Brief Report

Bio-Based Construction Materials in the Context of the EU Bioeconomy: Overcoming Systemic Barriers to Mainstream Adoption

F. Pacheco-Torgal *

Posted Date: 16 April 2026

doi: 10.20944/preprints202604.0356.v2

Keywords: bio-based materials; sustainable construction; bioeconomy; life cycle assessment (LCA); supply chain resilience

doi:10.20944/preprints202604.0356.v2

Brief Report

Bio-Based Construction Materials in the Context of the EU Bioeconomy: Overcoming Systemic Barriers to Mainstream Adoption

F. Pacheco-Torgal

C- TAC Research Centre, University of Minho, Campus de Azurem, 4800-058 Guimarães, Portugal;
torgal@civil.uminho.pt

Abstract

The construction sector faces a dual challenge: meeting growing global demand while achieving deep decarbonisation in line with the European Green Deal and the EU Bioeconomy Strategy. Bio-based construction materials offer significant potential to reconcile these objectives through carbon sequestration, reduced embodied emissions, improved indoor environmental quality, and compatibility with circular economy principles. However, their transition from niche applications to mainstream specification remains limited. This paper provides a comprehensive review of bio-based construction materials and examines the systemic barriers constraining their large-scale adoption. The analysis identifies four interrelated categories of constraints—structural, economic, technical, and enabling—and emphasises the conditional relationships between them, highlighting the implications for policy prioritisation and sequencing. The strategic urgency of this transition has been reinforced by the 2026 Strait of Hormuz crisis, which triggered severe disruptions to global petrochemical supply chains and exposed the structural vulnerability of European construction to fossil-derived material inputs, reframing bio-based alternatives as a supply security imperative alongside an environmental one. The findings show that the primary obstacles to adoption are not technological, but institutional and economic, particularly regulatory fragmentation, the absence of harmonised standards, supply chain limitations, and persistent market failures that disadvantage bio-based solutions.The paper concludes that scaling bio-based construction materials requires coordinated action across governance, market design, and industrial policy. Without addressing these systemic constraints, advances in material innovation and performance are unlikely to translate into widespread adoption.

Keywords: bio-based materials; sustainable construction; bioeconomy; life cycle assessment (LCA); supply chain resilience

1. Sustainability Challenges, Resource Scarcity and the Bioeconomy's Path Forward

In a world grappling with limited resources exacerbated by unsustainable patterns of production and consumption and a burgeoning global population, the urgency to transition towards more sustainable economic models is widely recognised. Differing viewpoints emerge on the achievability of this transition. While Stoknes and Rockström (2018) express pessimism, contending that current approaches are insufficient to align human activity with the ecological capacities of the planet, Randers et al. (2018) suggest that meeting all Sustainable Development Goals by 2030, or even by 2050, may prove elusive. A study conducted by researchers at the University of Cambridge builds upon the seminal work of "The Limits to Growth," projecting temperature increases of approximately 8–12 °C under a 'runaway global warming' scenario and forecasting a precipitous decline in food production, with an estimated 6 billion lives at risk of perishing due to starvation by the year 2100 (Richards et al., 2023). In the absence of immediate systemic breakthroughs, incremental

doi:10.20944/preprints202604.0356.v2

improvements represent the most viable short-term pathway. Institutions such as UNEP, the World Bank, and the European Commission accordingly advocate for the adoption of green economy and green growth principles, approaches that aim to achieve more with less by fostering enhanced human well-being and social equity.

Recent years have seen a surge in demand for natural, bio-derived, and biotechnology-based products in industrial settings, driven by concerns about environmental impact, waste management challenges, and the depletion of non-renewable resources. In 2002, the EU initiated its Strategy on Biotechnology (EU, 2002), followed by a significant milestone in 2012 when the European Commission introduced the world's first bioeconomy strategy and action plan. The bioeconomy is defined as an economic framework in which the fundamental components for materials, chemicals, and energy are sourced from renewable biological resources, encompassing all sectors and systems dependent on biological resources — including animals, plants, microorganisms, and derived biomass (Schanes et al., 2019). Global demand for bio-based products is on the rise, with EU demand projected to reach a market value of 50 billion euros and help create one million new jobs by 2030.

The European Green Deal, launched by the European Commission in December 2019, seeks to transition the EU towards a low-carbon, sustainable growth model that prioritises food and energy security, biodiversity, and effective natural resource management, with the bioeconomy playing a crucial role. Pianta and Lucchese (2020) argue that the Green Deal must be integrated with a more ambitious industrial policy and a unified vision of future challenges, recognising that market-based solutions alone cannot resolve environmental problems and that public authorities must lead economic transformation.

D'Amato and Korhonen (2021) compared the green, circular, and bioeconomy models for their potential to achieve global net sustainability, emphasising the need for an economy grounded in renewable and biodiversity-friendly processes. They caution that without explicitly considering global net sustainability, implementing these models individually or jointly can result in unintended negative effects — such as problem displacement, cascade effects, and rebound effects — that undermine sustainability efforts. Ronzon et al. (2022) demonstrated that the bioeconomy has maintained its relative importance within the EU27 economy, with agriculture and the food industry as key drivers of the transition, though meaningful progress remains largely elusive in Eastern and Central Europe. Firoiu et al. (2023) emphasised the importance of bioeconomy statistics for evidence-based policymaking, finding that Western European countries consistently outperformed the Baltic states and Central and Eastern Europe, though the latter showed growth potential exceeding 20% above the EU average, with Belgium and Denmark highlighted as role models.

The policy landscape surrounding the bioeconomy has continued to evolve significantly. On 27 November 2025, the European Commission adopted a new Strategic Framework for a Competitive and Sustainable EU Bioeconomy (European Commission, 2025), marking the most substantial revision of EU bioeconomy policy since the original 2012 strategy. Unlike its predecessors, which prioritised research and innovation, the 2025 Framework explicitly shifts focus towards industrial deployment, market scale-up, and geopolitical competitiveness, positioning the bioeconomy as a core pillar of EU industrial resilience and strategic autonomy. The document sets a 2040 vision in which sustainable bio-based materials — including construction materials, biochemicals, textiles, fertilisers, and bio-based plastics — are widely deployed across the EU as fossil-free alternatives to petroleum-derived products. In quantitative terms, the EU bioeconomy already generates up to €2.7 trillion in value added and supports an estimated 17.1 million direct jobs, equivalent to approximately 8% of total EU employment (European Commission, 2025). The Framework establishes lead markets for bio-based materials, explicitly listing construction products, and creates a Bio-based Europe Alliance targeting €10 billion in collective procurement by 2030. Key legislative instruments including the revised Construction Products Regulation and the Ecodesign for Sustainable Products Regulation are expected to be progressively adapted to incorporate bio-based content criteria, certification pathways, and carbon storage accounting (European Commission, 2025). These developments

doi:10.20944/preprints202604.0356.v2

represent a decisive institutional signal that the sector's transition from niche to mainstream is now an explicit political objective at EU level.

The strategic logic underpinning this reorientation has been rendered concrete and urgent by the ongoing 2026 Strait of Hormuz crisis, which constitutes what the International Energy Agency has described as the largest supply disruption in the history of the global oil market (IEA, 2026). Since Iran declared the strait effectively closed in March 2026, tanker traffic collapsed and crude oil prices exceeded USD 100 per barrel, triggering cascading effects throughout global petrochemical supply chains that are directly material to the European construction sector. Naphtha — the primary feedstock for European steam crackers and the precursor to key construction polymers including polyvinyl chloride (PVC), polyethylene (PE), polyurethane insulation foams, and polypropylene — surged by approximately 74% in the first two weeks of the crisis, with polymer prices rising between 41% and 75% across product lines (Polymerupdate, 2026).

Taken together, these cascading vulnerabilities illuminate a structural asymmetry at the core of Europe's industrial base: sectors reliant on petrochemical inputs sourced from a single geopolitical chokepoint are, by definition, incompatible with the EU's stated objectives of supply chain resilience, strategic autonomy, and long-term industrial competitiveness. The substitution of petroleum-derived construction materials — EPS insulation boards, synthetic sealants, PVC window profiles, and polyurethane panels — with domestically produced bio-based equivalents such as cellulose fibre insulation, bio-based polyurethane from castor oil, cork composites, and mycelium boards, is therefore not merely an environmental proposition: it is a supply security imperative whose strategic salience has been demonstrated empirically by the events of early 2026. In this reading, the EU Bioeconomy Framework's designation of construction products as a priority lead market for bio-based materials acquires a dimension that purely ecological or circular economy framings cannot capture — that of critical infrastructure resilience in the face of systemic geopolitical risk.

2. The Promise of Bio-Based Materials Toward a Sustainable Construction Industry

2.1. The Construction Industry and the Case for Bio-Based Materials

Although the future of humanity remains shadowed by serious environmental challenges, the construction industry is certain to continue growing due to an increasing world population, projected to reach 11 billion by 2100. In this context, the use of bio-based construction materials is crucial for reducing the industry's environmental footprint. While bio-based materials like timber have long been used, particularly for structural purposes, they have struggled to compete with the superior performance of steel and reinforced concrete in the construction of increasingly taller skyscrapers. However, the imperative of sustainable development in recent years is changing this dynamic, and the scientific community is actively contributing to the revival and advancement of bio-based materials.

