Research Article

Sustainable Textile-Based Nonwoven Composites for Thermal and Acoustic Insulation: Materials, Methods, Performance, and Circular Pathways

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ABSTRACT

Background: Growing concerns about energy efficiency, resource depletion, and the environmental footprint of building and transport sectors have directed attention toward sustainable insulation solutions derived from textile-based materials and natural fibres. Textile-derived nonwovens, recycled fibres, and agricultural waste streams present promising raw-material sources that can simultaneously address acoustic and thermal performance requirements while aligning with circular-economy strategies.

Objective: This article synthesizes contemporary literature on textile-based composites and nonwoven materials for thermal and acoustic insulation, critically examines material selection and processing pathways, proposes detailed experimental and characterization methodologies that are consistent with current best practice, and integrates insights on circularity, energy sustainability, and techno-economic considerations to provide a comprehensive roadmap for academic and industrial stakeholders.

Methods: We present an integrative methodological framework describing material sourcing (recycled nonwovens, agricultural residues such as luffa, and natural fibre blends), nonwoven manufacturing and consolidation techniques (carding, needlepunching, hydroentangling, thermal bonding, and environmentally compatible binders), and performance characterization (thermal conductivity, heat capacity proxies, sound absorption coefficients across broad frequency bands, moisture sorption, durability, and fire performance proxies). We emphasize descriptive, reproducible protocols and quality-control concepts.

Results: Collating evidence from experimental reports and material characterization studies, textile-based nonwovens and composites constructed from recycled cotton/polyester blends and natural fibres

demonstrate competitive sound absorption across mid-to-high frequencies and tunable thermal properties through density and porosity control. Agricultural fibres such as luffa show notable porosity and tortuosity characteristics that improve broadband acoustic absorption when structured as fibrous mats. Thermal performance benefits from low thermal conductivity inherent to porous fibrous structures, but moisture sensitivity and flammability remain obstacles that need mitigation.

Conclusions: Textile-based nonwoven composites are well-positioned to contribute to energy-efficient building envelopes and lightweight transport insulation systems when design practices emphasize porosity control, hybridization with other natural or mineral fillers, moisture management, and circular end-of-life planning. Policy-aligned industrial practices, integration with recycling infrastructures, and standards development will be central to scaling these solutions.

Implications: This paper offers researchers and practitioners a detailed descriptive methodological baseline and critical synthesis to design, test, and upscale sustainable textile-based insulation solutions that balance performance, life-cycle impacts, and circularity goals.

KEYWORDS

Textile-based composites; nonwoven insulation; natural fibres; acoustic absorption; thermal management; circular economy; recycled nonwovens

INTRODUCTION

The The imperative to reduce energy consumption and greenhouse gas emissions within buildings and transportation has intensified the search for insulation materials that are both high-performing and environmentally responsible (Kalair et al., 2022). Conventional insulators—glass wool, mineral wool, and petroleum-derived foams—provide high thermal performance but face scrutiny over embodied energy, recyclability, and human health concerns in manufacturing and disposal. This shift has accelerated research into bio-based, recycled, and textile-derived materials that can offer lower embodied energy, potential for reuse or recycling, and the additional advantage of acoustic performance in many application contexts (Singh & Bhatnagar, 2021; Kumar et al., 2023).

Textile-based composites and nonwovens occupy a unique niche because textiles are inherently fibrous and provide a morphology—high surface area, interconnected pores, tortuous flow pathways—that is advantageous for both thermal insulation (by trapping air and interrupting conductive pathways) and acoustic absorption (by viscous-thermal dissipation and frictional losses within fibre networks) (Zhang et al., 2024). Moreover, the global scale of textile production and waste generation offers an abundant raw-material feedstock for recycled nonwovens derived from post-consumer garments and industrial offcuts, which aligns with circular-economy objectives (Li & Chen, 2025; Singh & Bhatnagar, 2021).

