scale adoption is constrained by limited regulatory frameworks and investment, Africa highlights the potential of bio-based materials to improve housing affordability and resilience while supporting local economies.

Latin America presents a unique context where indigenous knowledge and modern sustainability practices converge (Vanhulst and Zaccai, 2016; Mato, 2016). Traditional construction methods, such as adobe and straw bale houses in Mexico or bamboo housing in Colombia and Ecuador, remain widely practiced. These techniques are increasingly being formalized and adapted into sustainable building programs. For instance, Guadua bamboo in Colombia is recognized as a structural material in building codes, supporting its use in resilient housing and infrastructure.

Bio-based materials are also being integrated into urban projects, with governments and architects experimenting with hempcrete, timber, and agricultural composites. Brazil, for example, has research initiatives focused on bioplastics derived from sugarcane, aligning with its bioeconomy strategy. The fusion of indigenous traditions with modern engineering demonstrates the cultural and environmental value of bio-based construction in Latin America, where sustainability is often viewed through both ecological and social lenses.

The global adoption of bio-based construction materials reflects diverse trajectories shaped by policy, markets, traditions, and local contexts (Philippidis *et al*., 2016; Antikainen *et al*., 2017). Europe leads with policy-driven circular construction, North America emphasizes market-led timber innovations, Asia balances traditional bamboo and residue-based practices with modern applications, Africa focuses on affordable housing through local resources, and Latin America integrates indigenous knowledge with contemporary sustainability approaches. Together, these regional practices highlight the versatility and global relevance of bio-based materials, underscoring their role as central to sustainable infrastructure futures.

2.3 Benefits and Performance Outcomes

The global transition toward sustainable infrastructure has positioned bio-based construction materials as critical enablers of environmental protection, economic development, social well-being, and technical innovation. Their adoption not only addresses pressing climate challenges but also generates value across multiple dimensions of performance. An examination of environmental, economic, social, and technical outcomes reveals the holistic benefits of integrating bio-based resources into construction practices as shown in figure 2 (Mansouri *et al*., 2017; Lokesh *et al*., 2018).

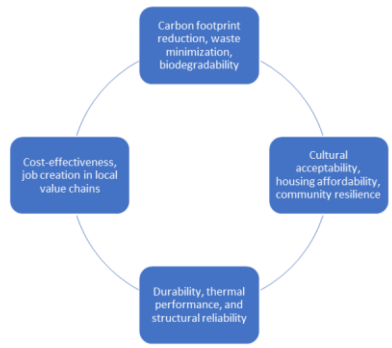

Figure 2: Benefits and Performance Outcomes

One of the most compelling advantages of bio-based materials lies in their capacity to significantly reduce the environmental footprint of construction. Conventional materials such as cement, steel, and plastics are highly carbon-intensive, accounting for nearly 40% of global carbon dioxide emissions associated with the built environment. Bio-based materials, by contrast, often have lower embodied energy and can even function as carbon sinks. For example, timber and bamboo sequester atmospheric carbon during growth, which remains stored for the lifespan of the building. Hempcrete extends this benefit by continuing to absorb carbon dioxide through the carbonation of lime binders.

Waste minimization is another major environmental outcome. Agricultural residues, such as rice husks, straw, and coconut coir, are often discarded or burned, contributing to pollution. Transforming these by-products into construction materials not only reduces waste but also mitigates emissions from open burning. Biodegradability further enhances the environmental credentials of bio-based materials. Unlike plastics or cement-based products that persist in landfills for centuries, materials such as mycelium composites, straw bales, and bioplastics naturally decompose, facilitating circular construction models where end-of-life products are reintegrated into ecological cycles.

Bio-based materials also deliver substantial economic benefits, particularly in the context of cost-effectiveness and local value creation. Many bio-based resources, such as bamboo, hemp, and straw, are locally abundant and require minimal processing compared to industrial alternatives. Their use reduces transportation costs, energy expenditures, and dependency on imported building materials. Hempcrete, for instance, offers long-term savings through its excellent thermal insulation properties, which reduce energy costs for heating and cooling.

