

# Thermohygro-Acoustic Performance and Lifecycle Implications of Plant- and Animal-Based Biocomposite Insulation Systems for Sustainable Buildings

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**Received:** 01 October 2025; **Accepted:** 15 October 2025; **Published:** 31 October 2025

## Abstract

**Background:** The drive to reduce embodied carbon in the built environment has refocused attention on bio-based insulation materials derived from plant and animal agricultural residues and by-products. These materials—ranging from hemp and bagasse to sheep wool, poultry feather blends, and puffed rice composites—offer potential advantages in thermal resistance, hygrothermal buffering, acoustic absorption, lightweight construction, and circularity. However, their in-use performance is multifaceted and sensitive to manufacturing, binder chemistry, moisture history, ageing, and fire/flotation properties. Comprehensive assessment that integrates thermophysical characterization, hygrothermal ageing behavior, acoustic performance, mechanical compatibility with structural substrates, and lifecycle implications is required to credibly position these materials for mainstream adoption.

**Objectives:** This study synthesizes the contemporary literature to construct a cohesive, theory-rich analysis of bio-based insulation systems, interrogating mechanisms of thermal and acoustic insulation in plant- and animal-fibre aggregates, the influence of binders and cementitious matrices, hygrothermal ageing processes and their effects on composite performance, and the broader consequences for lifecycle carbon and regulatory compliance. The objective is not merely to summarize findings but to theorize material–environment interactions, show where empirical evidence converges or diverges, and recommend rigorous research protocols for future validation.

**Methods:** The approach combines critical synthesis and theoretical elaboration rooted in published experimental characterizations, finite element and micromechanical interpretations, and lifecycle assessment frameworks. Evidence is drawn from thermal and acoustic measurement studies, hygroscopic aging experiments, bond and fatigue behavior of composites in hygrothermal environments, and LCAs of hemp concrete and lime binders. Emphasis is placed on mechanistic explanations (pore architecture, fibre–matrix interfaces, capillary condensation, and sorption hysteresis) and on reconciling disparate measurement techniques (steady-state vs transient methods).

**Results:** Patterns emerge showing that aggregate geometry and porosity dominate thermal conductivity, while fibres with hollow or corrugated structure provide enhanced thermal resistance and acoustic absorption (Sáez-Pérez et al., 2020; Liao et al., 2022). Binders (lime, magnesium oxychloride, geopolymeric routes) critically influence moisture buffering, mechanical cohesion, and CO<sub>2</sub>-related benefits (Forster et al., 2019; Zorica et al., 2022). Hygrothermal ageing reduces interfacial adhesion in composite systems and can increase thermal conductivity through moisture-driven heat transport and microstructural collapse (Wang et al., 2019; Liu et al., 2020; Al-Lami et al., 2020). Life cycle analysis indicates net benefits for hemp and similar bio-aggregates when production pathways minimize transport and energy-intensive processing (Prétot et al., 2014; Viel et al., 2018).

**Conclusions:** Bio-based insulation systems present a compelling pathway toward lower-carbon building envelopes, provided material selection, binder chemistry, moisture management, and fire safety are rigorously engineered. Future research should prioritize standardized hygrothermal ageing protocols, multi-scale modelling linking microstructure to thermal-acoustic performance, and integrated LCA coupled with durability modeling to quantify long-term carbon and service-life tradeoffs. Policy frameworks should evolve to recognize hygrothermal buffering, biogenic carbon storage, and reparability as legitimate credits in building performance standards.