The imperative to decarbonise the construction sector has given renewed urgency to the study of fast-growing bio-based materials. A 2026 review identifies bamboo, hemp, straw and mycelia as a critical cluster of materials with substantial potential for simultaneous carbon capture and storage in the built environment, arguing that achieving a net-zero built environment will require the creation of intersectoral synergies and a deliberate move away from single-material solutions such as timber, which faces growing constraints from deforestation pressures and land-use competition (Göswein et al., 2026). A comparative life cycle analysis by Cosentino et al. (2024), employing the Building Emissions Accounting for Materials (BEAM) methodology, demonstrated that fast-growing bio-based materials — bamboo, straw, hemp and flax — store carbon more rapidly than conventional alternatives and contribute to healthier indoor environments through superior moisture regulation, directly supporting progress towards UN Sustainable Development Goals 11 and 12 on sustainable cities and responsible consumption. The carbon credentials of bamboo extend beyond its biological sequestration potential to its industrial production chain. Liu et al. (2024), providing the world's first

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 April 2026 doi:10.20944/preprints202604.0356.v2

life cycle inventory of structural glued laminated bamboo produced from moso bamboo, demonstrate that SGLB stores 1,140 $kgCO_2e/m^3$ — more than twice the biogenic CO_2 emitted during its production — with electricity, adhesive, and transportation identified as the three principal emission sources. These findings position industrially processed bamboo as a structurally credible and environmentally robust alternative whose supply chain emissions are both quantified and reducible through co-generation and optimised logistics.

These findings reinforce earlier work by Pittau et al. (2018, 2019) while extending its scope to a broader range of fast-growing species and adding an explicit SDG framework. Mechanically, a comprehensive 2025 review of bio-based structural members concludes that, while moisture absorption and temperature sensitivity remain performance constraints relative to steel and concrete, advances in hybridisation and nanotechnology are progressively improving the mechanical robustness, durability and load-bearing capacity of bio-based composites (Barbhuiya et al., 2025). Taken together, these contributions confirm that the scientific trajectory of bio-based construction materials is shifting from demonstrating feasibility to quantifying system-level performance at the scale of buildings and urban stocks. The maturity and breadth of this research effort is reflected in the edited volume by Pacheco-Torgal and Tsang (2025), which consolidates advances across bio-based materials for construction and energy efficiency and provides a comprehensive reference framework against which the specific material categories reviewed in the following subsections can be situated

2.2. Bio-Based Admixtures and Polymer Composites for Concrete

Approximately 15% of the total ordinary Portland cement (OPC) concrete production — the most widely used construction material on Earth — contains chemical admixtures to modify its properties in both fresh and hardened states. These superplasticizers, based on synthetic polymers such as melamine, naphthalene condensates, or polycarboxylate copolymers, improve workability, strength, and durability. However, these admixtures are derived from the fossil fuel industry, which is responsible for significant environmental disasters. As oil exploration ventures into deeper, stormier, and icier seas, the associated risks escalate, underscoring the need for new biodegradable polymers derived from renewable sources. Examples of bio-based admixtures used in concrete include lignosulfonate, starch, chitosan, pine root extract, protein hydrolysates, and vegetable oils. However, investigations into the use of biopolymers in OPC remain limited; of the 10,000 Scopus-referenced journal papers on OPC published since 2000, less than 1% explore biopolymer applications.

Recent research has begun to address this gap more systematically. Boutouam et al. (2024) conducted a comprehensive bibliometric and systematic review of plant-based biopolymers as viscosity-modifying admixtures (VMAs) in cement-based materials, evaluating cellulose, starch, alginate, pectin, and carrageenan as sustainable alternatives to synthetic VMAs. Their analysis, covering publications from 2000 to 2023, confirms a significant upward trend in research activity since 2017, while also noting that bio-based VMAs remain in an early commercialisation phase, constrained by inconsistencies in dosage optimisation and compatibility with superplasticizers. Complementing this, Ševčík et al. (2025) demonstrated a new class of bio-based latex admixtures synthesised from camelina, linseed, and rapeseed vegetable oils incorporated into OPC fine-grained mortars at 0.1 wt%, finding that the water absorption coefficient was reduced by approximately 40% compared to control mixes and that compressive strength was maintained at comparable levels to conventional cement mortar. These findings provide experimental confirmation that bio-based polymer admixtures can deliver functional equivalence to their petrochemical counterparts at relevant dosage levels.

Carbon fibre reinforced polymers (CFRP) represent a widely recognised technological solution for structural strengthening in civil engineering applications. Nevertheless, their expense and high environmental footprint are significant concerns raised by some authors. Ghorbel et al. (2021) confirmed that bio-sourced flax fibre-reinforced polymer is a promising material for confining recycled aggregate concretes, providing consistent strength and strain enhancements. This line of research has been extended by a systematic bibliometric review covering 87 experimental studies, which demonstrated that natural fibre reinforced polymer (NFRP) materials — using flax, jute, hemp, and bio-based epoxy matrices — can effectively strengthen concrete beams and columns, with some formulations achieving cost efficiencies 20–40% higher than CFRP, while also identifying durability and standardisation of design frameworks as the principal barriers to adoption (Adesina & Olutoge, 2022). Jahami et al. (2024) further synthesised the broader literature on natural fibre reinforcement in structural concrete, establishing that fibre chemical composition — dependent on species, environment, and geography — has profound implications for mechanical properties, and that optimal fibre concentrations vary considerably across species, underscoring the need for species-specific design guidance. Sain et al. (2021) synthesised formaldehyde-free bioresin adhesives from lignin and tannin obtained from softwood bark, an approach that has gained further traction as the pressure to eliminate formaldehyde from construction adhesives has intensified under EU indoor air quality regulations.

2.3. Bio-Based Polyurethanes and Thermal Insulation Polymers

Another important polymer widely used by the construction industry is polyurethane, applied primarily in thermal insulation. In recent years many investigators have dedicated effort to the development of bio-based polyurethanes derived from renewable polyols. Andersons et al. (2020) developed rigid high-density polyurethane foams using polyols derived from renewable tall oil fatty acids for use as structural thermal break materials. Oliveira et al. (2022) studied castor oil-based polyurethane reinforced with açaí waste as an alternative for eco-efficient building insulation. More recently, Zarmehr et al. (2024) published a state-of-the-art comparative review of bio-based polyurethane insulations specifically in the construction context, concluding that bio-based components such as plant oils and natural fillers maintain the mechanical integrity of insulation panels, enhance acoustic absorption and heat-transfer properties through their porous microstructure, and that the overall eco-friendliness of these systems depends critically on the selection of bio-components throughout the supply chain rather than being an automatic consequence of bio-based content. At the market scale, over 57% of polyurethane manufacturers globally had integrated at least one bio-based grade into their portfolio by 2025, with bio-based rigid foam applications accounting for approximately 30% of total bio-based polyurethane volume and representing roughly 34% of the total construction insulation market share in leading markets. This trajectory confirms that bio-based polyurethanes are completing the transition from research curiosity to mainstream commercial offering, though performance parity in fire resistance and long-life durability under real service conditions remains an active area of research.

2.4. Nanocellulose and Cellulose Aerogels

The nanotechnological advancements of the past decade have paved the way for the development of new and improved biopolymer-based materials. Research on cellulose nanocrystals — cellulose elements with at least one dimension in the 1–100 nm range — represents a significant and recent nanotech field that promises eco-efficient, high-performance materials. As the most abundant organic polymer on Earth, cellulose — producing about 1.5 trillion tons annually — is renewable, biodegradable, and carbon neutral, with the potential for industrial-scale, low-cost processing, making it a green biotech source for future building materials. Cellulose aerogel is another promising application for developing high-performance thermal insulator building materials. These insulators, with thermal conductivity lower than 0.020 W/mK, outperform current petroleum-based insulation materials like expanded polystyrene (EPS) and extruded polystyrene (XPS), which have values around 0.03–0.06 W/mK. The use of high-performance thermal insulation is critical for reducing heat losses in buildings, thereby increasing energy efficiency. Additionally, as non-flammable materials, aerogels do not release toxic fumes under fire conditions, unlike current insulation materials like EPS and XPS, providing a significant safety advantage.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 April 2026 doi:10.20944/preprints202604.0356.v2

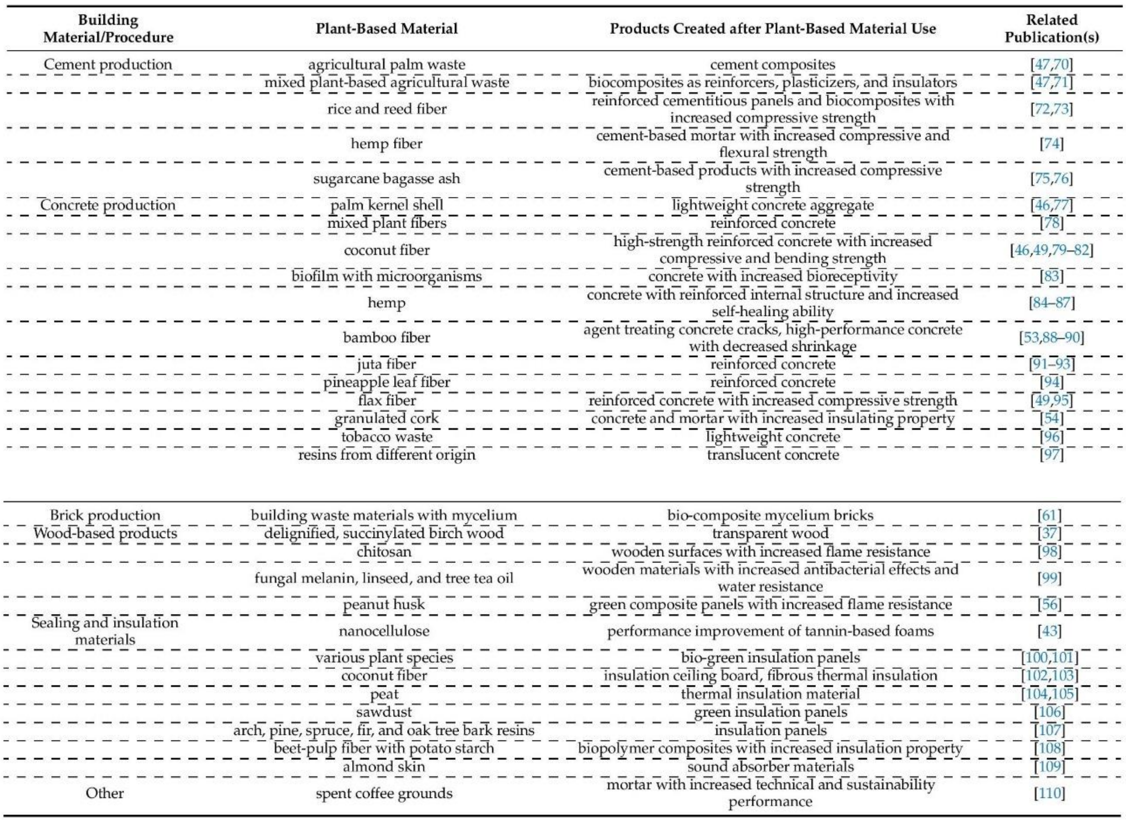
Since the publication of Sen et al. (2022), the commercialisation landscape for bio-based aerogels has progressed considerably. At the market level, the global aerogel insulation sector is projected to grow at a compound annual growth rate of approximately 17% over the 2025–2035 period, driven by tightening energy efficiency regulations in the construction sector and improvements in ambient-pressure drying processes that reduce production costs relative to traditional supercritical drying (CAS, 2025). At the materials innovation level, Nanoplume, a Cambridge-based start-up, has demonstrated a cellulose-based aerogel manufactured through a bio-based, ambient-pressure process that achieves thermal conductivities within the super-insulating category, addressing the dual barriers of cost and scalability that have historically constrained cellulose aerogel deployment (Wakley, 2025). A particularly noteworthy development concerns the application of cellulose aerogels to building glazing.

