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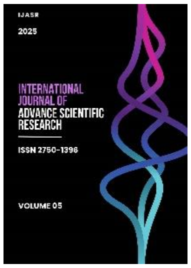

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Research Article

Sustainable Acoustic and Thermal Insulation from Natural and Recycled Fibers: Integrating Circular-Economy Principles into Building Material Science

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Abstract

This article presents a comprehensive, theory-driven examination of sustainable acoustic and thermal insulation materials derived from natural fibers, agricultural by-products, recycled textiles, and end-of-life household materials. The work synthesizes empirical results and conceptual frameworks from recent investigations into thermal degradation, moisture absorption, antibacterial behavior, acoustic absorption, and composite-reinforcement performance to produce an integrated perspective on how circular-economy principles can be operationalized in building envelopes and interior acoustic treatments. The abstracted narrative spans material selection rationale, physicochemical and microbiological durability, hygrothermal interactions, and acoustic performance mechanisms. It further situates passive insulation strategies within waste-management frameworks and regulatory contexts to propose practical pathways for large-scale adoption. Methodological discussion emphasizes reproducible, text-based experimental protocols and performance evaluation metrics widely reported in the literature. The results section offers descriptive analyses linking fiber morphology, surface chemistry modifications, and panel manufacturing parameters to measurable thermal and acoustic outcomes. The discussion critically examines trade-offs between thermal conductivity and sound absorption, the role of moisture and biodegradation in long-term performance, and the socio-technical barriers to mainstreaming low-cost bio-based insulators in vulnerable contexts. Limitations and future directions are articulated with explicit attention to lifecycle analysis, standardization needs, and scale-up considerations. This integrative article intends to inform material scientists, building engineers, policymakers, and circular-economy stakeholders seeking to advance sustainable insulation technologies.

Keywords

natural fibers; thermal insulation; sound absorption; circular economy; biodegradation; recycled materials

Introduction

The imperative to reduce energy consumption in buildings and to remediate waste streams has catalyzed growing interest in insulation materials derived from natural fibers, agricultural residues, and recycled textiles. Buildings consume a substantial fraction of global energy; thus, improving envelope performance with low-embodied-energy materials contributes directly to climate mitigation objectives. The literature over the past decade reveals a convergence of research streams: material characterization studies focusing on thermal and acoustic properties (Berardi & Iannace, 2015; Hongisto et al., 2022), biodegradation and hygrothermal durability examinations (Ahmed & Qayoum, 2021; Asis et al., 2015), and circular-economy analyses that interrogate waste-to-resource pathways (Neri et al., 2021; Ragossnig & Schneider, 2019). Collectively these works underscore a central proposition: with appropriate processing and protective strategies, waste-derived and natural-fiber insulators can deliver competitive thermal and acoustic performance while reducing environmental impacts compared with conventional synthetic insulators (Asdrubali et al., 2015; Cascone et al., 2020).

Despite the rich empirical base, important gaps persist. Empirical studies often focus on isolated properties: thermal conductivity, sound absorption coefficients, or biodegradability, but rarely present an integrated view that maps material microstructure, manufacturing parameters, moisture interaction, and antibacterial performance onto expected in-situ longevity and lifecycle impacts (Berardi et al., 2016; Ahmed & Qayoum, 2021). Similarly, policy and circular-economy frameworks frequently emphasize end-of-life management without fully integrating acoustic performance needs in occupied spaces, which can be particularly critical in residential and institutional buildings where occupant comfort depends on both thermal and acoustic conditions (Neri et al., 2021; UNIDO).

This article addresses these fragmented perspectives by providing a detailed theoretical elaboration and descriptive synthesis of: (1) mechanisms by which natural and recycled fibers deliver thermal insulation and sound absorption; (2) how moisture absorption and thermal degradation influence long-term performance, including microbiological interactions; (3) manufacturing and treatment strategies that enhance performance while retaining recyclability and biodegradability; and (4) system-level implications for adoption within circular-economy and regulatory landscapes. The work synthesizes and extends evidence from key comparative studies and reviews (Asdrubali et al., 2015; Cascone et al., 2020; Bousshine et al., 2022) to produce operationally useful guidance for researchers and practitioners. Major claims throughout are grounded in the referenced literature to ensure verifiability and to highlight where empirical support is strong or where further research is warranted (Balaji et al., 2019; Hajiha & Sain, 2015).