Despite these advantages, the design and adoption of textile-based insulation are not straightforward. Specific challenges include variability in feedstock properties (especially for recycled and

agricultural-waste fibres), moisture sensitivity that degrades thermal and acoustic performance, flammability concerns, and the need for reproducible manufacturing processes that can be economically scaled (Periyasamy, 2023; Sakthivel et al., 2020). Moreover, bridging laboratory-scale demonstrations and commercial deployment requires explicit attention to life-cycle impacts, energy payback, standards compatibility, and integration into existing recycling and building supply chains (Kalair et al., 2022; Li & Chen, 2025).

This paper synthesizes evidence from the provided literature to produce a detailed, publication-ready discussion that addresses these challenges. Rather than a cursory review, the work aims to elaborate methodical pathways for material selection, processing, characterization, and lifecycle integration. The literature basis spans analyses of energy and sustainability in textile composites (Kalair et al., 2022), evaluations of recycled nonwovens for acoustics (Singh & Bhatnagar, 2021), studies on natural fibre composites for structural applications with implications for insulation (Kumar et al., 2023), targeted thermal and sound property characterization of eco-friendly nonwovens (Zhang et al., 2024), circular-economy discourse for textile recycling (Li & Chen, 2025), and focused investigations into agricultural waste-based nonwovens, including luffa mats (Thilagavathi et al., 2017; Madara et al., 2017; Periyasamy, 2023). Thermogravimetric and activation-energy approaches to agricultural waste fibres also provide insight into thermal stability and processing windows (Alwani et al., 2013). Foundational perspectives on natural-fibre reinforcement mechanics and potential applications are provided by broader composite reviews (Fuqua et al., 2012; Wang & Zhang, 2009).

The core objectives of this article are: (1) to provide a comprehensive theoretical and practical synthesis of textile-based nonwoven composites for acoustic and thermal insulation; (2) to present an explicit, reproducible methodology for material processing and characterization that integrates best practices from the literature; (3) to descriptively report consolidated results from the cited works and reason about the interplay of microstructure, composition, and performance; and (4) to provide an in-depth discussion of limitations, trade-offs, and pathways to industrialization under circular-economy principles (Kalair et al., 2022; Li & Chen, 2025). The following sections systematically address these objectives, prioritizing depth and theoretical elaboration over summary, and citing each major claim to the literature base provided.

Methodology

This section presents a detailed, text-based methodological framework for the production and evaluation of textile-based nonwoven composites tailored for thermal and acoustic insulation. The methodology synthesizes practices reported across the literature into a coherent, reproducible sequence covering feedstock selection, pre-processing, nonwoven formation, consolidation, conditioning, and performance measurement. Each step includes theoretical rationale, practical considerations, and references to empirical studies that justify the recommendations.

Feedstock selection and characterization

Selecting appropriate feedstocks is the first critical decision. Options include recycled textile fibres (post-consumer cotton, polyester blends), virgin natural fibres (flax, hemp, jute), and agricultural

residues (luffa, rice husk fibers, pith) (Singh & Bhatnagar, 2021; Periyasamy, 2023; Thilagavathi et al., 2017; Madara et al., 2017). Recycled nonwovens from garment waste are attractive due to established availability and demonstrated acoustic performance in experimental studies (Sakthivel et al., 2020; Singh & Bhatnagar, 2021). Agricultural fibres offer very low-cost inputs with structural porosity but often require cleaning and processing to remove impurities and optimize fibre length distributions (Periyasamy, 2023; Alwani et al., 2013).

Characterization at the feedstock stage should include fibre length distribution, linear density (fineness), bulk density, moisture content, ash content, and thermogravimetric properties to estimate thermal stability and decomposition onset temperatures for downstream processing (Alwani et al., 2013; Fuqua et al., 2012). Simple protocols include sieve-based length fractionation, gravimetric moisture determination at 105°C, ash testing per standardized calcination procedures, and thermogravimetric analysis (TGA) scans to determine onset of major mass loss events and approximate activation-energy windows for thermal treatments (Alwani et al., 2013).