Beyond direct cost advantages, bio-based materials contribute to job creation and rural economic development. Value chains for bio-based products—spanning cultivation, processing, and construction—generate employment opportunities in agricultural and semi-industrial sectors. This is particularly significant in developing economies where agriculture remains a major source of livelihood. By supporting local industries, bio-based construction materials help diversify economies, reduce poverty, and enhance resilience to global supply chain disruptions.

Social outcomes are equally significant in the adoption of bio-based construction materials, particularly in terms of cultural acceptability, affordability, and community resilience. Many bio-based materials, such as adobe, bamboo, and straw, have deep cultural roots in traditional construction practices. Their reintroduction in modern sustainable infrastructure projects often aligns with local identities and values, facilitating higher acceptance rates among communities.

Housing affordability is another major social benefit. By leveraging locally available bio-based resources, construction costs can be reduced, making housing more accessible for low- and middle-income populations (Salzer, 2016; Bracco *et al*., 2018). In Africa and Latin America, for example, bio-based materials such as straw bales and Guadua bamboo are increasingly used in affordable housing programs, offering dignified and sustainable shelter solutions to underserved communities.

Community resilience is also strengthened through the use of bio-based materials. Locally sourced construction reduces dependence on external markets, while the regenerative nature of bio-based resources ensures sustainable supply over time. Moreover, bio-based housing often demonstrates improved adaptability to local climates and conditions, enhancing the resilience of communities to environmental stresses such as heat waves or resource scarcity.

Contrary to outdated perceptions of bio-based materials as inferior, modern innovations demonstrate strong technical performance in terms of durability, thermal regulation, and structural reliability. Engineered timber products such as cross-laminated timber (CLT) and glulam exhibit high structural strength and can be used in multi-story buildings, rivaling steel and concrete in performance. Fire safety, once a limitation, has been addressed through engineering and protective coatings, making timber viable in urban construction.

Thermal performance is another key advantage. Materials such as hempcrete, straw bales, and mycelium composites offer excellent insulation properties, reducing the energy demands of buildings and improving occupant comfort. Bamboo, with its tensile strength comparable to steel, has proven reliable in both housing and infrastructure, particularly in seismic-prone regions.

Durability varies by material but is improving rapidly with advances in treatment and engineering. Timber, once susceptible to pests and moisture, now benefits from advanced lamination and preservative technologies that extend its lifespan significantly. Bioplastics and mycelium, though emerging, are undergoing continuous research to enhance resilience to moisture, heat, and load-bearing requirements. Together, these technical outcomes demonstrate that bio-based materials are not only environmentally and socially beneficial but also technically competitive with conventional alternatives.

The integration of bio-based materials in construction offers multidimensional benefits that extend far beyond environmental performance. They contribute to carbon reduction, waste minimization, and biodegradability while simultaneously stimulating local economies, generating jobs, and enhancing affordability. Socially, they align with cultural traditions and strengthen community resilience, while technically, innovations in timber, bamboo, hempcrete, and emerging composites prove their structural reliability and functional efficiency.

Collectively, these outcomes underscore the potential of bio-based materials to redefine construction practices and establish a foundation for sustainable infrastructure. As adoption scales globally, their benefits will become increasingly evident across environmental, economic, social, and technical domains, reinforcing their position as central to the transformation of the built environment (Greenhalgh *et al*., 2017; Chan *et al*., 2017).

2.4 Challenges and Barriers

Despite the growing momentum surrounding bio-based construction materials, their widespread adoption faces significant challenges as shown in figure 3. While these materials offer promising environmental, social, and economic benefits, technical limitations, policy gaps, economic constraints, and shortages in skills and knowledge continue to hinder their integration into mainstream construction practices. Addressing these barriers is essential to unlock the full potential of bio-based materials in advancing sustainable infrastructure globally.

One of the foremost challenges lies in the technical limitations of bio-based construction materials, particularly regarding standardization, fire resistance, and durability in different climatic conditions. Unlike steel and concrete, which are extensively studied and standardized, bio-based materials often lack consistent performance benchmarks (Kutnik *et al*., 2017; Amziane *et al*., 2017). The variability in biological resources, such as differences in timber species, bamboo growth conditions, or hemp quality, results in uneven material properties that complicate widespread adoption.