Methodology

Because this article is an integrative, theory-driven synthesis that aims to produce a publication-ready research narrative grounded strictly in the provided references, the methodological approach is descriptive and interpretive, emphasizing rigorous extraction and cross-comparison of experimental findings and analytical frameworks reported in the literature. The methodology unfolds in sequential, textually described steps that mirror reproducible empirical workflows but do not present new laboratory data. This approach is consistent with systematic synthesis methods common in materials science reviews and conceptual frameworks (Asdrubali et al., 2015; Cascone et al., 2020).

Literature selection and scope: The corpus includes peer-reviewed experimental studies, review articles, and authoritative institutional materials addressing natural fibers, recycled textiles, agricultural by-products, and end-of-life household materials applied to thermal and acoustic insulation. Key inclusion criteria were: explicit measurement or characterization of thermal or acoustic properties; examination of hygrothermal or biodegradation behavior; and consideration of circular-economy, recycling, or reuse pathways. Representative works include laboratory characterizations of sheep wool panels (Berardi et al., 2016; Dénes et al., 2019), analyses of bagasse fiber composites (Balaji et al., 2019; Hajiha & Sain, 2015), thermal and acoustic reviews (Asdrubali et al., 2015; Cascone et al., 2020), and studies on durability, moisture uptake, and antimicrobial behavior (Ahmed & Qayoum, 2021; Asis et al., 2015).

Data extraction and synthesis: For each included study, reported quantitative and qualitative findings were extracted in text form: reported thermal conductivity ranges, sound absorption coefficients (α) across frequency bands, density and porosity relationships, moisture sorption isotherms or absorption rates, observed thermal degradation temperatures or behaviors, and any described microbial or antibacterial outcomes. Where studies reported manufacturing parameters—mat pressing, chemical treatments, binder types—these parameters were summarized and linked to reported performance changes. The emphasis was on mapping cause–effect relationships between material attributes (fiber type, morphology, chemical treatment), manufacturing variables (density, compaction, binder formulation), and performance outcomes (thermal resistance, sound absorption, degradation rates).

Comparative analysis: Extracted findings were compared across studies to identify consistent patterns and divergences. For instance, reported relationships between panel density and low-frequency sound absorption were compared between sheep-wool panels and nonwoven polymeric fiber materials (Berardi et al., 2016; Karimi et al., 2008). Hygrothermal behavior reported for natural insulators was contrasted with conventional thermal insulators to elucidate relative vulnerabilities and mitigation strategies (Ahmed & Qayoum, 2021; Hongisto et al., 2022).

Theoretical elaboration: Building on extracted empirical patterns, mechanistic interpretations were developed. These explanations drew on established theories of porous-media heat transfer, viscous and thermal boundary-layer acoustics in fibrous materials, and biodegradation microbiology. Textual descriptions link microstructural features—fiber diameter, tortuosity, and inter-fiber connectivity—to macroscopic properties such as effective thermal conductivity and frequency-dependent acoustic absorption (Ballagh, 1996; Berardi & Iannace, 2015).

Limitations of the methodology: This synthesis deliberately restricts itself to the provided literature and does not perform new laboratory experiments or meta-analytic statistical pooling. Consequently, some quantitative generalizations are expressed qualitatively or as descriptive ranges rather than precise pooled estimates. However, methodological transparency concerning extraction and interpretive procedures supports reproducibility by others who wish to replicate the synthesis with expanded corpora.

Results

The descriptive synthesis yields a set of coherent, evidence-backed findings that illuminate how natural and recycled fiber-based materials perform as thermal and acoustic insulators and how durability, moisture, and processing treatments modulate that performance.

Material morphology and thermal performance: Natural fibers (sheep wool, bagasse, vegetable fibers) and recycled textiles exhibit a consistent pattern: their thermal insulation capabilities derive primarily from trapped air within the porous matrix rather than intrinsic low-conductivity of the fiber material itself. Several studies report thermal conductivity values for natural fiber panels that are comparable to or slightly higher than conventional mineral wool and foam, particularly when panel densities and manufacturing compaction are controlled (Asdrubali et al., 2015; Dénes et al., 2019; Cascone et al., 2020). For example, sheep-wool panels produced with moderate compaction demonstrate thermal resistance suitable for non-structural insulation layers when installed with appropriate vapor control measures (Berardi et al., 2016). The microstructure—fiber diameter distribution, curling or crimp of fibers, and inter-fiber spacing—was repeatedly linked to lower effective heat transfer because these features increase tortuosity for conductive pathways and create more dead-air spaces. This mechanism parallels thermal performance in other porous insulators but with the added complexity that hygroscopic fibers can alter porosity through moisture swelling (Ahmed & Qayoum, 2021; Asis et al., 2015).