Pre-processing: cleaning, blending, and fibre modification

Cleaning and removal of contaminants (dyes, residual finishes, soil) are necessary, particularly for post-consumer textiles and agricultural wastes. Wet-washing with mild detergents or low-impact solvent processes can be used, followed by thorough drying to a controlled moisture content not exceeding application-specific thresholds (Sakthivel et al., 2020). Alkali treatments (e.g., NaOH) and enzymatic retting can be used for

natural and agricultural fibres to remove pectin and surface impurities and to slightly increase surface roughness, which can enhance mechanical interlocking in composites but can also affect hydrophilicity and thermal stability and thus must be applied judiciously (Fuqua et al., 2012; Alwani et al., 2013).

Blending strategies allow tailoring of thermal and acoustic properties. For example, mixing recycled cotton with polyester fibres can improve durability and resilience while maintaining porosity that benefits acoustic absorption (Sakthivel et al., 2020). Hybridization with a small fraction of mineral fillers (e.g., perlite, vermiculite) can be applied externally or interspersed within the nonwoven to increase thermal mass and fire resistance; however, such additives change density and stiffness and thus their proportion must be optimized for each application (Kumar et al., 2023; Zhang et al., 2024).

Nonwoven formation techniques and rationale

Nonwoven formation techniques determine fibre orientation, pore structure, and mechanical integrity—key parameters controlling acoustic and thermal behavior. Common techniques are carding (to open and align fibers), air-laying (particularly valuable for short staple and recycled fibres), wet-laying (for more uniform mats), and web consolidation processes such as needle-punching, hydroentangling, and thermal bonding (Periyasamy, 2023; Zhang et al., 2024).

Needle-punching mechanically entangles fiber webs and yields strong, bulky mats with high porosity—beneficial for acoustic absorption due to increased frictional paths for sound waves. Hydroentangling uses high-pressure water jets to

entangle fibres and can produce softer, more uniform fabrics with less dust retention. Thermal bonding requires thermoplastic components (e.g., polyester fibers or bicomponent fibres with low-melting cores), which allow bonding without chemical adhesives; such strategies are especially useful for recycled blends containing synthetic scraps (Singh & Bhatnagar, 2021; Periyasamy, 2023).

Binder systems and environmental considerations

Binders are often required to achieve dimensional stability and mechanical strength. Options include synthetic binders (polyacrylics, styrene-butadiene latex) and more sustainable alternatives such as polymeric starch, bio-based resins, and minimal-use thermoplastic fibres. The selection must balance durability, moisture resistance, flammability, and recycling end-of-life scenarios; for example, synthetic binders can complicate recycling or biodegradation, whereas bio-based starch binders may be sensitive to humidity (Kalair et al., 2022; Periyasamy, 2023).

Consolidation and shaping

After web formation, consolidation through compression, calendaring (where appropriate), or localized thermal treatment can be used to adjust density and thickness. Compression reduces porosity and can increase thermal conductivity—useful where higher mechanical stability is required but detrimental to thermal insulation performance. Therefore, consolidation must be tuned based on target properties: acoustic absorption favors open, low-density structures with interconnected pores; thermal insulation favors low thermal conductivity, which similarly

benefits from trapped air in porous structures but can be compromised by convective air flow if voids are too large (Zhang et al., 2024; Thilagavathi et al., 2017).

Conditioning and environmental pre-treatments

Moisture conditioning to equilibrium under specified relative humidity (e.g., 23°C, 50% RH) prior to testing is necessary for reproducibility, since humidity changes the hygroscopic mass and influences both thermal conductivity and acoustic damping. Where moisture sensitivity is problematic, hydrophobic treatments (e.g., silane-based surface coatings) or encapsulation strategies may be used; trade-offs include potential reductions in biodegradability and recycling complexity (Sakthivel et al., 2020; Periyasamy, 2023).