Abraham et al. (2023) demonstrated highly transparent silanised cellulose aerogels — designated SiCellA — with visible-range light transmission of 97–99%, haze of approximately 1%, and thermal conductivity lower than that of still air, compatible with roll-to-roll processing and suitable for integration into multi-pane insulating glass units and window retrofits. This application extends the utility of cellulose aerogels well beyond opaque insulation panels and into the building envelope's weakest thermal link. In April 2024, Empa researchers further demonstrated the integration of cellulose aerogels into 3D-printable biodegradable materials, opening a path towards geometrically complex, customised insulation components fabricated through additive manufacturing (Sivaraman et al, 2024). These converging advances suggest that the commercialisation barriers identified in earlier literature are progressively being resolved, though large-scale industrial deployment in the construction sector remains at an early stage.

2.5. Plant-Based Materials: Biocomposites, Prefabrication, and Circular Economy Assessment

Petrescu et al. (2021) provided insights into the steps necessary for biocomposites to become ready-to-use products in the construction industry, specifically in structural roles. Their study addresses the development and adoption of these materials through two key concepts: technology readiness level and roadmapping. This approach is illustrated with a case study on "liquid wood." The study resulted in a customised roadmap highlighting a predominantly non-technical viewpoint regarding the material, identifying potential adoption and diffusion challenges and offering further recommendations to address these issues. A review by Boros and Tőzsér (2023) of 977 publications revealed a yearly increase in relevant papers, with most belonging to the engineering discipline. The literature thoroughly evaluates a wide range of plant-based building materials, which are primarily used to enhance the mechanical properties of conventional materials; many are also tested as substitutes for traditional ones. The most assessed plant-based materials and their documented uses in the construction industry are summarised in Table 1 (Boros & Tőzsér, 2023).

Table 1. - The most assessed plant-based materials and their use in the construction industry in the studied literature Boros and Tőzsér (2023). This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).



Building Material/Procedure	Plant-Based Material	Products Created after Plant-Based Material Use	Related Publication(s)
Cement production	agricultural palm waste	cement composites	[47,70]
	mixed plant-based agricultural waste	biocomposites as reinforcers, plasticizers, and insulators	[47,71]
	rice and reed fiber	reinforced cementitious panels and biocomposites with increased compressive strength	[72,73]
	hemp fiber	cement-based mortar with increased compressive and flexural strength	[74]
	sugarcane bagasse ash	cement-based products with increased compressive strength	[75,76]
Concrete production	palm kernel shell	lightweight concrete aggregate	[46,77]
	mixed plant fibers	reinforced concrete	[78]
	coconut fiber	high-strength reinforced concrete with increased compressive and bending strength	[46,49,79–82]
	biofilm with microorganisms	concrete with increased bioreceptivity	[83]
	hemp	concrete with reinforced internal structure and increased self-healing ability	[84–87]
	bamboo fiber	agent treating concrete cracks, high-performance concrete with decreased shrinkage	[53,88–90]
	juta fiber	reinforced concrete	[91–93]
	pineapple leaf fiber	reinforced concrete	[94]
	flax fiber	reinforced concrete with increased compressive strength	[49,95]
	granulated cork	concrete and mortar with increased insulating property	[54]
	tobacco waste	lightweight concrete	[96]
	resins from different origin	translucent concrete	[97]
Brick production	building waste materials with mycelium	bio-composite mycelium bricks	[61]
Wood-based products	delignified, succinylated birch wood	transparent wood	[37]
	chitosan	wooden surfaces with increased flame resistance	[98]
	fungal melanin, linseed, and tree tea oil	wooden materials with increased antibacterial effects and water resistance	[99]
	peanut husk	green composite panels with increased flame resistance	[56]
Sealing and insulation materials	nanocellulose	performance improvement of tannin-based foams	[43]
	various plant species	bio-green insulation panels	[100,101]
	coconut fiber	insulation ceiling board, fibrous thermal insulation	[102,103]
	peat	thermal insulation material	[104,105]
	sawdust	green insulation panels	[106]
	arch, pine, spruce, fir, and oak tree bark resins	insulation panels	[107]
	beet-pulp fiber with potato starch	biopolymer composites with increased insulation property	[108]
	almond skin	sound absorber materials	[109]
Other	spent coffee grounds	mortar with increased technical and sustainability performance	[110]

Le et al. (2023) reviewed 97 articles with the aim of categorising case studies, examining the state-of-the-art in sustainability assessments, and highlighting the pros and cons of circular bio-based building materials. The results indicate that material scale is the most researched aspect, with environmental analysis — primarily using life cycle assessment — being the most frequently studied dimension, followed by economic analysis. Research on social impact is still in its early stages. Regarding the balance of advantages and disadvantages, circular bio-based building materials generally outperform traditional materials in reducing initial production costs and mitigating environmental impacts, particularly in terms of climate change and abiotic resource use. However, some bio-based materials perform worse in categories such as eutrophication and land use, and may not be economically viable when considering the entire life cycle. These findings underscore that the sustainability case for bio-based materials, while broadly compelling, requires nuanced assessment at the level of individual material types, applications, and geographic contexts.

2.6. *Mycelium-Based Composites: An Emerging Frontier*

Among emerging bio-based materials, fungal mycelium-based composites (MBCs) have attracted exceptional research interest since 2022 and merit dedicated attention beyond the limited references available at the time of writing. MBCs are biocomposites produced through the controlled growth of filamentous fungi on lignocellulosic substrate waste — typically agricultural by-products such as straw, sawdust, or hemp shiv — which the mycelium colonises and binds into a dense, self-reinforced matrix upon drying or heat-treatment. Their appeal for construction applications derives from a combination of properties that few conventional materials can match simultaneously: thermal conductivities in the range of 0.036–0.06 $W \cdot m^{-1} \cdot K^{-1}$, acoustic absorption 70–75% superior to conventional ceiling tiles and polyurethane foams, inherent fire resistance conferred by chitin and β-glucan cell wall components, and a global warming potential that can be net-negative when biogenic carbon sequestered during cultivation exceeds lifecycle emissions (Motamedi et al., 2025; Parhizi et al., 2025). A critical review further reported Young's moduli of up to 3.66 GPa in optimised MBC formulations, indicating mechanical performance approaching that of low-density wood products, while separate analysis found that MBCs exhibit up to 70% lower embodied carbon than conventional insulation materials such as expanded polystyrene (Parhizi et al., 2025).

An analysis of 90 real-world architectural and design projects between 2007 and 2024 confirms that modular building blocks and bricks represent the fastest-growing application category, though construction use remains largely confined to temporary and demonstration structures (Bonenberg & Bonenberg, 2025). A study focused on the Helsinki metropolitan area demonstrated that large-scale substitution of conventional insulation with mycelium-wood composites could enable building stocks to act as net carbon sinks, with stored CO_2 potentially equalling or surpassing the carbon storage of equivalent forest areas — though realising this potential is heavily contingent on increasing annual renovation rates (Ruta et al., 2024). Key barriers to wider adoption include process standardisation, moisture sensitivity, and the absence of harmonised performance standards, though recent advances in additive manufacturing and microstructural optimisation suggest a viable pathway towards broader industrial deployment (Motamedi et al., 2025).

A further technical knowledge gap of direct relevance to construction certification concerns the fire performance of mycelium-based composites. Although MBCs exhibit inherently favourable fire behaviour — with thermal conductivities as low as 0.03 $W \cdot m^{-1} \cdot K^{-1}$, low heat release rates, minimal smoke production, and self-extinguishing behaviour in some formulations attributable to chitin and β-glucan cell wall components (Cascione et al., 2025) — performance varies substantially with fungal species, substrate composition, and density. Critically, the natural fire-retardant components alone have been found to be insufficient to meet regulatory thresholds without substrate modification (Jones et al., 2020). No standardised fire classification protocol currently exists for MBCs under building codes across EU Member States, meaning that demonstrating code compliance requires bespoke testing on a project-by-project basis — a direct and tangible link between the Level 3 technical gap and the Level 1 regulatory vacuum identified in this framework. Incorporating substrates with high natural silica content — such as rice hulls or bamboo leaves — has shown promise in improving fire retardancy without compromising biodegradability (Jones et al., 2020), but systematic cross-species and cross-substrate research protocols remain absent from the literature.