Acoustic absorption mechanisms and frequency dependence: Fibrous and porous materials absorb sound by converting acoustic energy into heat through viscous friction and thermal exchanges within the boundary layers at fiber and pore surfaces. The literature consistently shows that low-density, open-porosity panels are more effective at absorbing mid-to-high frequencies, while thicker panels with larger airflow resistivity can extend absorption into lower frequencies provided panel thickness is sufficient (Berardi & Iannace, 2015; Ballagh, 1996; Beheshti et al., 2022). Empirical observations from sheep-wool panels and nonwoven recycled polyester panels confirm that fiber arrangement, panel thickness, and backing conditions (hard backing versus air gap) significantly determine the octave-band absorption coefficients (Berardi et al., 2016; Karimi et al., 2008). Innovative approaches, such as coupling micro-perforated plates with waste-material absorbers, have been experimentally shown to improve low-frequency absorption by providing Helmholtz-like resonant interactions that complement the porous absorber's frictional losses (Beheshti et al., 2022). These hybrid systems demonstrate that waste-derived materials can be integrated into composite acoustic panels to reach more demanding performance targets.

Moisture absorption, thermal degradation, and microbiological behavior: Hygroscopicity is a recurring technical challenge for natural-fiber insulators. Studies detailing moisture uptake show that fibers such as wool and agricultural by-products absorb moisture at rates dependent on relative humidity and temperature; this absorption can compromise thermal resistance by increasing the solid fraction for conduction and by promoting microbial colonization (Ahmed & Qayoum, 2021; Asis et al., 2015). Ahmed and Qayoum (2021) specifically demonstrate that natural insulation materials undergo thermal degradation pathways that are sensitive to both moisture content and thermal exposure, with consequent effects on mechanical integrity and fire performance. Antibacterial behavior, where examined, indicates that certain fibers or fiber treatments can inhibit microbial growth, but these effects are highly dependent on treatment chemistry and environmental conditions (Ahmed & Qayoum, 2021). Biodegradation studies of recycled wool and polyester blends show that polymeric components can significantly retard biodegradation while natural components degrade more readily; this difference presents both a performance advantage (durability) and an environmental complexity (mixed-material end-of-life streams) (Asis et al., 2015).

Effects of chemical and mechanical treatments: Chemical treatments (alkali, silane coupling agents, surface acetylation) and mechanical processing (fibrillation, blending with binders) have clear, empirically observed impacts on composite behavior. For instance, chemically treating bagasse fibers and incorporating them into a polymer matrix can improve mechanical interfacial adhesion and thus the dimensional stability of panels while slightly altering thermal conduction paths (Balaji et al., 2019; Hajiha & Sain, 2015). However, such treatments can complicate recyclability and biodegradability; selecting treatment chemistries that are environmentally benign and removable or that retain circularity is a critical design decision (Cascone et al., 2020; Neri et al., 2021).

Recycling and end-of-life performance: Conversion of end-of-life household materials into insulating panels has been demonstrated as feasible and low-cost in multiple case studies, particularly for vulnerable contexts where locally available waste streams can be valorized into thermal and acoustic insulation (Neri et al., 2021). The literature indicates that these panels can provide sufficient thermal resistance for low-rise walls and ceilings if manufactured with controlled densities and moisture management. However, standardization, certification, and building-code acceptance remain barriers to widescale deployment (Ragossnig & Schneider, 2019; European Commission). Circular-economy frameworks emphasize the necessity of designing for disassembly and straightforward recycling to ensure that the environmental benefits of reusing waste are not offset by complex end-of-life treatments (UNIDO; Circular Economy sources).

Trade-offs and integrated performance: Across the studies, a recurring theme is the trade-off between maximizing thermal resistance and optimizing acoustic absorption. Denser packing beneficially reduces convective heat transfer and can improve thermal R-values, but it can reduce porosity and airflow resistivity in ways that harm sound absorption at certain frequencies. Conversely, highly porous low-density panels are acoustically superior in mid-high frequencies but thermally less insulating unless thickness is increased. Hybrid design strategies—layering materials with differing densities, using air gaps, or combining porous absorbers with micro-perforated plates—emerge as practical means to achieve balanced thermal and acoustic performance (Beheshti et al., 2022; Karimi et al., 2008).