Performance characterization protocols

Thermal characterization should include steady-state thermal conductivity measurements using guarded-hot-plate or heat-flow-meter methods for applicable thicknesses, supplemented by analysis of thermal diffusivity and specific heat capacity proxies derived from differential scanning calorimetry where available. Because porous materials often display directional thermal properties, anisotropy should be measured when relevant. All thermal tests must be reported with specimen density, thickness, conditioned moisture content, and boundary conditions. (Zhang et al., 2024; Kalair et al., 2022).

Acoustic characterization is typically conducted in two complementary ways: normal-incidence sound absorption (using an impedance tube) and random-incidence sound absorption (using a

reverberation chamber). Impedance tube testing provides high-resolution absorption coefficient data at discrete frequencies for small specimens and is ideal for initial material screening, while reverberation chamber tests yield broadband random-incidence absorption coefficients appropriate for full-scale room acoustics modeling. Both tests should report specimen thickness, backing conditions (rigid or air gap), and porosity parameters. (Thilagavathi et al., 2017; Singh & Bhatnagar, 2021).

Hygrothermal and durability testing should include cyclic humidity exposures, mechanical fatigue (compression-set tests to simulate long-term load-bearing), and aging at elevated temperatures to probe binder degradation and fibre embrittlement. Fire performance testing should at least include small-scale flammability screening (e.g., NFPA 701 or ISO equivalents) and char-formation observations; for building applications, more stringent flame-spread testing is typically required. (Alwani et al., 2013; Kumar et al., 2023).

Life-cycle and circularity assessment approaches

A complete methodological program incorporates life-cycle thinking. Even basic cradle-to-gate assessments—estimating embodied energy, greenhouse-gas emissions from feedstock processing, and waste generation—provide necessary context for claims of sustainability. Allocation strategies must be transparent for recycled feedstocks (e.g., cut-off vs. substitution approaches) and should include end-of-life scenarios: mechanical recycling, chemical recycling, composting (if biodegradable), or energy recovery. Integration with existing textile recycling infrastructures and collection systems is an essential practical consideration. (Kalair et al., 2022; Li & Chen, 2025).

Quality control and standardization recommendations

To enable comparability across studies and industrial practices, specimens should be prepared and tested following established international standards where possible. Where standards do not exist for novel composites, detailed reporting of specimen conditioning, sample geometry, and testing apparatus is critical. Metadata such as fibre origin, batch variability, and processing parameters must be recorded to support reproducibility. (Zhang et al., 2024; Periyasamy, 2023).

Ethical and safety considerations

Sourcing of agricultural residues must be sensitive to land-use implications and possible competition with food systems. Chemical treatments should prioritize low-toxicity reagents and waste minimization. Worker exposure to dust during fibre processing and binding steps should be mitigated through engineering controls and PPE. (Fuqua et al., 2012; Alwani et al., 2013).

This methodological framework is descriptive, integrating theoretical and practical elements from the literature and recommending explicit steps to produce and evaluate textile-based nonwoven composites for insulation applications. The subsequent sections use this framework to synthesize existing findings, interpret performance trade-offs, and outline concrete pathways for future research and industrial deployment.

Results

This section presents a descriptive synthesis of empirical findings and reported results from the literature, organized by material class and performance domain. As the present manuscript is a literature-integrative work rather than an original experimental report, results are reported as consolidated and interpreted findings drawn from the referenced studies. Each claim is anchored to the sources and described in detail to maximize clarity.

Thermal performance of textile-based nonwovens and natural fibre mats

Across multiple studies, porous fibrous structures derived from recycled textiles and natural fibres display low thermal conductivities relative to dense solids because their morphology traps air and impedes conduction and convection at the microscale (Zhang et al., 2024; Kalair et al., 2022). Zhang et al. (2024) report that eco-friendly nonwovens optimized for thermal insulation achieve effective thermal conductivities that place them within a useful range for building insulation when density and fibre orientation are appropriately controlled. The underlying mechanics are well-established: thermal conductivity in porous media is governed by the solid conduction pathway, the trapped-air conduction, and micro-scale radiation, with pore sizes on the order of microns to millimetres affecting the relative importance of each mechanism (Zhang et al., 2024).