**Keywords:** bio-based insulation, hygrothermal ageing, hemp concrete, sheep wool, thermal conductivity, acoustic absorption, lifecycle assessment

## **INTRODUCTION**

The global building sector accounts for a substantial portion of embodied and operational greenhouse gas emissions, motivating urgent transformation toward low-carbon materials and circular construction models. Within this transition, bio-based insulation—derived from plant aggregates such as hemp, bagasse, rice husk, and animal-derived fibres like sheep wool and poultry feathers—has attracted research and commercial interest because of its potential to reduce embodied carbon, utilize agricultural by-products, and provide beneficial hygrothermal and acoustic properties (Amziane & Sonebi, 2016; Sáez-Pérez et al., 2020). These materials promise to perform multiple environmental services: thermal insulation to reduce heating and cooling loads; moisture buffering that moderates indoor humidity swings; acoustic absorption for occupant comfort; and carbon storage within biomass-derived matrices. Yet, the move from promising laboratory demonstrations to robust, normative adoption requires rigorous investigation into mechanisms, standardizable performance metrics, ageing and durability, interactions with binders, and lifecycle consequences.

Research to date has produced a rich but fragmented evidence base. Thermal characterization studies demonstrate that porosity, pore connectivity, and the intrinsic thermal properties of constituents determine thermal conductivity (Khoukhi et al., 2021; Huang & Liu, 2009). Acoustic studies show that fibre orientation, tortuosity, and pore size distribution are dominant in sound absorption, with needle-punched and nonwoven formats demonstrating favorable broadband absorption (Moghaddam et al., 2016; Liao et al., 2022). At the same time, engineering studies into fibre–matrix interfaces and the hygrothermal sensitivity of composites reveal vulnerability to moisture cycling, salt migration, and biological attack if not properly detailed (Wang et al., 2019; Liu et al., 2020; Al-Lami et al., 2020). Meanwhile, lifecycle assessments of hemp concrete indicate that wall thickness, coating choices, and processing paths materially affect net environmental outcomes (Prétot et al., 2014; Zorica et al., 2022).

This paper identifies and explores the central tensions and research gaps that impede confident upscaling: (1) a lack of standardized methods for long-term hygrothermal ageing of bio-aggregates and their role in changing thermal and mechanical properties; (2) limited mechanistic integration linking microstructure to macroscopic thermal and acoustic behavior; (3)

insufficiently comprehensive LCAs that incorporate durability-driven service-life differences and reparability benefits; and (4) regulatory and fire-safety concerns that often hinge on binder choice and processing conditions (Kim et al., 2018; Forster et al., 2019). Addressing these gaps requires synthesizing evidence across disciplines—materials science, building physics, structural engineering, and environmental assessment—to develop a robust, transferable knowledge base.

The aim of this research article is to provide a deep, theory-rich synthesis of the literature provided, generate mechanistic hypotheses that explain observed performance patterns, and propose a rigorous methodological agenda for future experimental and modelling work. We emphasize descriptive, conceptual explanations over mere summary and provide detailed, actionable insights for researchers, material manufacturers, and regulators.

## **METHODOLOGY**

The approach adopted here is a structured, critical synthesis that integrates empirical findings, theoretical constructs, and lifecycle frameworks from the supplied literature. The methodology can be conceptualized as four interlinked strands: thermophysical characterization synthesis, hygrothermal ageing analysis, acoustic performance synthesis, and lifecycle integration. Below we describe each strand and the rationale for integrating them.

**Thermophysical characterization synthesis.** The thermophysical strand aggregates experimental results and measurement techniques reported across studies—steady-state methods, transient plane-source (TPS) techniques, guarded hot-plate, and adapted transient methods for porous media (Huang & Liu, 2009; Khoukhi et al., 2021). We examine how measurement protocol choices influence reported thermal conductivity values and how sample preparation (bulk density, compaction, moisture content) is reported and standardized. Key variables analyzed conceptually include volumetric heat capacity, thermal diffusivity, porosity, pore size distribution, and the thermal conductivity of the solid phase.

**Hygrothermal ageing analysis.** Hygrothermal ageing effects are synthesized from studies of composite adhesion, bond performance, and fatigue under cyclic environmental loading (Wang et al., 2019; Liu et al., 2020; Al-Lami et al., 2020). We compare protocols—

immersion, cyclic humidity-temperature chambers, wet-dry cycles—and interpret outcomes in terms of mechanisms: hygroscopic swelling, capillary condensation, salt crystallization, microbial degradation, and chemical alteration of binders. We also draw on chemical and multiphysical characterization literature for agro-resources to link composition to ageing susceptibility (Viel et al., 2018).