At the frontier of bio-based material research lies a domain almost entirely unexplored in construction contexts: the deliberate biological and genetic engineering of construction organisms. Unlike any other materials category, MBCs and bacterial concretes involve living organisms whose fundamental properties are in principle programmable through strain selection, directed evolution, or synthetic biology. Genetic modification of fungal species such as Ganoderma lucidum or Fomes fomentarius to enhance hyphal density, moisture resistance, or compressive strength represents a plausible medium-term research trajectory (Elsacker et al., 2024). Similarly, bacterial concrete exploiting microbial self-healing combined with supplementary cementitious materials offers a convergent innovation pathway that could address durability limitations from a biological rather than a chemical engineering direction (Shaikh et al., 2024). Bridging the gap between construction materials science and synthetic biology represents one of the highest-potential, lowest-competition research opportunities currently available in the field.

2.7. Barriers, Upscaling, and the Path to Mainstream Adoption

Despite a growing body of evidence confirming the technical viability of bio-based construction materials, their transition from demonstrator projects to mainstream specification practice remains slow and uneven. The core argument of this section is that technical performance, while necessary, is not the binding constraint on adoption. The evidence consistently points instead to a compounding set of economic, institutional, and governance failures that reinforce one another, and which cannot be resolved through material innovation alone. Building on the practitioner and systems-level literature reviewed below, this section introduces a hierarchical analytical framework that organises barriers into four levels according to their systemic character and their conditional relationships to one another — an approach informed by sustainability transitions theory and, in particular, the multi-level perspective on sociotechnical change (Le et al., 2023).

The most systematic practitioner assessment of these failures is provided by Dams et al. (2023), who conducted semi-structured interviews with senior professionals experienced in bio-based construction, identifying barriers clustered around three persistent categories: finance, knowledge, and policy. Within these, the most disabling constraints were difficulties scaling production, inconsistent life cycle assessment methodologies, and a lack of material certification frameworks that specifiers could rely upon. Critically, vested interests within the established construction industry were also identified as an active rather than merely passive obstacle — a point that distinguishes this analysis from purely technical accounts of the adoption problem. This diagnosis is corroborated at the methodological level by Silva Santana and Ouellet-Plamondon (2025), whose systematic review of LCA methods applied to bio-based construction materials documents significant heterogeneity in system boundaries, functional units, and impact categories across published studies — a lack of standardisation that directly undermines the comparability of environmental performance claims and sustains the specifier uncertainty identified throughout this review.

Buro Happold (2024) reached broadly compatible conclusions from an industry perspective, confirming that while bio-based materials demonstrate sufficient technical performance across a range of construction applications, mainstream adoption remains contingent on resolving supply chain fragmentation, improving cost predictability, and building specifier confidence through documented project evidence. Together, these two assessments establish that the gap between demonstrated capability and routine specification is not primarily a performance gap — it is a market and institutional gap.

The technical performance case is, in fact, substantially established. Ye et al. (2025), in one of the most extensive reviews yet published in this field, synthesised findings from 395 experimental studies across a range of engineered and natural bio-based insulators, providing quantitative relationships that were previously unavailable to practitioners at this scale. Their analysis confirms that thermal conductivity scales linearly with density and is largely unaffected by ambient temperature, while acoustic noise absorption increases with material thickness and decreases at higher densities — relationships that provide a solid empirical foundation for design optimisation. Critically, bio-based insulation materials were shown to enable near-zero carbon footprints through the combined mechanisms of biogenic carbon sequestration and displacement of petrochemical insulants, a finding that substantially strengthens the environmental case for adoption. However, Ye et al. also highlight that improved moisture resistance and standardised durability testing remain outstanding requirements before widespread adoption can be responsibly recommended — a qualification that directly explains the persistent caution of specifiers identified by Dams et al. (2023) and Buro Happold (2024). The technical evidence base is maturing, but it has not yet closed on the durability questions that matter most to practitioners operating under long-term liability.

For mycelium-based composites specifically, moisture sensitivity is acute enough to impose a hard constraint on application scope independent of regulatory conditions. Unprotected MBC specimens have been observed to decompose within approximately 60 days under normal ambient conditions as water resistance deteriorates rapidly upon exposure (Davison, 2022) — directly explaining why, as shown in Table 2, no MBC product currently certified for structural exterior use has reached the market. The production process compounds this problem: achieving adequate moisture resistance in MBCs currently requires energy-intensive sterilisation and drying steps that partially undermine the materials' sustainability credentials and raise production costs (Cascione et al., 2025). Protective surface treatments, hybrid substrate compositions incorporating silica-rich materials such as rice hulls or bamboo fibres, and renewable-energy-integrated manufacturing represent the most promising mitigation routes identified in the literature, but systematic multi-variable research combining these approaches is absent. The practical consequence for the barrier hierarchy proposed in this paper is that moisture sensitivity is one of the few Level 3 technical barriers

doi:10.20944/preprints202604.0356.v2

severe enough to function as a de facto market access constraint independently of the Level 1 and Level 2 failures — a qualification that justifies targeted R&D investment in this specific problem even ahead of the resolution of regulatory and market conditions.

At the policy and systems level, Chen et al. (2024) offer the broadest synthesis reviewed here, examining relevant policies and life cycle assessments across multiple case studies and estimating that bio-based materials in construction hold potential to mitigate over 320,000 tonnes of carbon dioxide emissions by 2050. Their findings also demonstrate more immediate operational benefits, including reductions in water absorption of up to 40% and decreases in energy consumption of close to 10%. Yet their conclusions are candid about the structural conditions that continue to impede realisation of this potential: a lack of harmonised standards across jurisdictions, durability risks arising from bioerosion, and regulatory frameworks that, while increasingly supportive of innovation in principle, can simultaneously impose constraints that slow commercialisation in practice. The policy environment is therefore neither uniformly enabling nor uniformly obstructive — it is inconsistent, and inconsistency is itself a barrier, as it raises risk for investors and discourages the long-term production commitments needed to bring costs down.

Prefabrication has emerged as one of the more promising structural responses to these commercialisation challenges. Sutkowska et al. (2024), drawing on a bibliometric analysis of 949 research articles and focusing on single-family housing in Central and Eastern Europe, argue that natural material prefabrication technologies offer the production consistency, quality control, and cost competitiveness that bio-based materials require to compete at scale. The trajectory of research in this area is itself instructive: publications in this field grew from 29 in 2015 to 175 in 2023, with 17 already recorded in the first months of 2024 — a pattern that reflects both increasing practical interest and an emerging consensus that manufacturing process innovation, not only material innovation, is essential to the scaling problem.

What remains underexplored in much of this literature, however, is the governance dimension — specifically, the question of which institutional actors and policy configurations are most capable of orchestrating the systemic change required. This is the contribution of Rohrbeck and Kulkov (2026), who develop four plausible futures for the European Architecture, Engineering, and Construction industry to 2040. Their scenario analysis demonstrates that the conditions under which green finance, circular procurement, and regulatory instruments successfully accelerate material innovation vary substantially depending on who orchestrates systemic coordination and under what policy stability conditions. Importantly, they find no automatic alignment between environmental ambition and broader social or economic outcomes across any of the four futures — meaning that even in scenarios where bio-based materials achieve significant market penetration, this does not reliably translate into equitable or economically sustainable outcomes without deliberate governance design.

Before analysing the barrier hierarchy in detail, it is necessary to establish an important distinction that the literature reviewed in Section 2 does not make explicit: bio-based construction materials are not at a uniform stage of technical maturity, and their proximity to volume adoption is determined in the first instance by whether the durability question has been resolved through documented in-use performance rather than laboratory characterisation alone. Table 2 below classifies the principal material categories reviewed in this paper according to three dimensions: durability as demonstrated in real buildings (not laboratory specimens), the realistic near-term application domain, and the estimated horizon for volume adoption under current EU market and regulatory conditions. This classification carries direct implications for how the barrier hierarchy should be read: for materials in the 0–5 year column, the argument that barriers are primarily institutional and economic — advanced in the framework below — is well supported by evidence. For materials in the >10 year column, unresolved technical barriers constitute an independent constraint that institutional reform alone cannot overcome. The framework therefore applies with different force to different material categories, and policy instruments should be sequenced accordingly.

Table 2. Durability maturity and near-term volume adoption horizon for key bio-based construction material categories. Horizon estimates reflect EU market conditions as of 2026, assuming no major regulatory acceleration. Materials in the 0–5 year category have resolved the durability question through documented in-use performance; barriers for these materials are primarily institutional (Levels 1–2). Materials in the >10 year category face unresolved technical barriers (Level 3a) that are independent of regulatory conditions.

Material / Category	Durability in Use	Realistic Near-Term Application	Volume Horizon	Key References
Engineered timber (CLT, LVL, Glulam)	Documented (decades)	Structural — all typologies	0–5 years	Göswein et al., 2026; Barbhuiya et al., 2025
Cellulose insulation (recycled paper)	Documented (decades)	Thermal insulation — retrofit & new build	0–5 years	Ye et al., 2025; Chen et al., 2024
Wood fibre panels (high-density)	Documented (>15 years)	Insulation, façade cladding	0–5 years	Ye et al., 2025
Cork composites	Documented (decades)	Insulation, flooring, wall finish	0–5 years	Boros & Tőzsér, 2023
Hempcrete	Partial (10–15 years)	Non-structural infill, envelope	5–10 years	Kore & Sudarsan, 2021; Dams et al., 2023
Natural fibre composites (NFRP)	Partial (lab-dominant)	Secondary structural strengthening	5–10 years	Jahami et al., 2024; Adesina & Olutoge, 2022
Geopolymer + vegetable fibre composites	Partial (lab-dominant)	Prefab façade panels, masonry blocks	7–12 years	Jahami et al., 2024
Bio-based polyurethane (PU foams)	Partial (emerging)	Thermal insulation panels	5–10 years	Zarmehr et al., 2024
Cellulose aerogels	Partial (emerging)	High-performance insulation, glazing	5–10 years	Abraham et al., 2023; Wakley, 2025
Mycelium composites (MBC)	Not yet (~60 days exposed)	Interior acoustic, temporary structures	>15 years (structural)	Cascione et al., 2025; Davison, 2022
Straw bale systems	Partial (moisture-dependent)	Low-rise residential, self-build	>10 years	Ye et al., 2025
Structural bamboo (engineered)	Partial (supply-limited in EU)	Structural — non-EU markets	>10 years (in EU)	Göswein et al., 2026; Liu et al., 2024

A Hierarchical Framework for Barrier Analysis

The literature reviewed above points to a clear hierarchy of constraints rather than a flat catalogue of independent factors. Drawing on insights from the multi-level perspective on sociotechnical transitions, the framework proposed here organises barriers into four levels according to two principal analytical criteria: the *systemic character* of the barrier — whether it is structural and embedded in governance architecture, or more contextual and amenable to resolution through professional change — and the *conditional relationship* of each level to those adjacent to it. Upper-level barriers are argued to create the institutional, economic, and epistemic conditions under which lower-level barriers are generated and perpetuated. Failure to resolve a barrier at Level 1 directly amplifies the severity of barriers at Levels 2, 3, and 4 by sustaining market uncertainty, suppressing private investment, and removing the institutional preconditions for sustained technical progress. This hierarchical conditionality carries direct implications for the sequencing of policy interventions.