The density–performance trade-off is a consistent finding: lower density generally corresponds to lower thermal conductivity due to a higher fraction of trapped air, but excessively low density can permit convective loops and mechanical instability, which compromise long-term performance in situ (Kalair et al., 2022; Zhang et al., 2024). Consequently, material designers aim for an optimal density window where porosity is maximized without enabling convective pathways—typically achieved by fine-to-medium fibre diameters and tortuous pore connectivity generated during carding and needlepunching processes (Sakthivel et al., 2020).

Natural fibres and agricultural residues present particular behavior. Luffa mats, for example, have intrinsic structural porosity characterized by a fibrous network arranged in macro-channels that can be exploited for both thermal and acoustic applications (Thilagavathi et al., 2017; Madara et al., 2017). Madara et al. (2017) characterize luffa-based nonwovens and demonstrate that their bulk structure—when processed into nonwoven mats—provides low thermal conductivity values commensurate with their high porosity. However, the hygroscopic nature of luffa and many natural fibres increases thermal conductivity under high-moisture conditions due to water's higher thermal conductivity relative to air, a fact repeatedly observed and emphasized by experimental studies (Alwani et al., 2013; Periyasamy, 2023).

Acoustic absorption properties and frequency dependence

Acoustic absorption in fibrous materials is strongly frequency-dependent, and many textile-based nonwovens show superior absorption at mid-to-high frequencies due to viscous dissipation as air oscillates within narrow pores and along fibre surfaces (Thilagavathi et al., 2017; Singh & Bhatnagar, 2021). Studies on recycled cotton/polyester nonwovens indicate that thickness, porosity, and fibre composition together control the absorption peaks: increasing thickness

and porosity tends to shift maximum absorption to lower frequencies and increase overall absorptive efficacy (Sakthivel et al., 2020; Singh & Bhatnagar, 2021).

Thilagavathi et al. (2017) demonstrate that luffa fibrous mats exhibit sound absorption across a broad band, attributed to the hierarchical porous channels and surface roughness that enhance viscous friction. The concept of acoustic impedance matching is central: open, porous structures present an impedance that facilitates transmission of incident sound energy into the material where it is attenuated; abrupt impedance mismatches (as with rigid solid panels) lead to reflection instead. Textile-based nonwovens, when designed with appropriate porosity gradients and backing conditions (air gap or porous facing), can be tuned to target problematic frequency bands in building and vehicle interiors (Thilagavathi et al., 2017; Singh & Bhatnagar, 2021).

Hybrid and composite strategies to enhance multi-functionality

Single-material nonwovens often require trade-offs; designers therefore employ hybrids to secure multiple desirable properties. For example, combining recycled textile fibres with small fractions of mineral or bio-based fillers can improve thermal inertia and fire performance, while preserving acoustic porosity when fillers are dispersed without blocking pores (Kumar et al., 2023; Zhang et al., 2024). Another hybrid approach is layering: an external dense layer provides mechanical protection, while an internal porous nonwoven acts as the primary insulating/absorbing medium. Layering strategies are frequently recommended for building envelopes where mechanical loads and environmental exposure necessitate a protective skin without sacrificing insulating performance (Kumar et al., 2023; Periyasamy, 2023).

Moisture effects and mitigation strategies

Multiple studies confirm that moisture uptake degrades both thermal and acoustic performance in natural and recycled textile insulators due to increased thermal conduction via water and altered airflow through pores (Alwani et al., 2013; Sakthivel et al., 2020). Standard mitigation strategies include hydrophobic surface treatments and vapor-permeable membranes paired with hydrophobic facings. However, hydrophobic treatments can complicate end-of-life options and reduce biodegradability. Consequently, material design must balance moisture resistance with circularity goals—either by optimizing for in-service durability and later mechanical recycling, or by selecting biodegradable treatments compatible with composting at end-of-life (Kalair et al., 2022; Li & Chen, 2025).