Fire resistance is another critical issue. Although advances in engineered timber and surface treatments have improved fire safety, public and regulatory perceptions continue to view bio-based materials as more vulnerable compared to conventional options. Similarly, materials like straw bale, hempcrete, and mycelium composites require additional testing and certification to demonstrate their compliance with modern fire codes.

Durability also raises concerns, particularly in regions with extreme climatic conditions. Bamboo, for instance, is susceptible to moisture and insect attack if not properly treated, while timber may degrade in humid environments. The long-term resilience of emerging materials such as bioplastics and mycelium remains under-researched. Without robust performance data across diverse climatic zones, confidence in bio-based materials remains limited, particularly for high-value or large-scale infrastructure projects.

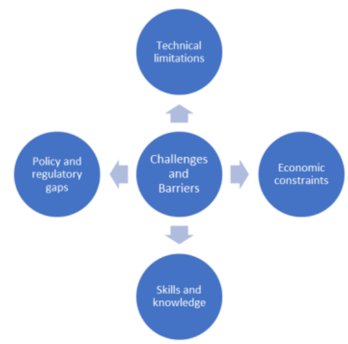

Figure 3: Challenges and Barriers

Policy frameworks and regulatory standards for bio-based construction materials remain fragmented, creating barriers to global adoption. Unlike Europe, where the European Union has introduced strong policy instruments under the Green Deal and Circular Economy Action Plan, many regions lack formal guidelines or incentives to support bio-based material use. In North America, although market demand is driving timber skyscrapers and hempcrete construction, regulations vary significantly across states and provinces, leading to inconsistent implementation.

Globally, there is an absence of unified standards or certification systems specific to bio-based materials. While sustainability rating systems such as LEED, BREEAM, and EDGE reward bio-based construction, they are not substitutes for material-specific technical standards. This regulatory ambiguity limits investor confidence and discourages large-scale integration of bio-based materials in commercial projects. In developing economies, weak building codes and insufficient government support further exacerbate the problem, resulting in limited uptake despite the availability of raw materials.

Market competitiveness presents another barrier. Conventional materials such as cement and steel benefit from decades of industrial optimization, established supply chains, and large-scale economies of production, making them relatively cheap and widely available. Bio-based materials, by contrast, often require specialized processing, smaller-scale production, and investment in new supply chains, which raise costs. For instance, engineered timber and bamboo composites remain more expensive than their conventional counterparts in many markets, limiting their competitiveness for cost-sensitive projects.

Hempcrete and mycelium-based products face similar challenges, as their production processes are not yet optimized for mass deployment. In addition, access to finance for bio-based construction projects is limited. Banks and investors are often reluctant to fund projects involving less-tested materials due to perceived risks, creating financial barriers for innovators and early adopters. Without targeted subsidies, tax incentives, or carbon pricing mechanisms that internalize the environmental costs of conventional materials, bio-based options struggle to compete on equal economic footing.

Another critical challenge is the lack of skills and knowledge in the design and construction of bio-based materials. Architects, engineers, and contractors are often trained primarily in the use of steel, concrete, and plastics, leaving them less equipped to work with timber, bamboo, hempcrete, or agricultural residue composites. This lack of technical expertise not only slows adoption but also increases the risk of poor implementation, which can reinforce negative perceptions about material reliability.

In many regions, vocational training and higher education curricula have yet to integrate bio-based construction methods comprehensively. While universities and research institutes in Europe and North America are beginning to expand research and education on mass timber and hempcrete, knowledge dissemination remains uneven across the Global South, where the potential for bio-based resources is high. Limited awareness among policymakers and the general public further constrains demand, as bio-based materials are often perceived as inferior or "traditional," rather than as modern, high-performance solutions.

Taken together, these barriers illustrate the complexity of transitioning from conventional to bio-based construction systems. Technical limitations, including challenges of durability, fire safety, and standardization, highlight the need for robust testing and innovation. Policy and regulatory gaps emphasize the importance of harmonized global standards and stronger government support (Pekdemir, 2018; Lambin and Thorlakson, 2018). Economic constraints, rooted in supply chain immaturity and market competitiveness, call for financial incentives and investment in scaling production. Skills and knowledge gaps underscore the necessity of education, training, and awareness-building among professionals and communities alike.