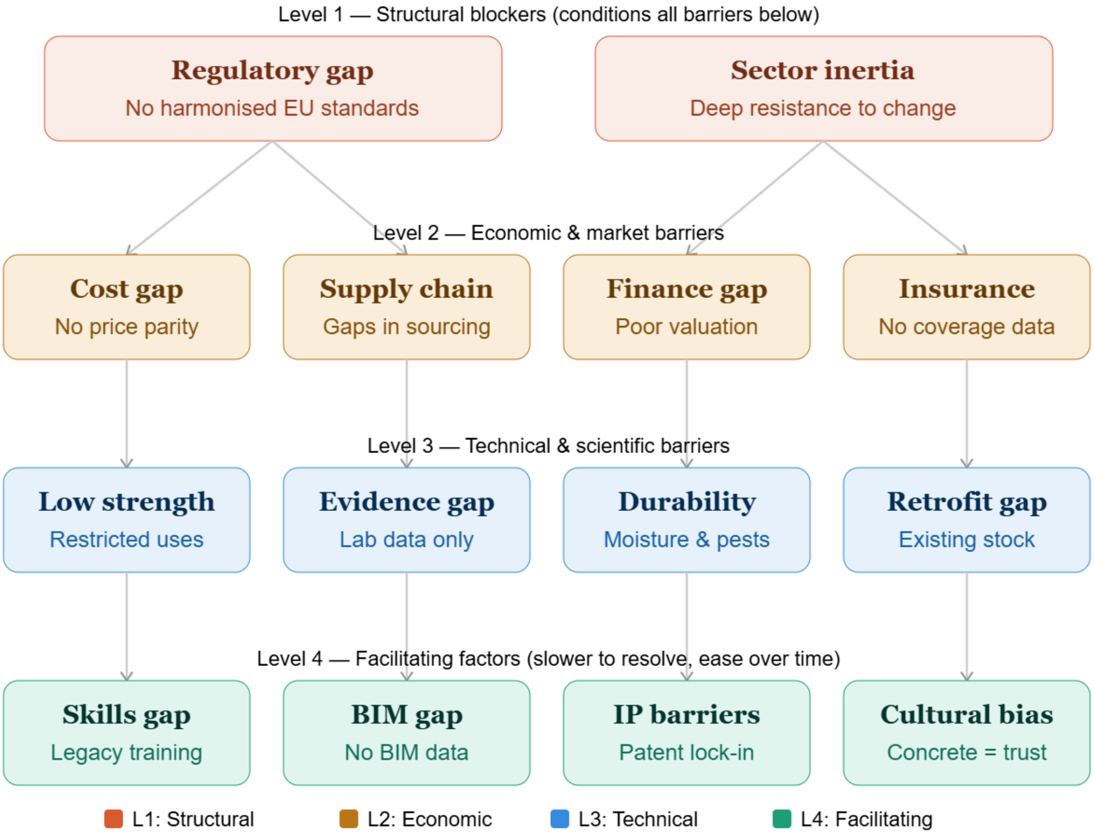


Figure 1. Hierarchical schematic of barriers to bio-based material adoption in construction. Upper-level blockers condition and amplify the severity of barriers at lower levels. Resolving Levels 1 and 2 is a necessary precondition for progress at Levels 3 and 4.

Level 1: Structural Blockers

At the apex of the proposed hierarchy reside two structural blockers whose resolution constitutes a necessary, though not sufficient, precondition for substantive progress at all subordinate levels. The first concerns the governance architecture of bio-based material certification and standardisation. The absence of harmonised European standards represents, in the present assessment, the single most consequential systemic barrier currently impeding market development. Certification requirements — encompassing fire resistance, structural performance, and hygrothermal behaviour — vary substantially across Member State jurisdictions, and test validity is commonly limited to periods of three years, necessitating costly and repetitive reassessment procedures (Sutkowska et al., 2024). This regulatory fragmentation imposes significant transaction costs on manufacturers operating across multiple national markets and, more critically, sustains a condition of pervasive market uncertainty that suppresses investment in production capacity and product development. The European Construction Products Regulation (CPR), presently under revision, has yet to establish adequate provisions for novel bio-based materials, including their heterogeneous composition, sensitivity to regional climatic variation, and the diversity of fabrication methods through which they are produced. The resulting regulatory vacuum is self-reinforcing: without harmonised standards, certification becomes prohibitively expensive; without certification, market access is restricted; and without market access, the commercial case for investment in certification cannot be established.

The second structural blocker is the deep-seated conservatism that characterises professional culture and institutional practice within the construction sector. The industry exhibits among the lowest rates of innovation adoption of any major sector of the European economy — a disposition reflecting the long asset lives of buildings, the fragmented and risk-averse structure of the supply chain, and the legacy of liability frameworks calibrated to conventional material performance data (Le et al., 2023). In this context, even well-designed regulatory instruments and financial incentives may fail to generate the intended market response if the designers, contractors, and procurement officers responsible for translating policy into practice remain sceptical of, or inadequately trained in, bio-based alternatives. It is accordingly contended that regulatory reform and professional cultural change must be pursued as complementary and simultaneous objectives, rather than as sequential stages of a policy programme. The identification of vested interests as an active obstacle by Dams et al. (2023) is directly relevant here: institutional inertia is not merely a passive feature of the landscape but is actively reproduced by actors with material stakes in the conventional construction paradigm.

Level 2: Economic and Market Barriers

Conditioned directly by the structural blockers at Level 1, the economic and market barriers at Level 2 represent the most immediately tangible impediments to the commercial scaling of bio-based construction. The most fundamental is the cost differential between bio-based and conventional materials — but it is important to note that this differential is not primarily attributable to the inherent production costs of bio-based materials per se. Rather, it reflects a structural market failure: the life-cycle environmental externalities of conventional alternatives — including the greenhouse gas emissions associated with cement clinker production, the energy intensity of steel manufacturing, and the end-of-life disposal costs of synthetic composites — are systematically underpriced in prevailing market structures. Were these externalities internalised through appropriately designed carbon pricing or fiscal instruments, the commercial competitiveness of bio-based alternatives would improve substantially (Mouton et al., 2023). In the absence of such internalisation, bio-based materials compete on a structurally asymmetric playing field, irrespective of their demonstrated environmental and technical merits.

Supply chain fragmentation constitutes a further and compounding economic barrier. The predominantly semi-industrial scale of bio-based material production, combined with the seasonal and geographically dispersed character of agricultural raw material sourcing, prevents the realisation of the economies of scale required to achieve cost parity with conventional alternatives — a constraint that is self-reinforcing in character. Insufficient market demand discourages investment in large-scale production facilities, while elevated unit costs associated with small-scale production suppress demand in turn. Breaking this cycle is likely to require coordinated public investment in production infrastructure, strategic procurement initiatives, and the deliberate development of regional bio-based material value chains anchored in local agricultural residue streams. Buro Happold (2024) identifies supply chain fragmentation and cost predictability as the most pressing practical barriers from a specifier perspective, consistent with this structural diagnosis.

A more granular diagnosis of why LCA heterogeneity is structurally embedded — rather than merely a product of inconsistent research practice — is provided by the specific limitations of BS EN 15804 and EN 15978, the dominant standards governing environmental product declarations in the European construction sector. These frameworks were designed for inorganic materials and are

doi:10.20944/preprints202604.0356.v2

methodologically ill-suited to the dynamic carbon behaviour of bio-based alternatives: they do not adequately capture the timing of biogenic carbon sequestration and release across the material lifecycle; they do not consistently incorporate land-use change, which can substantially increase net emissions depending on feedstock origin; and they restrict end-of-life scenarios to incineration and landfill, entirely excluding composting — the most environmentally appropriate end-of-life pathway for many bio-based systems (Hawkins et al., 2023). A material that sequesters carbon during its service life but releases it at demolition has a fundamentally different temporal emissions profile from one that is simply low-carbon at manufacture, and current LCA cannot distinguish between them in a policy-relevant way (Stelzer et al., 2024). Until a dynamic, bio-specific LCA methodology reaches standardisation — with validated open-access datasets for hemp, bamboo, and mycelium — the environmental case for bio-based materials rests on figures that cannot be robustly compared across studies, materially weakening their position in procurement decisions and in policy instruments designed around verified emissions reductions.