Thermal stability and fire performance considerations

Thermogravimetric and activation-energy analyses, as reported by Alwani et al. (2013), reveal that agricultural waste fibers have distinct decomposition profiles that inform processing temperatures and potential thermal treatments. Natural fibres typically begin significant mass loss at temperatures that are lower than those of synthetic polymers, requiring careful thermal bonding strategies and avoidance of excessive processing temperatures (Alwani et al., 2013). Fire performance remains a critical hurdle: untreated natural fibers are flammable, and while mineral additives and flame-retardant treatments can

mitigate this risk, they can also increase embodied energy or impede recyclability (Kumar et al., 2023). The literature argues for integrated solutions combining structural design, passive protection (e.g., barrier layers), and judicious chemical treatments that prioritize low-toxicants and minimal environmental impact (Kalair et al., 2022; Zhang et al., 2024).

Mechanical performance and dimensional stability

Needle-punched and thermally bonded nonwovens show satisfactory mechanical integrity for use as insulation blankets or panels when designed with appropriate basis weight and consolidation degree (Sakthivel et al., 2020). Compression-set behavior is a vital metric, as long-term compressive deformation reduces thickness and hence thermal resistance. Studies reveal that incorporating a fraction of synthetics or using bicomponent fibres for thermal bonding can enhance recovery after compression, at the cost of introducing non-biodegradable components that complicate life-cycle outcomes (Singh & Bhatnagar, 2021; Periyasamy, 2023).

Circular economy prospects and industrial practices

 Life-cycle studies and industry analyses indicate growing progress in textile recycling infrastructure and commercial practices that can support the feedstock supply chain for recycled nonwovens (Li & Chen, 2025). However, systemic barriers persist: collection logistics, contamination in post-consumer streams, and heterogeneous fibre blends complicate high-quality mechanical recycling and necessitate pretreatment and sorting. Chemical recycling offers promise for mixed-fibre streams, but its energy intensity and current technological maturity limit near-term scalability. The literature therefore emphasizes hybrid strategies that combine improved collection and sorting, mechanical recycling to produce nonwoven feedstocks, and selective chemical recycling for problematic blends, all supported by policy incentives and extended producer responsibility frameworks (Li & Chen, 2025; Kalair et al., 2022).

Synthesis of performance consensus and variability

Drawing these threads together, the literature converges on the following descriptive conclusions: textile-based nonwovens and natural fibre composites can provide effective acoustic absorption and meaningful thermal insulation properties when design accounts for porosity, thickness, and moisture management (Zhang et al., 2024; Thilagavathi et al., 2017; Sakthivel et al., 2020). Variability in reported properties stems from divergent feedstock origin, processing parameters (e.g., needle density, bonding energy), and test conditions (moisture, backing). Consequently, harmonized testing methodologies and more comprehensive life-cycle assessments are needed to quantify comparative sustainability benefits relative to incumbent materials (Kalair et al., 2022; Li & Chen, 2025).

Discussion

The discussion expands on the implications of the results synthesis, delves into theoretical explanations for observed behaviors, addresses counter-arguments and limitations, and outlines strategic research and industrial agendas. Each subsection here engages with the key trade-offs—performance vs. sustainability, porosity vs.

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mechanical robustness, moisture resistance vs. circularity—and offers nuanced interpretation supported by the literature.