Addressing these challenges requires coordinated action from policymakers, researchers, industry stakeholders, and communities. Without overcoming these barriers, the transformative potential of bio-based construction materials will remain constrained, limiting progress toward a low-carbon, resource-efficient, and socially inclusive built environment.

2.5 Emerging Trends and Future Directions

The evolution of bio-based construction materials reflects a growing recognition of their potential to reshape the future of infrastructure. As global sustainability goals intensify, research and practice are shifting toward integrating digital technologies, developing hybrid construction models, advancing bio-composites, and strengthening international collaboration. These emerging trends and future directions highlight how bio-based materials are moving from niche applications to mainstream solutions capable of transforming the built environment.

One of the most promising future directions for bio-based construction lies in the integration of digital tools such as Building Information Modeling (BIM) and digital twins. BIM has already revolutionized construction by enabling detailed visualization, simulation, and coordination across project stakeholders. When applied to bio-based materials, BIM can optimize material selection, predict performance, and minimize waste by aligning design with the specific properties of resources like timber, hempcrete, and bamboo. For example, BIM can model the carbon sequestration potential of different bio-based materials, enabling architects and engineers to make environmentally informed decisions.

Digital twins extend this capability by creating real-time, data-driven replicas of buildings, allowing for continuous monitoring of bio-based material performance throughout the lifecycle. This is particularly valuable for evaluating durability, thermal regulation, and moisture resistance under varying climatic conditions. By coupling sensor data with predictive analytics, digital twins can support proactive maintenance, prolonging the lifespan of bio-based materials and increasing confidence in their reliability (Tao *et al*., 2018; Qi and Tao, 2018). The integration of digital technologies thus promises not only to optimize design but also to address one of the major barriers to adoption: limited empirical data on long-term performance.

Another emerging trend is the rise of hybrid construction models that combine bio-based and conventional materials. While bio-based materials offer significant environmental benefits, challenges related to durability, load-bearing capacity, and fire resistance mean they are not yet able to replace steel or concrete entirely in all contexts. Hybrid models provide a pragmatic solution, blending the strengths of both material categories.

For example, mass timber structures reinforced with steel connectors or concrete foundations are becoming increasingly common in mid- and high-rise buildings. Similarly, hempcrete can serve as insulating infill within conventional structural frames, while agricultural residue panels can complement steel or concrete shells. Such hybrid approaches enable the scalability of bio-based solutions without compromising safety or performance, while also easing the transition for industries and professionals accustomed to conventional practices. Future research is likely to focus on optimizing these hybrid systems, ensuring that material synergies are maximized while minimizing costs and environmental impacts.

The future of bio-based construction is also being shaped by advances in materials science, particularly in the development of advanced bio-composites and nanotechnology-enhanced materials. Bio-composites, which combine natural fibers such as hemp, flax, or coconut coir with bio-resins, are gaining attention for their high strength-to-weight ratios, durability, and thermal efficiency. These composites can be engineered for specific applications, ranging from insulation boards to structural panels, offering versatility beyond traditional bio-based materials.

Nanotechnology is further expanding the performance capabilities of bio-based materials. For example, nanocellulose derived from plant fibers can enhance mechanical strength and barrier properties, enabling lighter yet stronger construction components. Nanocoatings can also improve fire resistance, water repellency, and durability of bio-based products such as timber and bamboo. Research into nano-enabled bioplastics and mycelium composites is opening new pathways for creating materials that are not only sustainable but also competitive with or superior to conventional alternatives. As these technologies mature, they are expected to accelerate the industrial scalability and mainstream adoption of bio-based construction.

The success of bio-based construction materials depends heavily on global collaboration for knowledge sharing, technology transfer, and policy harmonization. Currently, adoption patterns vary widely: Europe leads through policy-driven initiatives, North America through market-led innovations, while Asia, Africa, and Latin America focus on locally available resources and affordability. Bridging these regional disparities requires collaborative platforms that enable the exchange of best practices, empirical data, and technological expertise.