Access to finance presents a further market failure of significant practical consequence. Real estate valuation methodologies, as currently practised across most European jurisdictions, do not adequately account for the long-term operational cost advantages or the carbon-related regulatory risk profiles of bio-based buildings, potentially resulting in conservative loan-to-value assessments that constrain mortgage financing (Le et al., 2023). Concurrently, the insurance sector's response to bio-based construction has been characterised by risk aversion in the absence of actuarial performance data, with premium structures that either penalise non-conventional material use or are effectively prohibitive for projects unable to demonstrate compliance with established performance norms. This insurance market gap has received comparatively limited attention in the scientific literature, yet it constitutes a substantial hidden cost that systematically inflates the effective price of bio-based construction.

A further market failure that has received insufficient attention in the literature concerns the practical infrastructure for end-of-life material recovery — the mechanism through which the circular economy proposition of bio-based materials is supposed to be realised. A comprehensive semi-systematic review of the full material lifecycle identified 22 distinct barriers and gaps concentrated specifically in end-of-life planning, component collection and sorting, and matrix compatibility for recycling (Edalat, 2025). In practice, there is almost no operational infrastructure for recovering and reusing bio-based construction elements at building end-of-life across EU markets. The fundamental question of what happens to biogenic carbon when a bio-based building is demolished — whether materials are landfilled, composted, or incinerated — remains inadequately resolved in the LCA literature (Hawkins et al., 2023), meaning that the circular economy proposition of these materials is largely theoretical at the system level. This gap directly suppresses the credibility of bio-based materials in EU Taxonomy assessments and green finance instruments that require verifiable end-of-life carbon accounting. Developing coordinated collection infrastructure, bio-material passports tracking bio-content and reuse eligibility, and circular hub intermediaries capable of linking construction, demolition, and agricultural sectors constitutes a governance challenge whose resolution sits at the intersection of the Level 1 and Level 2 barriers identified in this framework.

Level 3: Technical and Scientific Barriers

The technical and scientific barriers at Level 3 are real and in some cases non-trivial, but they are more tractable — and more amenable to targeted research investment — than the systemic failures at Levels 1 and 2. Chief among them is the structural performance limitation of several prominent bio-based material categories. Hempcrete, for example, exhibits excellent thermal and acoustic insulation characteristics, a favourable hygrothermal regulation capacity, and a negative carbon footprint attributable to biogenic carbon sequestration during hemp cultivation; however, its low compressive strength precludes its use as a primary load-bearing element, necessitating the provision of a complementary structural frame (Kore and Sudarsan, 2021). This constraint restricts hempcrete — and analogous materials such as unfired earth products and straw bale systems — to building

doi:10.20944/preprints202604.0356.v2

typologies in which infill, envelope, or secondary structural applications predominate, thereby limiting their potential market scope.

Level 3a: Technical Barriers Where Durability Remains the Primary Constraint

For a subset of bio-based material categories, the technical barrier is not merely a residual limitation within an otherwise-viable market proposition — it is the primary obstacle to adoption, independent of regulatory conditions or market structure. In these cases, even full resolution of the Level 1 and Level 2 barriers would not generate volume adoption, because the materials have not yet demonstrated the durability that the construction industry requires as a baseline condition for specification. This distinction is critical for the policy implications of the framework: institutional reform and financial instruments directed at these materials will yield minimal market response until the underlying technical limitations are resolved through sustained R&D investment.

Mycelium-based composites (MBCs) are the most prominent case. As discussed in Section 2.6, unprotected MBC specimens degrade within approximately 60 days under ambient conditions (Cascione et al., 2025; Davison, 2022), and no MBC product currently holds certification for structural exterior use in any EU jurisdiction. The combination of moisture sensitivity, absence of standardised fire classification, and mechanical variability places MBCs firmly in this category for all but interior acoustic and temporary applications. Straw bale construction faces an analogous constraint: while thermal performance is excellent and embodied carbon is strongly negative, moisture management is highly dependent on workmanship quality, and the insurance sector has not developed actuarial models adequate to price the risk at scale. Natural fibre composites in conventional Portland cement matrices (as distinct from geopolymer matrices) face the well-documented problem of alkaline degradation of cellulose and lignin at pH 12–13, which progressively embrittles the composite over time — a mechanism whose long-term consequences (20–50 year building lifetimes) are not yet fully characterised at the system level (Jahami et al., 2024). Geopolymer matrices partially mitigate this mechanism through lower pH, but introduce alternative degradation pathways through alkali ion migration into fibres, and long-term in-use data over construction-relevant timescales do not yet exist. For all materials in this sub-level, the research priority is accelerated ageing protocols, long-term exposure studies in real climatic conditions, and bioengineering approaches (strain selection, genetic modification, surface functionalisation) that could fundamentally alter the durability envelope (Elsacker et al., 2024).

Level 3b: Technical Barriers in Materials Where Durability Is Established

For the materials where in-use durability is documented — engineered timber, cellulose insulation, wood fibre panels, hempcrete in non-structural roles, and cork composites — the technical barriers at Level 3 are real but secondary relative to the structural and economic conditions at Levels 1 and 2. These barriers do not prevent adoption in principle; they limit the range of applications and introduce residual professional caution that the institutional framework should be designed to manage. The following paragraphs describe the principal technical limitations in this category.

A further constraint of considerable scientific and practical significance is the scarcity of longitudinal performance data from buildings constructed with bio-based materials under real-world operational conditions. The existing evidence base rests predominantly on laboratory characterisation studies and computational simulation, which, while methodologically rigorous, cannot replicate the complex, time-varying boundary conditions that buildings experience across their operational lifetimes (Galimshina et al., 2022). In particular, the performance of bio-based materials under extended exposure to moisture cycling, freeze-thaw loading, biological colonisation, and structural loading across multiple decades remains insufficiently characterised. This evidence gap constitutes a legitimate basis for professional caution on the part of specifiers and building control authorities, and directly explains the persistent conservatism identified by Dams et al. (2023) and Buro Happold (2024). Ye et al. (2025) confirm that improved moisture resistance and standardised durability testing are outstanding requirements before widespread adoption can be responsibly recommended, and Chen et al. (2024) similarly identify durability risks from bioerosion as an ongoing structural concern.

The compatibility of bio-based material systems with the existing European building stock represents a further technical challenge of considerable strategic relevance. Given that the deep renovation of existing buildings — rather than new construction alone — constitutes the primary mechanism through which the European built environment will be decarbonised over the coming decades, the capacity of bio-based systems to function effectively in retrofit applications is a matter of significant policy importance. The hygrothermal compatibility of bio-based insulation systems with historic masonry substrates, the structural connection of prefabricated bio-based panels to existing reinforced concrete frames, and the management of interstitial condensation risk in hybrid assemblies combining bio-based and conventional materials are among the specific technical questions that require more extensive empirical investigation than has hitherto been undertaken. De Serres-Lafontaine et al. (2024) provide empirical evidence for these concerns, demonstrating through climate chamber testing of four CLT wall assemblies that wood fibre insulation outperforms stone wool in moisture regulation, acting as a buffer that delays moisture migration through the envelope — a finding with direct implications for the design of bio-based retrofit assemblies in humid climates. Their LCA results further confirm that biogenic carbon stored in CLT and wood fibre insulation significantly reduces the global warming potential of the wall system, while highlighting metal sheathing as the component with the highest embodied carbon impact.

Level 4: Facilitating Factors

At the base of the proposed hierarchy reside a set of barriers that, while independently capable of retarding adoption, are expected to diminish progressively as the higher-level blockers described above are resolved. These facilitating factors share the characteristic that their resolution is primarily a function of time, sustained investment in human capital, and the gradual accumulation of professional experience and market confidence — processes that will naturally follow from, though not necessarily precede, the resolution of structural, economic, and technical barriers.

The most consequential of these facilitating barriers is the professional skills deficit currently characterising the construction workforce with respect to bio-based materials. University curricula in architecture and civil engineering devote limited attention to bio-based material specification, structural detailing, and construction management, and continuing professional development provision in this domain remains sparse across most European jurisdictions (Bourbia et al., 2023). This deficit manifests in specification errors, inappropriate material selection, and failures of on-site execution that — when they occur — exert a disproportionately damaging effect on market confidence. Digital tool limitations compound this challenge: the Building Information Modelling (BIM) platforms that underpin contemporary design practice maintain material libraries largely restricted to conventional products, making accurate energy, structural, and life-cycle modelling of bio-based designs unnecessarily difficult. Intellectual property concentration in the emerging biomaterials sector, with several promising material technologies protected by patents held by a restricted number of commercial entities, represents a further constraint on the pace of innovation diffusion. Finally, deeply rooted cultural associations between conventional masonry construction and attributes of permanence, quality, and social status — particularly pronounced in Southern and Eastern European markets — constitute a demand-side constraint that is likely to respond only gradually to changes in professional practice and regulatory frameworks.

It is important to note that the consumer acceptance dimension identified here is not merely a passive attitudinal feature that will erode naturally as bio-based buildings accumulate in the built environment. It constitutes an active, under-researched knowledge gap with its own methodological requirements. The aesthetic, sensorial, and perceptual attributes of bio-based materials — their visual texture, smell, tactile properties, and perceived durability — are poorly quantified, and their influence on specifier and occupant decision-making has not been systematically studied (Göswein et al., 2026). There is a documented shortage of real-world case studies, particularly outside European markets where bio-material research has historically been under-resourced, limiting practitioners' ability to learn from existing evidence or communicate performance credibly to sceptical clients (Hawkins et al., 2023). Without a richer empirical base on what specifically drives and blocks

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 April 2026 doi:10.20944/preprints202604.0356.v2

professional and consumer acceptance — distinguishing aesthetic preference from perceived risk from cultural association — education and communication strategies remain poorly calibrated. Mixed-methods research combining surveys, living lab experiments, and longitudinal occupant studies is needed to transform this from an assumed barrier into an evidence-based one that is amenable to targeted policy and communication intervention.