Understanding the dual role of porosity in thermal and acoustic performance

Porosity underpins both thermal insulation and acoustic absorption yet operates through different physical mechanisms for each domain. For thermal insulation, porosity traps still air, which has low thermal conductivity; however, as pore sizes increase and connectivity allows convective cells, thermal performance degrades (Zhang et al., 2024). For acoustic absorption, smaller interconnected pores and high surface area produce viscous and thermal boundary-layer losses that attenuate sound energy (Thilagavathi et al., 2017). The theoretical implication is that an ideal fibrous insulator must produce a hierarchical pore structure: micro-scale pores to impede conduction and dissipate sound at higher frequencies, and macro-scale heterogeneities or gradient porosity (e.g., layered structures) to extend absorption to lower frequencies without enabling convection that undermines thermal performance (Singh & Bhatnagar, 2021; Zhang et al., 2024).

This insight suggests practical design prescriptions: use fibre blends and processing methods that produce multimodal pore-size distributions (e.g., a mixture of fine recycled cotton fibres and coarser luffa strands), employ layered architectures where outer layers restrict convective flows while inner layers provide acoustic damping, and consider air gaps or cavities as part of panel systems to extend low-frequency absorption while maintaining overall thermal

resistance (Kumar et al., 2023; Thilagavathi et al., 2017).

Moisture dynamics: challenge and opportunity

The hygroscopic nature of many natural and recycled textile fibres is both a challenge and a lever for innovation. Moisture increases thermal conductivity and alters acoustic properties, yet the capacity of fibrous insulators to buffer transient humidity can be beneficial in building assemblies that moderate indoor moisture swings (Periyasamy, 2023). This duality suggests that material systems should be evaluated not only for steady-state conductivities but for hygrothermal buffering behavior over diurnal and seasonal cycles—an approach that better captures service-level performance and occupant comfort implications (Kalair et al., 2022).

From a design perspective, internal hydrophobic-hydrophilic gradients may create moisture management pathways: hydrophobic outer facings reduce ingress, while more hygroscopic inner layers can equilibrate interior moisture. However, this complicates end-of-life pathways and recyclability. An alternative is to integrate passive moisture barriers at the cladding level, preserving biodegradable inner insulation layers that can be mechanically recycled or composted if removed correctly (Li & Chen, 2025; Periyasamy, 2023).

Addressing fire safety without undermining sustainability

Fire safety is a decisive constraint for adoption in many applications. Conventional approaches use halogenated flame retardants or mineral fillers, which can undermine the sustainability profile. The literature reflects a need for low-toxicity, low-energy flame-retardant strategies compatible with

circularity. One promising direction is the development of intumescent, bio-based coatings that char to form insulating layers while minimizing toxic byproducts; another is the physical incorporation of non-combustible mineral layers that provide a barrier without contaminating the fibre stream. Both approaches require life-cycle evaluation to ascertain net benefits and to ensure regulatory compliance (Kumar et al., 2023; Kalair et al., 2022).

Trade-offs in binder and bonding choices

Binders provide essential dimensional stability but can dramatically influence recyclability and biodegradability. Synthetic latex binders ensure robust performance but often prevent composting and make fiber recovery more difficult. Biopolymer binders such as starch or lignin derivatives are attractive but have lower humidity resilience. The literature suggests a case-by-case decision matrix: in building applications where long service life and moisture exposure are high, durable synthetic binders may be justified if accompanied by design-for-disassembly strategies enabling mechanical separation and recycling; in temporary or low-moisture contexts, bio-based binders may be preferred (Periyasamy, 2023; Kalair et al., 2022).

Scalability and feedstock quality control

A persistent industrial challenge is securing feedstock streams of consistent composition. Post-consumer textile streams are heterogeneous in fibre content, finishes, and contaminants, complicating mechanical processing and property predictability. Advances in sorting technologies, including near-infrared spectroscopy and automated separation, promise improvements, but they remain imperfect and add cost. The literature therefore encourages hybrid sourcing strategies combining sorted recycled textiles with purpose-grown natural fibres or agricultural residues to stabilize input properties while retaining circularity gains (Li & Chen, 2025; Singh & Bhatnagar, 2021).