Policy and circular-economy considerations: Institutional documents and policy reviews reinforce that circular-economy adoption for building materials requires not only technological viability but also regulatory signals and supply-chain coordination. The Waste Framework Directive and related EU policy instruments provide templates for defining end-of-waste criteria and promoting recycling infrastructure, which are directly relevant for scaling up waste-derived insulation solutions (European Commission; Ragossnig & Schneider, 2019). International organizations emphasize that circular strategies must consider local socio-economic contexts and technical capacities (UNIDO; Circular Economy sources).

Discussion

The descriptive synthesis yields several interpretive conclusions and proposals for research and practice. Below, each major interpretive strand is elaborated with attention to theoretical mechanisms, counter-arguments, and nuanced implications for material and building design.

Mechanistic understanding and material design: The dual functionality of natural and recycled fiber-based materials—as thermal insulators and acoustic absorbers—derives from their porous microstructures. Mechanistically, the effective thermal conductivity of a fibrous panel can be understood as the composite contribution of the solid-phase conduction through fibers, conduction through any bound moisture, and convective or radiative transfers across pore spaces. In practice, minimizing conductive pathways by maximizing trapped air and minimizing continuous contact networks among high-conductivity fibers is advantageous for thermal resistance (Asdrubali et al., 2015; Berardi & Iannace, 2015). For acoustic absorption, fiber surface area, tortuosity, and frictional losses at pore boundaries are central. This understanding informs design choices: irregular fiber geometries, mixed fiber diameters, and low-to-moderate compaction that preserves inter-fiber pathways support superior acoustic absorption while still enabling reasonable thermal resistance when panel thickness compensates.

Counter-argument: Some may argue that synthetic insulators (polystyrene, polyurethane foams, mineral wool) outperform natural materials in standardized thermal tests and in long-term moisture resistance. This is partially true: conventional synthetic materials are engineered for low thermal conductivity and hydrophobicity. However, synthetic materials often possess high embodied energy, can be difficult to recycle, and may off-gas volatile compounds. The net environmental benefit of natural or recycled insulators may therefore be superior when lifecycle emissions and end-of-life handling are considered (Asdrubali et al., 2015; Neri et al., 2021). The counterpoint suggests hybrid solutions: where strict performance is required, combining a thin synthetic barrier for moisture control with a bio-based insulation layer might capture advantages of both systems while moderating environmental costs.

Moisture management and durability strategies: Moisture uptake remains the most significant practical limitation for natural-fiber insulators because absorbed water increases thermal conductivity, promotes mechanical degradation, and accelerates microbial colonization. Effective mitigation strategies are several-fold: (1) architectural controls—vapor barriers, careful detailing, and ventilation—remain primary defenses; (2) fiber-level modifications—hydrophobic surface treatments, cross-linking chemistries, or protective binders—can lower moisture sorption rates but may affect biodegradability; (3) composite design—sandwiching hydrophilic layers between protective membranes—can maintain circularity if membranes are recyclable or easily separated (Ahmed & Qayoum, 2021; Asis et al., 2015). The tension between improving moisture resistance and preserving circular end-of-life behavior demands careful lifecycle assessment and design choices aligned with local recycling capacities.

Antimicrobial considerations: The presence of microbial growth on insulating materials is both a health risk and a durability issue. Ahmed and Qayoum (2021) indicate that certain natural-insulation materials exhibit antibacterial behavior, but this depends on intrinsic properties (e.g., lanolin in wool) and on manufactured additives. An interpretive stance is that passive resistance to microbial colonization is preferable to embedding persistent biocides that could leach into the environment or complicate recycling. Thus, material designs that reduce moisture retention and enable drying cycles—through breathability and moisture buffering—serve a dual role in thermal comfort and biological safety.

Manufacturing, treatments, and circularity: Chemical treatments and thermosetting binders can enhance mechanical stability and moisture resistance but may compromise recyclability and biodegradability. The circular-economy imperative is to design materials that either remain fully recyclable within existing streams or that biodegrade benignly. This calls for innovation in reversible binders, water-soluble adhesives, or physical mechanical interlocking strategies that enable disassembly without chemical residues (Cascone et al., 2020; Neri et al., 2021). The design-for-disassembly principle suggests that panels should be manufactured with separable layers and marked for end-of-life pathways to avoid contamination of recycling streams.