**Acoustic performance synthesis.** Acoustic performance data from nonwoven and composite formats (Moghaddam et al., 2016; Malawade & Jadhav, 2020; Liao et al., 2022) are examined with attention to frequency-dependent absorption coefficients, airflow resistivity, and the role of panel thickness and backing conditions. We analyze how fibre morphology, bulk density, and manufacturing processes (needle-punching, compression molding) influence pore structure and viscous/thermal damping mechanisms in porous absorbers.

**Lifecycle integration.** Life cycle considerations are integrated through reported LCAs and carbon accounting studies, focusing on hemp concrete and lime binder systems (Prétot et al., 2014; Forster et al., 2019; Zorica et al., 2022). We analyze methodological choices in LCAs—system boundaries, allocation rules for co-products, transport assumptions, and end-of-life scenarios—and discuss how durability and service-life assumptions can shift carbon payback times. Where direct LCA data are absent, we infer likely impacts by synthesizing process energy estimates, binder emissions factors, and known material densities.

**Synthesis and theoretical modelling.** While not conducting new laboratory tests, we develop mechanistic explanations that connect microstructural features to observed macroscale behavior. These explanations draw on micromechanical concepts and heat/mass transport theory applied to porous, hygroscopic media, and on well-established porous acoustic theories adapted qualitatively for the fibre-aggregate context. Our analysis identifies sensitive parameters, suggests prioritized experiments, and articulates performance envelopes for practical design.

**Evidence selection and citation practice.** All major claims are anchored to the provided references and logically related peer-reviewed work within that set. When asserting general principles not explicitly contained in the provided set but necessary to link phenomena (for example, capillary condensation behavior in porous hygroscopic materials), we cite studies from the supplied list that discuss chemical and multiphysical characterization and aging behavior (Viel et al., 2018; Wang et al., 2019; Liu et al., 2020).

## **RESULTS**

The synthesis reveals coherent themes and nuanced divergences across the literature. These are reported here as descriptive findings across thermophysical behavior, hygrothermal aging effects, acoustic performance, binder interactions, mechanical compatibility, and lifecycle outcomes.

**Thermophysical behavior of bio-aggregates.** A recurrent observation across thermal studies is that thermal conductivity is strongly correlated with bulk density and open porosity. Materials composed of low-conductivity solid phases (cellulose, lignin, keratin) combined with high porosity exhibit thermal resistances competitive with conventional insulators when processed to moderate densities (Khoukhi et al., 2021; Huang & Liu, 2009). For example, puffed rice-based composites demonstrate the role of hollow or porous particle morphology in reducing effective solid conduction pathways (Khoukhi et al., 2021). Similarly, sheep wool and feather blends, owing to hollow fibres and trapped air within fibre crimp, yield low effective thermal conductivities at practical panel densities, while also offering higher volumetric heat capacities that contribute to transient thermal buffering (Dénes et al., 2019; Ilangovan et al., 2022).

**Measurement technique sensitivity is a key finding.** Transient plane-source methods, when properly adapted, provide both thermal conductivity and diffusivity, enabling separation of thermal storage from conduction phenomena (Huang & Liu, 2009). However, reported values vary significantly depending on moisture content control, contact resistance during measurement, and whether samples are measured in compressed form or as loose-fill. This heterogeneity in reported results complicates direct comparison and suggests urgent need for normative sample preparation protocols.

**Hygrothermal ageing and interface degradation.** Composite systems incorporating synthetic or mineral binders frequently exhibit marked changes in mechanical and thermal performance after hygrothermal ageing (Wang et al., 2019; Liu et al., 2020; Al-Lami et al., 2020). For CFRP- and GFRP-strengthened systems, hygrothermal exposure leads to interfacial debonding and reductions in fatigue life; by analogy, fibre-binder interfaces in biocomposite boards and hemp-lime matrices are similarly vulnerable to moisture-driven deterioration. Key mechanisms include differential swelling between hydrophilic plant aggregates and hydrophobic binders, weak adhesion due to surface chemistry mismatches, and binder leaching in repeated wetting cycles (Liu et al., 2020; Al-Lami et al., 2020).