Techno-economic and policy levers for adoption

Economic competitiveness depends on both material costs and system-level impacts (e.g., reduced heating/cooling demand, lifecycle savings). Kalair et al. (2022) emphasize that energy and sustainability claims must be substantiated through rigorous life-cycle assessment; policy measures such as building code recognition, subsidies for low-embodied-energy materials, and extended producer responsibility can accelerate adoption. The literature also suggests industry consortia and standards development to unify performance metrics, which will reduce market fragmentation and facilitate procurement decisions that favor textile-based insulation (Kalair et al., 2022; Li & Chen, 2025).

Research gaps and future directions

Despite encouraging results, several knowledge gaps limit progress. First, comprehensive, standardized life-cycle assessments comparing textile-based nonwovens against incumbent materials under realistic service conditions are lacking, especially studies that incorporate end-of-life scenarios and multiple allocation approaches for recycled feedstocks (Kalair et al., 2022; Li & Chen, 2025). Second, more systematic investigations into hierarchical pore design and layered architectures are needed to reconcile thermal and acoustic optimization. Third, long-

term hygrothermal aging studies and fire-behavior research using low-toxicity retardant systems are required to build regulatory confidence. Finally, techno-economic analyses that incorporate collection, sorting, and processing logistics will be essential to scale pilot successes into commercial supply chains (Periyasamy, 2023; Kumar et al., 2023).

Counter-arguments and critical reflection

Skeptics may argue that textile-based insulators cannot match the thermal R-values of mineral wools or foams on a per-thickness basis. This is frequently true for specific metrics, and consequently textile-based systems are often positioned for multi-functional roles—where acoustic absorption, lower embodied energy, and circular economy benefits offset slightly lower thermal performance metrics. The counter-argument is that insulation selection is inherently a systems decision: a slightly thicker but lower-embodied-energy insulator that reduces heating-related emissions substantially over a building's lifetime can be preferable. Therefore, integration into systems thinking, not single-parameter optimization, is essential (Kalair et al., 2022; Li & Chen, 2025).

Another critique concerns durability; textile-based materials may degrade faster under mechanical or environmental stress. The literature recommends mitigation through proper installation, protective facings, and design-for-replacement or modularity—strategies that again frame the issue as one of lifecycle design rather than intrinsic material deficiency (Sakthivel et al., 2020; Periyasamy, 2023).

Conclusion

Textile-based nonwoven composites and natural fibre mats constitute a compelling class of materials for integrated thermal and acoustic insulation, particularly where sustainability, circularity, and multi-functional performance are priorities. The literature demonstrates that when properly designed—accounting for porosity, hybridization, moisture management, and fire performance—these materials can achieve service-level properties compatible with many building and transport applications (Zhang et al., 2024; Thilagavathi et al., 2017; Sakthivel et al., 2020).

Key takeaways include the centrality of porosity control for balancing thermal and acoustic outcomes, the necessity of rigorous feedstock characterization to manage variability, the potential of hybrid and layered architectures to reconcile competing requirements, and the crucial role of life-cycle and circular-economy thinking in evaluating overall sustainability (Kalair et al., 2022; Li & Chen, 2025; Kumar et al., 2023). Practical adoption will hinge on improvements in textile recycling infrastructure, harmonized testing and reporting standards, and policy frameworks that reward low-embodied-energy materials and support collection and recycling logistics (Li & Chen, 2025; Kalair et al., 2022).

Future research should prioritize standardized life-cycle assessments, exploration of hierarchical pore designs and hybridization strategies, long-term hygrothermal and fire performance studies using low-toxicity systems, and techno-economic modeling that includes the cost and energy impacts of collection and processing. These investigations, combined with iterative industry demonstrations and codes recognition, can enable textile-based nonwovens to transition from promising

laboratory curiosities to mainstream insulation solutions that contribute to decarbonizing buildings and vehicles while advancing circular material flows (Periyasamy, 2023; Kalair et al., 2022).

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