International organizations such as the United Nations Environment Programme (UNEP), the International Energy Agency (IEA), and the World Green Building Council are already promoting sustainable building practices, but greater emphasis on bio-based materials is needed. Harmonizing certification standards across regions would also help address regulatory fragmentation, improving investor confidence and facilitating cross-border trade in bio-based products. Joint research initiatives, capacity-building programs, and collaborative pilot projects could further accelerate adoption, particularly in developing economies where the potential for bio-based resources is high but technical and financial barriers persist.

Emerging trends and future directions in bio-based construction highlight a dynamic trajectory where digitalization, hybrid models, advanced material research, and global cooperation converge to overcome current barriers. The integration of digital tools such as BIM and digital twins will provide unprecedented insights into performance optimization and lifecycle management. Hybrid construction models offer practical pathways for scaling adoption while balancing performance and sustainability. Advances in bio-composites and nanotechnology are expanding the technical frontier, ensuring that bio-based materials can compete directly with conventional alternatives (Yee *et al*., 2016; Rejeski *et al*., 2018). Finally, global collaboration is essential to align policies, disseminate knowledge, and support equitable adoption worldwide.

Together, these directions point to a future where bio-based construction materials are not peripheral alternatives but central pillars of sustainable infrastructure. By leveraging innovation, collaboration, and policy alignment, the construction industry can transition toward a regenerative model that balances environmental stewardship, economic viability, and social resilience.

2.6 Research Gaps

The growing body of literature on bio-based construction materials demonstrates their potential to transform the building industry into a more sustainable and resource-efficient sector. However, despite advancements in materials science, pilot projects, and policy support, significant research gaps persist. These gaps limit the ability to scale bio-based materials from experimental or niche applications to widespread adoption in mainstream construction. Key areas requiring further investigation include the lack of long-term performance data, limited lifecycle cost-benefit analysis, insufficient attention to scalability in large-scale urban projects, and the need for region-specific studies that consider socio-economic and climatic contexts (Samset and Volden, 2016; Maresova *et al*., 2017).

One of the most critical research gaps is the limited availability of long-term performance data for bio-based construction materials in real-world projects. Much of the existing evidence stems from laboratory studies, small-scale prototypes, or short-term demonstrations, which provide valuable insights but fail to capture the complexities of real-life environmental conditions. Materials such as hempcrete, bamboo composites, and mycelium panels are still relatively new in construction, meaning their durability under decades of use remains largely unknown.

Timber and engineered wood, while more established, also require broader datasets across diverse climates to better understand how moisture, temperature fluctuations, pests, and fire exposure affect long-term reliability. Without empirical evidence from longitudinal studies, stakeholders—including architects, engineers, investors, and policymakers—remain cautious, slowing mainstream adoption. Expanding real-world monitoring, coupled with post-occupancy evaluations and digital twin technologies, is essential to build confidence in the technical robustness of bio-based materials.

Another major gap is the lack of comprehensive lifecycle cost-benefit analyses for bio-based materials. While many studies highlight environmental benefits such as carbon sequestration and waste reduction, fewer examine the full economic implications over a building's lifespan. Conventional materials like concrete and steel dominate construction markets partly because of their perceived cost-effectiveness, despite their high environmental costs. Bio-based materials often face skepticism due to higher upfront expenses or limited supply chains, but these perceptions rarely account for long-term energy savings, lower maintenance needs, or potential end-of-life reuse.

For example, hempcrete provides substantial thermal insulation, reducing energy costs over decades, but such benefits are not consistently quantified in economic models. Similarly, the carbon storage capacity of timber is rarely monetized in cost assessments, even though it contributes to climate goals. Developing robust frameworks that integrate environmental externalities, operational savings, and social benefits into lifecycle analyses will provide a clearer comparison with conventional materials. This evidence is crucial for policymakers and investors to justify financial incentives and accelerate adoption.

While bio-based materials have been successfully deployed in small- to medium-scale projects, their scalability in urban megaprojects remains underexplored. Cities are the largest consumers of construction materials and generate significant environmental impacts. Yet, most bio-based material research focuses on residential housing, rural applications, or niche architectural projects. There is limited understanding of how these materials can be integrated into the massive demands of urban infrastructure, including high-rise buildings, transportation hubs, and large commercial complexes.