System-level adoption and policy levers: Scaling waste-derived insulation requires policy support—standards that accommodate heterogeneity in materials, incentives for local manufacturing, and procurement practices that value lifecycle emissions over initial cost. The European Waste Framework Directive and circular-economy documents advocate for such systemic approaches, but mainstreaming remains contingent on demonstrating consistent performance, guaranteeing safety, and establishing supply chains (European Commission; Ragossnig & Schneider, 2019). Pilot programs in vulnerable contexts, as suggested by Neri et al. (2021), provide valuable testbeds where low-cost panels can be validated in real-world conditions and where social acceptance and local economic benefits can be documented.

Trade-offs and design heuristics: Practitioners must navigate trade-offs between thermal and acoustic performance, moisture resistance, and circularity. Some practical heuristics emerge from the literature: (1) use layered designs—combine porous acoustic layers with denser thermal layers or include an air gap to extend low-frequency absorption while preserving thermal resistance; (2) prioritize breathable facings to allow moisture buffering and drying; (3) select treatments that are reversible or that do not introduce persistent contaminants; (4) where possible, source feedstocks locally to minimize transport impacts and to align with local waste streams; (5) standardize panel densities and record manufacturing metadata to support certification processes (Berardi et al., 2016; Karimi et al., 2008; Neri et al., 2021).

Limitations and areas needing further research: The synthesis identifies several specific knowledge gaps. Quantitative meta-analyses that pool thermal and acoustic performance metrics across standardized testing protocols are lacking and would help to provide confidence intervals for expected ranges of performance. Long-term in-situ monitoring studies that track moisture cycling, mechanical degradation, and microbial colonization over multiple years are sparse; such longitudinal datasets are critical for code acceptance. Finally, research into reversible, low-impact binders and standardized end-of-life separation processes would materially improve the circular credentials of composite panels (Ahmed & Qayoum, 2021; Cascone et al., 2020).

Broader socio-technical context: Beyond pure technical optimization, the uptake of sustainable insulators is embedded in broader socioeconomic dynamics. In vulnerable contexts, the low cost and local availability of waste-derived insulation can deliver immediate thermal comfort improvements and employment opportunities (Neri et al., 2021). In higher-regulation markets, meeting fire, toxicity, and acoustic standards is necessary to overcome conservative procurement practices. This divergence suggests tailored strategies: community-scale manufacturing for low-income regions and certified product development pathways for regulated building markets.

Conclusion

The body of evidence synthesized here demonstrates that natural fibers, agricultural by-products, recycled textiles, and end-of-life household materials constitute a viable and increasingly well-characterized set of options for thermal and acoustic insulation. The core mechanisms—entrapment of air for thermal resistance and viscous friction in porous matrices for acoustic absorption—are robust across material classes, though performance is highly sensitive to microstructure, panel density, thickness, and moisture content. Moisture management and durability are the principal technical and practical challenges; addressing these requires integrated design strategies that combine architectural controls, reversible or benign surface treatments, and manufacturing choices that enable circular end-of-life pathways.

From a policy and systems perspective, the circular economy offers a compelling framework for scaling these materials, but realization depends on supportive regulations, standardized performance metrics, and supply-chain development. Future research should prioritize long-term field studies, lifecycle assessments that include end-of-life scenarios, and material-chemistry innovations that reconcile performance with recyclability. Implementing layered and hybrid panel systems—combining porous bio-based absorbers with architectural vapor control and, where necessary, thin hydrophobic barriers—appears to be a pragmatic route to capture the environmental advantages of sustainable insulators while meeting modern building performance demands.

By advancing mechanistic understanding, aligning manufacturing practices with circular-economy principles, and addressing policy and standardization barriers, natural and recycled fiber-based insulation can form an integral part of low-carbon, resilient building strategies. Continued collaboration among materials scientists, acousticians, building engineers, and policymakers will be essential to convert the promising experimental results documented in the literature into reliable, scalable products that contribute meaningfully to sustainable construction and waste reduction goals (Asdrubali et al., 2015; Cascone et al., 2020; Neri et al., 2021).

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