Moisture acts as both a facilitator and antagonist: it

enhances heat transport by increasing effective thermal conductivity through liquid conduction and increases thermal mass through added moisture heat capacity; conversely, sustained high moisture can induce biological colonization and hydrolytic degradation, increasing solid-phase conductivity and lowering insulation performance (Viel et al., 2018; Mehrzad et al., 2022). Hygrothermal cycling data indicate that initial rapid changes occur in the first cycles—associated with pore-filling and drying hysteresis—followed by slower mechanical and chemical changes in binder interfaces (Wang et al., 2019).

Acoustic performance and multi-functionality. Fibre-based panels consistently show effective sound absorption across mid to high frequencies, with performance enhancements achievable by tailoring thickness, bulk density, and backing conditions (Moghaddam et al., 2016; Malawade & Jadhav, 2020; Liao et al., 2022). Hemp and wool-based nonwovens perform well as porous absorbers, where tortuosity and internal friction dissipate acoustic energy. Studies indicate that hybridization—mixing wool with poultry feathers or combining hemp with lime matrices—can extend absorption across wider frequency bands and improve mechanical cohesion (Ilangovan et al., 2022; Ilangovan et al., 2022; Liao et al., 2022). These multifunctional properties enhance the value proposition of bio-based insulation beyond mere thermal resistance.

Binder influence: lime, magnesium oxychloride, and alternative matrices. Binder chemistry emerges as a pivotal determinant of both environmental and functional outcomes. Lime binders, long used in repair and conservation, offer low embodied carbon pathways and chemical compatibility with certain plant aggregates; moreover, lime carbonation can sequester CO<sub>2</sub> over time under favourable conditions, influencing net carbon balance (Forster et al., 2019). Magnesium oxychloride binders can yield mechanically stronger hemp biocomposite boards but may complicate moisture resistance if not correctly formulated (Zorica et al., 2022). Novel approaches that reduce Portland cement use—critical to embodied carbon reductions—while maintaining mechanical integrity and durability are central to the feasibility of large-scale adoption (Prétot et al., 2014; Amziane & Sonebi, 2016).

Lifecycle outcomes and the importance of system boundaries. LCAs reviewed indicate that hemp concrete walls and other plant-aggregate systems can provide lifecycle carbon benefits, but results are highly sensitive to allocation choices, transport distances, and whether biogenic carbon is credited (Prétot et al., 2014; Viel et al., 2018; Zorica et al., 2022). Thicker walls,

while improving thermal mass and embodied carbon payback by reducing operational loads, also increase material use and transport impacts. The trade-offs demand careful, context-specific LCA modelling that includes durability: a material with lower initial embodied carbon but shorter service life or higher maintenance needs may not deliver lifecycle benefits. Repairs and reuse potential—particularly when lime-based binders are used—represent additional, but often underappreciated, benefits in circularity (Forster et al., 2019).

Cross-cutting insights. Several cross-cutting themes surface. First, manufacturing and processing strongly condition final performance: densification, fibre alignment, and binder penetration influence thermal and acoustic function as much as the raw aggregate identity (Viel et al., 2018). Second, moisture management at the building envelope level—detailing, vapour control layers, and rain-screen design—remains critical; bio-based insulations can supply beneficial hygroscopic buffering but should not be relied upon to compensate for poor envelope detailing (Sáez-Pérez et al., 2020). Third, standardization and normative testing regimes remain nascent; without harmonized ageing tests and reporting conventions, comparative claims remain speculative.

## DISCUSSION

Interpreting the integrated evidence requires confronting both the promise and the pitfalls of bio-based insulation systems. Below we elaborate theoretical explanations for observed behaviors, discuss counter-arguments and limitations, and outline an agenda for research and practice.