Synthesis and Implications

The evidence reviewed points to a clear hierarchy of constraints. The technical case for bio-based materials is increasingly robust, though meaningful gaps in durability standardisation persist. The economic and supply chain conditions for scaling are improving but not yet self-sustaining, and depend heavily on a degree of policy consistency that currently varies considerably by jurisdiction. The most intractable barrier is arguably institutional: the combination of vested interests, fragmented governance, and insufficient specifier confidence that multiple authors identify from different vantage points. The hierarchical framework advanced here makes this conditionality explicit: policy programmes concentrating resources on technical research or professional training in the absence of prior or concurrent action on regulatory harmonisation and market correction are unlikely to generate commensurate gains in market uptake. The social return on investment in technical research and professional development will be substantially higher when the structural and economic preconditions for market development have first been established.

The governance dimension identified by Rohrbeck and Kulkov (2026) reinforces this conclusion. Their scenario analysis demonstrates that no automatic alignment exists between environmental ambition and broader social or economic outcomes: even in futures where bio-based materials achieve significant market penetration, equitable and economically sustainable outcomes require deliberate governance design. This is a significant corrective to narratives that treat the scaling of sustainable materials as straightforwardly beneficial. The distribution of costs and benefits, and the institutional configuration that determines them, matter as much as the aggregate environmental outcome.

Resolving the institutional barrier requires not only more documented case studies — though these remain necessary — but a more deliberate effort to build the actor coalitions, certification infrastructure, and policy stability that would allow market signals to function effectively. At Level 1, the most impactful regulatory intervention would be the establishment of a harmonised European performance standard for bio-based construction materials, embedded within the revised Construction Products Regulation and supported by a certification pathway with mutual recognition across Member States. At Level 2, targeted fiscal and financial interventions — including extension of the EU Taxonomy to bio-based construction investments, reform of real estate valuation methodologies, and a transitional public risk-sharing mechanism to address the insurance gap — would correct the market failures currently suppressing investment. The integrated implementation of these Level 1 and Level 2 interventions would create the institutional and economic conditions under which technical research could yield its maximum social return, and under which the cultural and professional changes required for widespread adoption would accelerate naturally through accumulating market experience. Without this foundation, bio-based materials risk remaining technically proven but institutionally stranded: capable of mainstream adoption in principle, but not yet positioned to achieve it in practice.

Two additional research frontiers with high innovation potential remain largely absent from the construction literature. The first concerns the systematic characterisation of non-conventional feedstocks. Research has been overwhelmingly concentrated on hemp, bamboo, straw, timber, and mycelium, while a wide range of agricultural and marine by-products remain understudied for construction applications. Marine algae and seagrasses have been identified as high-potential feedstocks for particleboards and composite matrices, with the added benefit of valorising beach-stranded biomass that currently represents an environmental and economic liability in coastal Member States. Sugarcane bagasse, spent coffee grounds, rice husks, and other agricultural residues have shown early promise as insulation components and mycelium substrates, but lack the

doi:10.20944/preprints202604.0356.v2

systematic hygrothermal and structural characterisation required for construction-grade specification. Establishing regional resource maps linking locally available bio-feedstocks to appropriate construction applications would reduce supply chain fragmentation while expanding the material palette available to European specifiers. The second frontier concerns the deliberate engineering of biological organisms for construction purposes. If fungal strains can be developed with demonstrably superior moisture resistance and fire performance, the regulatory and technical barriers currently impeding mycelium-based construction could be substantially weakened by a single biological innovation — making early public investment in this domain, through instruments such as Horizon Europe and the Bio-based Industries Joint Undertaking, a potentially high-return strategic bet.

3. Conclusions

Bio-based construction materials are now technically validated across multiple categories and represent a credible pathway for reducing the environmental footprint of the built environment. Their performance in thermal efficiency, carbon sequestration, and indoor environmental quality is well established. Yet large-scale adoption remains blocked not by technical limitations but by systemic barriers: regulatory fragmentation, lack of standardisation, market asymmetries, and supply chain immaturity. These constraints interact hierarchically, with structural and economic conditions shaping the effectiveness of even well-designed technical and educational interventions. Strategies focused predominantly on research or skills development will therefore not deliver meaningful market transformation unless accompanied by regulatory harmonisation, improved certification pathways, and economic instruments that correct existing market distortions — including the internalisation of environmental externalities and the creation of stable, large-scale demand signals. The 2026 Strait of Hormuz crisis reinforces the strategic urgency of this transition, exposing European construction's deep vulnerability to petrochemical supply disruptions and positioning bio-based materials as a matter of industrial resilience and strategic autonomy, not only environmental policy.

A critical qualification concerns policy sequencing across material maturity levels. For materials with well-documented durability in use — engineered timber, cellulose insulation, wood fibre panels, hempcrete in non-structural applications, and cork composites — barriers are genuinely institutional and economic. Regulatory and market instruments here offer high and relatively immediate returns. For materials where durability remains unresolved — mycelium composites, straw bale systems, natural fibre composites in cementitious matrices, and geopolymer-fibre hybrids — sustained public R&D investment must be the policy priority. Applying harmonisation or procurement mandates to immature materials before durability is established risks product failures, liability exposure, and a loss of professional and public confidence capable of setting back the entire bio-based agenda.

The Hormuz disruption further demonstrates that exogenous shocks can rapidly compress adoption timelines. Policy responses should channel substitution pressure towards mature materials — cellulose insulation, bio-based polyurethanes, engineered timber — rather than generating undifferentiated demand that draws in products not yet ready for deployment at scale. Strategic material readiness is as essential to supply chain resilience as any aggregate bio-based content target.

Acknowledgments: This research was supported by FCT-Fundação para Ciência e Tecnologia within the scope of the project CEECIND/00609/2018.

References

Abraham, E., Cherpak, V., Senyuk, B., ten Hove, J.B., Lee, T., Liu, Q., & Smalyukh, I.I. (2023). Highly transparent silanized cellulose aerogels for boosting energy efficiency of glazing in buildings. *Nature Energy*, 8(4), 381–396. https://doi.org/10.1038/s41560-023-01226-7

Andersons, J., Kirpluks, M., Cabulis, P., Kalnins, K., & Cabulis, U. (2020). Bio-based rigid high-density polyurethane foams as a structural thermal break material. *Construction and Building Materials*, *260*, 120471.

Barbhuiya, S., Das, B.B., Kapoor, K., Das, A., & Katare, V. (2025). Mechanical performance of bio-based materials in structural applications: A comprehensive review. *Structures*, 75, 108726. https://doi.org/10.1016/j.istruc.2025.108726

Boros, A., & Tőzsér, D. (2023). The Emerging Role of Plant-Based Building Materials in the Construction Industry—A Bibliometric Analysis. *Resources*, *12*(10), 124.

Bonenberg, M., & Bonenberg, A. (2025). A review of mycelium-based composites in architectural and design applications. *Sustainability*, 17(24), 11350. https://doi.org/10.3390/su172411350

Boutouam, Y., Hayek, M., Bouarab, K., & Yahia, A. (2024). A comprehensive review of plant-based biopolymers as viscosity-modifying admixtures in cement-based materials. *Applied Sciences*, 14(10), 4307. https://doi.org/10.3390/app14104307

Bourbia, S., Kazeoui, H., Belarbi, R. (2023). A review on recent research on bio-based building materials and their applications. *Materials for Renewable and Sustainable Energy*, 12, 117–139

Cosentino, L., Fernandes, J., & Mateus, R. (2024). Fast-growing bio-based construction materials as an approach to accelerate United Nations Sustainable Development Goals. *Applied Sciences*, 14(11), 4850. https://doi.org/10.3390/app14114850

Buro Happold. (2024). *Are bio-based materials suitable for mainstream construction?* Urban C:lab programme report. London: Buro Happold Engineering. Retrieved from https://www.burohappold.com/news/are-bio-based-materials-suitable-for-mainstream-construction/

Chen, L., Zhang, Y., Chen, Z., Dong, Y., Jiang, Y., Hua, J., ... & Yap, P. S. (2024). Biomaterials technology and policies in the building sector: a review. *Environmental Chemistry Letters*, *22*(2), 715-750.

Cascione, V., Roberts, M., Maskell, D., Allen, S., Shea, A., & Walker, P. (2025). Towards carbon-neutral built environment: A critical review of mycelium-based composites. Sustainable Materials and Technologies, 44. https://doi.org/10.1016/j.susmat.2025.e01107

Davison, H. (2022). Why the construction industry needs hemp and fungi. World Bio Market Insights. https://worldbiomarketinsights.com/why-the-construction-industry-needs-hemp-and-fungi/

Dams, B., Maskell, D., Shea, A., Allen, S., Cascione, V., & Walker, P. (2023). Upscaling bio-based construction: challenges and opportunities. *Building Research & Information*, *51*(7), 764-782.

D'amato, D., & Korhonen, J. (2021). Integrating the green economy, circular economy and bioeconomy in a strategic sustainability framework. *Ecological Economics*, *188*, 107143.

de Serres-Lafontaine, C., Blanchet, P., Charron, S., Delem, L. and Wastiels, L. (2024) 'Bio-based innovations in cross-laminated timber (CLT) envelopes: a hygrothermal and life cycle analysis (LCA) study', *Building and Environment*, 256, p. 111499.

European Commission. (2025). *A Strategic Framework for a Competitive and Sustainable EU Bioeconomy*. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2025) 960 final. Brussels: European Commission. Retrieved from https://environment.ec.europa.eu/strategy/bioeconomy-strategy_en

EU (2002) European Commission. Life sciences and biotechnology, a strategy for Europe. Communication from the commission to the European parliament, the council, the economic and social committee and the committee of the regions. Brussels: European Commission; 2002.

Edalat, S. (2025). Advancing Circular Economy of Bio-Based Building Materials: Critical Gaps and Future Prospects. Circular Economy and Sustainability.
https://doi.org/10.1007/s43615-026-00729-1

Elsacker, E., Vandelook, S., Van Wylick, A., Ruytinx, J., De Laet, L., & Peeters, E. (2024). A review of recent advances in fungal mycelium based composites. Discover Materials, 4. https://doi.org/10.1007/s43939-024-00084-8

Firoiu, D., Ionescu, G. H., Cojocaru, T. M., Niculescu, M., Cimpoeru, M. N., & Călin, O. A. (2023). Progress of EU Member States Regarding the Bioeconomy and Biomass Producing and Converting Sectors. *Sustainability*, *15*(19), 14128.