Challenges include structural requirements, supply chain logistics, and compatibility with existing construction technologies. For example, mass timber skyscrapers in Europe and North America demonstrate technical feasibility, but their global scalability requires further exploration of fire safety standards, regulatory harmonization, and construction workforce training. Similarly, integrating agricultural residue composites or mycelium-based materials into megaprojects demands large-scale production systems that do not yet exist (Attias *et al*., 2017; Karana *et al*., 2018). Research into industrial scalability, modular construction techniques, and hybrid models combining bio-based and conventional materials is urgently needed to unlock the potential of bio-based construction in urban contexts.

The adoption of bio-based materials is highly context-dependent, influenced by local resources, socio-economic conditions, and climate. However, much of the current research is generalized, focusing on technical material properties without fully accounting for regional variations. For instance, bamboo may thrive as a construction material in Asia and parts of Africa, but its relevance in colder climates with limited supply chains is questionable. Similarly, straw bale construction may offer affordability in rural contexts but faces challenges in dense urban settings where land scarcity and fire codes pose constraints (Allen *et al*., 2017; Malnar and Vodvarka, 2018).

Region-specific studies are essential to evaluate not only the technical feasibility but also the socio-economic acceptability of bio-based construction. This includes examining labor availability, cultural perceptions, policy environments, and financial mechanisms. Climate-responsive performance evaluations are also critical, as bio-based materials behave differently under conditions of humidity, heat, cold, or seismic stress. Without tailored insights, global strategies risk overlooking local realities, leading to uneven adoption or failed implementations.

These research gaps underscore the complexity of integrating bio-based construction materials into mainstream infrastructure systems. The absence of long-term performance data undermines confidence, while the lack of comprehensive lifecycle cost analyses limits economic competitiveness. Insufficient research on scalability in megaprojects restricts their role in addressing urban sustainability challenges, and the shortage of region-specific studies prevents effective localization of solutions.

Bridging these gaps requires multidisciplinary collaboration among material scientists, engineers, economists, social scientists, and policymakers. Longitudinal case studies, lifecycle modeling, industrial scalability research, and localized investigations will together provide the evidence base needed to accelerate adoption. Only by addressing these critical gaps can bio-based construction materials fulfill their promise of transforming the built environment into one that is environmentally regenerative, economically viable, and socially inclusive.

CONCLUSION

This global review of bio-based construction materials highlights their transformative potential in advancing sustainable infrastructure practices. By examining their definitions, applications, regional adoption patterns, benefits, challenges, and emerging innovations, the review underscores the role of bio-based materials as viable alternatives to conventional, carbon-intensive resources such as cement, steel, and plastics. Materials like timber, bamboo, hempcrete, agricultural residue composites, and mycelium not only reduce environmental footprints through carbon sequestration and biodegradability but also deliver socio-economic benefits such as affordability, local job creation, and cultural alignment. At the same time, technical advances in digital integration, hybrid systems, and nano-enhanced bio-composites indicate a dynamic trajectory toward mainstream adoption.

The insights derived from this review carry important implications for key stakeholders. Policymakers must prioritize supportive frameworks, including standards, certification schemes, and financial incentives, to accelerate bio-based adoption while ensuring safety and performance. Industry stakeholders—including developers, architects, and contractors—should invest in innovation, supply chain development, and workforce training to improve scalability and competitiveness. For researchers, pressing priorities include generating long-term performance data, conducting comprehensive lifecycle cost-benefit analyses, and developing region-specific knowledge that addresses socio-economic and climatic variations.

Ultimately, the successful integration of bio-based materials into global infrastructure depends on multidisciplinary and multi-stakeholder collaboration. Scientists, engineers, urban planners, economists, and community representatives must work together to align technological innovation with local realities and policy directions. International cooperation is equally vital for harmonizing standards, sharing knowledge, and enabling equitable access to sustainable practices. By bridging existing research gaps and fostering collaborative innovation, bio-based construction materials can shift from experimental alternatives to central components of resilient, low-carbon infrastructure, supporting both climate change mitigation and the global transition toward a circular economy.

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