Mechanisms underlying thermal performance and buffering. The thermal performance of bio-aggregates is fundamentally governed by the partition of heat transfer into conduction through the solid matrix, conduction within pore-filling air or liquid, and radiative transfer at larger pore scales. In highly porous materials dominated by small pores and tortuous paths, solid conduction is minimized and trapped air dominates, producing low thermal conductivity (Huang & Liu, 2009; Khoukhi et al., 2021). Hollow fibres (wool, feathers) add micro-scale dead air spaces and enhance this effect (Dénes et al., 2019; Ilangovan et al., 2022). Moreover, the higher volumetric heat capacity of organic matter contributes to thermal inertia, moderating transient indoor temperature swings. This hygrothermal buffering can reduce peak loads even if steady-state U-values are comparable to synthetic insulators.

However, moisture complicates the picture. Capillary condensation and liquid water penetration

dramatically increase effective thermal conductivity because liquid water has a much higher thermal conductivity than air. In addition, moisture increases volumetric heat capacity, altering transient responses. Therefore, the net operational benefit depends on the balance between enhanced damping of temperature swings and potential conductivity increases during moist periods (Viel et al., 2018; Mehrzad et al., 2022). From a design perspective, this indicates that bio-insulation is most advantageous in envelopes that limit liquid water exposure while allowing controlled vapour exchange—i.e., well-detailed rain-screen façades with breathable internal finishes.

Interface mechanics, ageing, and durability. The durability challenge centers on the interfaces: plant and animal fibres are chemically and mechanically distinct from common mineral binders. Adhesion depends on surface chemistry (functional groups), mechanical interlocking due to binder penetration into fibre surfaces, and differential hygrothermal expansion. Over cycles of wetting and drying, if adhesion is poor, micro-cracking and delamination occur; repeated cycles propagate damage, leading to loss of mechanical integrity and potentially channelling pathways for faster moisture ingress (Liu et al., 2020; Al-Lami et al., 2020). For composite panels used in load-bearing or semi-structural contexts, such degradation affects serviceability and safety. Thus, binder selection and surface treatments (e.g., silane coupling agents, bio-compatible resins) are critical variables. The trade-off is often between eco-friendliness of binders and their long-term protective action; lime-based castings are attractive because they offer carbonation-driven CO<sub>2</sub> sequestration and compatibility with historic repairs, but their slower strength gain and susceptibility under certain moisture regimes must be accounted for (Forster et al., 2019).

Acoustic mechanisms and co-benefits. Acoustic absorption in porous fibrous media arises from viscous dissipation in narrow channels and thermal exchanges near solid surfaces. Finer fibres and higher tortuosity increase viscous drag and convert acoustic energy more efficiently into heat, giving superior mid-high frequency absorption (Moghaddam et al., 2016; Liao et al., 2022). But too high density reduces porosity and airflow resistivity, potentially shifting absorption to higher frequencies and reducing low-frequency performance. Hybridisation—combining different fibre lengths or densities—emerges as a powerful strategy to tailor broadband absorption while also improving mechanical cohesion and reducing dusting. This dual functionality—thermal plus acoustic—enhances occupant comfort and can be a decisive factor for material selection in retrofit and new-build projects.

Lifecycle and systemic implications. The LCA literature underscores that bio-based materials can deliver meaningful lifecycle benefits, but only within carefully specified system boundaries (Prétot et al., 2014; Viel et al., 2018; Zorica et al., 2022). One critical oversight in many LCAs is the exclusion of service-life adjustments; when reparability and embodied carbon re-use are considered—particularly in lime-bonded systems that can be decarbonated and repaired—bio-based materials can show greater lifecycle resilience. Another overlooked factor is local sourcing: transporting low-density materials over long distances dramatically increases embodied emissions per functional unit. Policies and procurement should therefore encourage regional production and create credits for reparability and biogenic carbon storage.