Galimshina, A. et al. (2022). Bio-based materials as a robust solution for building renovation: a case study. *Applied Energy*, 316, 119102.

Göswein, V., Arehart, J., Carcassi, O., Lokko, M.-L., Silvestre, J., Tsiavos, A., Pittau, F., Pomponi, F., Ben-Alon, L., Zea Escamilla, E., & Habert, G. (2026). Towards net-zero with fast-growing biobased construction materials. *Sustainable & Green Materials*, 2(1), 2599796. https://doi.org/10.1080/29965292.2025.2599796

Ghorbel, E., Limaiem, M., & Wardeh, G. (2021). Mechanical performance of bio-based FRP-confined recycled aggregate concrete under uniaxial compression. *Materials*, *14*(7), 1778.

Hawkins, W., Cooper-Searle, S., Scott, M., Allen, S., & Ibell, T. (2023). Upscaling bio-based construction: challenges and opportunities. Building Research & Information, 51(7-8), 764-782. https://doi.org/10.1080/09613218.2023.2204414

Jones, M., Mautner, A., Luenco, S., Bismarck, A., & John, S. (2020). Application of Mycelium-Bound Composite Materials in Construction Industry: A Short Review. Symbiosis Online Publishing — Materials Science & Engineering.

IEA — International Energy Agency (2026). *Strait of Hormuz*. IEA Oil Security and Emergency Response. Available at: https://www.iea.org/about/oil-security-and-emergency-response/strait-of-hormuz

Ye, F., Wei, H., Xiao, Y., Berardi, U., Quaranta, G., & Demartino, C. (2025). Bio-based insulation materials in sustainable constructions: A review of environmental, thermal and acoustic insulation, durability, and mechanical performances. *Renewable and Sustainable Energy Reviews*, 223, 115872. https://doi.org/10.1016/j.rser.2025.115872

Jahami, A., Zeaiter, N., & Cheaib, M. (2024). Reviewing the potential: a comprehensive review of natural fibers (NFs) in structural concrete and their multifaceted influences. *Innovative Infrastructure Solutions*, 9, 102. https://doi.org/10.1007/s41062-024-01384-x

Le, D. L., Salomone, R., & Nguyen, Q. T. (2023). Circular bio-based building materials: A literature review of case studies and sustainability assessment methods. *Building and Environment*, 110774.

Liu, K., Jayaraman, D., Shi, Y., Xiong, Z., Yang, J., Symeonidis, A. and Zea Escamilla, E. (2024) 'Life cycle assessment (LCA) of the industrial production of structural glued laminated bamboo', *Journal of Cleaner Production*, 485, p. 144367.

Kore, S.D., Sudarsan, J.S. (2021). Hemp concrete: a sustainable green material for conventional concrete. *Journal of Building Materials Science*, 3(2), 1.

Mahdavi, H., Jafari, A., & Bagheri, M. (2024). Status and barriers to circular bio-based building material adoption in developed economies: The case of Flanders, Belgium. Resources, Conservation and Recycling, 211. https://doi.org/10.1016/j.resconrec.2024.107888

Mousavi, S., Brown, T., & Malmsheimer, R.W. (2025). Sustainable bioplastic products for building applications: recent trends and future opportunities. Biofuels, Bioproducts and Biorefining, 19, 2609-2630. https://doi.org/10.1002/bbb.70005

Motamedi, S., Rousse, D.R., & Promis, G. (2025). A review of mycelium bio-composites as energy-efficient sustainable building materials. *Energies*, 18(16), 4225. https://doi.org/10.3390/en18164225

Mouton, L., Allacker, K., Röck, M. (2023). Bio-based building material solutions for environmental benefits over conventional construction products. *Energy and Buildings*, 282, 112767.

de Oliveira, B. P., Balieiro, L. C., Maia, L. S., Zanini, N. C., Teixeira, E. J., da Conceição, M. O., ... & Mulinari, D. R. (2022). Eco-friendly polyurethane foams based on castor polyol reinforced with açaí residues for building insulation. *Journal of Material Cycles and Waste Management*, *24*(2), 553-568.

Parhizi, Z., Pal, P., Shelley, T., Dearnaley, J., Kauter, K., & Mikkelsen, D. (2025). The fungus among us: Innovations and applications of mycelium-based composites. *Journal of Fungi*, 11(8), 549. https://doi.org/10.3390/jof11080549

Petrescu, T. C., Voordijk, J. T., & Mihai, P. (2021). Developing a TRL-oriented roadmap for the adoption of biocomposite materials in the construction industry. *Frontiers of Engineering Management*, 1-14.

Pittau, F., Krause, F., Lumia, G., & Habert, G. (2018). Fast-growing bio-based materials as an opportunity for storing carbon in exterior walls. *Building and Environment*, *129*, 117-129.

Pittau, F., Lumia, G., Heeren, N., Iannaccone, G., & Habert, G. (2019). Retrofit as a carbon sink: The carbon storage potentials of the EU housing stock. *Journal of Cleaner Production*, *214*, 365-376.

Pianta, M., & Lucchese, M. (2020). Rethinking the European Green Deal: An industrial policy for a just transition in Europe. *Review of Radical Political Economics*, *52*(4), 633-641.

Polymerupdate (2026). *Polymer prices surge sharply amid supply disruptions as Middle East tensions escalate*. Polymerupdate, March 2026. Available at: https://www.polymerupdate.com/News/Details/1457397

Pacheco-Torgal, F., & Tsang, D. (Eds.). (2025). *Advances in Bio-Based Materials for Construction and Energy Efficiency*. Elsevier.

Randers, J., Rockstrøm, J., Stoknes, P. E., Goluke, U., Collste, D., & Cornell, S. (2018). Achieving the 17 sustainable development goals within 9 planetary boundaries. *EarthArXiv. October, 2*.

Richards, C. E., Gauch, H. L., & Allwood, J. M. (2023). International risk of food insecurity and mass mortality in a runaway global warming scenario. Futures, 150, 103173.

Ronzon, T., Iost, S., & Philippidis, G. (2022). Has the European Union entered a bioeconomy transition? Combining an output-based approach with a shift-share analysis. *Environment, Development and Sustainability*, *24*(6), 8195-8217.

Rohrbeck, R., & Kulkov, I. (2026). Building industry in 2040: An explorative scenario analysis of alternative sustainability pathways. *Futures*, 103814.

Ruta, M.F., Carcassi, O.B., Zanelli, A., & Pittau, F. (2024). Mycelium-wood composites as a circular material for building insulation. *Frontiers in Sustainable Cities*, 6, 1412247. https://doi.org/10.3389/frsc.2024.1412247

Shaikh, F.U.A., Barbhuiya, S., & Daniyar, A. (2024). Harnessing construction biotechnology for sustainable upcycled cement composites: A meta-analytical review. Journal of Building Engineering, 88. https://doi.org/10.1016/j.jobe.2024.109151

Stelzer, K.J., Ossendorf, G., Remmele, S., & Meissner, K. (2024). Life cycle assessment of mycelium-based composite materials. Resources, Conservation and Recycling, 204. https://doi.org/10.1016/j.resconrec.2024.107484

Sain, S., Matsakas, L., Rova, U., Christakopoulos, P., Öman, T., & Skrifvars, M. (2021). Spruce bark-extracted lignin and tannin-based bioresin-adhesives: effect of curing temperatures on the thermal properties of the resins. *Molecules*, *26*(12), 3523.

Schanes, K., Jäger, J., & Drummond, P. (2019). Three Scenario Narratives for a Resource-Efficient and Low-Carbon Europe in 2050. *Ecological Economics*, *155*, 70-79.

Ševčík, R., Šašek, P., Šídlová, M., Viani, A., & Pérez-Estébanez, M. (2025). Bio-based latex admixtures derived from vegetable oils for ordinary Portland cement mortars. *Frontiers in Built Environment*, 11, 1701378. https://doi.org/10.3389/fbuil.2025.1701378

Sen, S., Singh, A., Bera, C., Roy, S., & Kailasam, K. (2022). Recent developments in biomass derived cellulose aerogel materials for thermal insulation application: a review. *Cellulose*, *29*(9), 4805-4833.

Sivaraman, D. et al. (2024). Additive Manufacturing of Nanocellulose Aerogels with Structure-Oriented Thermal, Mechanical, and Biological Properties. *Advanced Science*. https://doi.org/10.1002/advs.202307921

Silva Santana, J. and Ouellet-Plamondon, C. (2025) 'The materials bio-based constructions: a review of the methods of LCA', in *Bio-Based Building Materials – Proceedings of ICBBM 2025*. Cham: Springer, pp. 259–265.

Stoknes, P. E., & Rockström, J. (2018). Redefining green growth within planetary boundaries. *Energy Research & Social Science*, *44*, 41-49.

Sutkowska, M., Stefańska, A., Vaverkova, M. D., Dixit, S., & Thakur, A. (2024). Recent Advances in Prefabrication Techniques for Biobased Materials Towards a Low-Carbon Future: From Modules to Sustainability. *Journal of Building Engineering*, 109558.

Wakley, M. (2025). Taking aerogel insulation from spacecraft to living space. *Chemistry World*, 5 December 2025. Royal Society of Chemistry. Available at: https://www.chemistryworld.com/news/taking-aerogel-insulation-from-spacecraft-to-living-space/4022593.article

Zarmehr, S., Kazemi, M., Madasu, N.G.A., Lamanna, A.J., & Fini, E.H. (2024). Application of bio-based polyurethanes in construction: A state-of-the-art review. *Resources, Conservation and Recycling*, 211, 107879. https://doi.org/10.1016/j.resconrec.2024.107879