Regulatory, fire safety, and health constraints. Fire performance remains a sensitive issue. Natural fibres are combustible and need careful treatment or encapsulation to meet fire regulations. Flame retardant treatments exist but may undermine environmental credentials or introduce toxicants (Kim et al., 2018). Encapsulation in mineral plasters or mixes with less combustible binders (e.g., lime) is a pragmatic route but changes hygrothermal interaction. Health aspects, such as dust generation during installation and potential for mould growth under poor detailing, require robust installer guidance and standardized testing for biological resistance.

Research agenda and methodological recommendations. To accelerate credible uptake, we recommend a focused research agenda:

1. Standardized hygrothermal ageing protocols. Develop and adopt community-agreed cycling regimes that simulate realistic indoor–outdoor conditions, including temperature–humidity cycles, salt exposure where relevant, and mechanical fatigue relevant to installation conditions. Ageing tests should combine moisture cycling with mechanical stress tests to reveal coupled degradation.
2. Multi-scale characterization linking microstructure to macroscopic properties. Use computed microtomography, pore-network analysis, and representative volume element experiments to parameterize models that predict effective thermal conductivity and acoustic absorption from measurable microstructural descriptors.
3. Durability-aware LCA. Integrate service-life modelling into LCA frameworks to quantify trade-offs between initial embodied carbon and long-term performance, including repair scenarios and end-of-life reuse or downcycling.
4. Binder innovation coupled with environmental

impact assessment. Investigate low-carbon binders (e.g., lime blends, magnesium oxychloride optimized for durability, geopolymer alternatives) and evaluate them not only on mechanical and hygrothermal grounds but also on toxicity, recyclability, and carbon sequestration potential.

5. Fire-safe system design. Explore combinations of passive encapsulation, intumescent treatments with benign chemistries, and compartmentation strategies that reconcile fire safety with circularity.

6. Field trials and post-occupancy monitoring. Laboratory tests must be complemented with long-term field monitoring of installed systems to capture service-life realities and occupant interactions.

Limitations and counter-arguments. The synthesis is constrained by the heterogeneity of experimental protocols in the source literature and by the absence of some direct comparative studies (e.g., side-by-side long-term hygrothermal ageing of a set of representative plant and animal fibre systems under common protocols). A counter-argument is that synthetic insulators deliver superior, predictable long-term performance and simpler compliance with building codes; while often true today, this view underestimates the value of repairability, low embodied carbon, and occupant comfort delivered by bio-based systems. The challenge is therefore not to replace synthetic insulators in all contexts immediately but to delineate contexts where biocomposites deliver clear lifecycle and performance benefits—namely, low-risk envelope zones, retrofits focusing on moisture-buffered interiors, and heritage-compatible repairs using lime binders.

## CONCLUSION

Bio-based insulation systems—drawn from hemp, bagasse, puffed rice, sheep wool, poultry feather blends, and other agro-residues—present a compelling pathway to reduce embodied carbon in buildings while offering hygrothermal buffering and acoustic benefits. However, the promise is conditional: performance is highly sensitive to microstructure, binder chemistry, moisture exposure, and detailing. Hygrothermal ageing can degrade interfaces and increase thermal conductivity, but appropriate binder selection, moisture-smart detailing, and processing can mitigate risks. Lifecycle benefits depend on local production, transport logistics, binder choices, and service life. To move from innovation to mainstream adoption, the field must converge on standardized ageing and measurement protocols, develop multi-scale predictive models, and align LCA methods with durability modeling.

Practitioners should approach bio-based insulation not as a simple like-for-like swap for synthetic insulators but as an integrated system requiring envelope-level design: breathable finishes, rain-screen façades, and maintenance plans that recognize hygrothermal dynamics. Policymakers and standards bodies should incorporate metrics that reward repairability, biogenic carbon storage, and hygrothermal buffering in energy and environmental performance codes. Finally, research must prioritize long-term field performance data and transparent, comparative LCAs that include service-life adjustments.

If these priorities are pursued, bio-based insulations can play a strategic role in low-carbon, healthy, and circular building futures—transforming agricultural and animal-fibre by-products into high-value components of resilient envelope systems.

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