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Sustainable Sound-Absorbing Nonwoven Biocomposites: Development, Characterization, and Application Potential

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Abstract

Background: The persistent growth in urbanization and the consequent rise in noise pollution have driven significant interest in developing sustainable, high-performance sound-absorbing materials. Traditional acoustic absorbers often rely on synthetic polymers and fossil-derived fibres that pose environmental disposal and life-cycle challenges. Recent advances have explored natural fibres, agricultural by-products, and recycled fibres processed into nonwovens and biocomposites, showing promise for eco-efficient acoustic solutions (Koruk et al., 2021; Chen et al., 2019; Santos et al., 2021).

Objective: This research article synthesizes current understanding and advances a theoretically grounded, methodologically rigorous framework for producing and characterizing sound-absorbing nonwoven biocomposites made from natural fibres, luffa scraps, jute, polyester recycled fibres, and optimized needle-punched architectures. The aim is to present a publication-ready, integrative exposition of methods, expected results, interpretation strategies, and future research pathways, rooted exclusively in the provided literature.

Methods: Methods described encompass fibre selection and pre-treatment protocols, fibre blending strategies (natural and recycled content), nonwoven web formation (carding, airlaid, wet-laid), consolidation by needle-punching and minimal resin or bio-binder usage, and controlled density/thickness tuning. Characterization approaches include standardized laboratory measures for sound absorption coefficient, transmission loss, thermal insulation-related parameters, air permeability, compression resilience, and microstructural analysis via descriptive morphological interpretation (Koruk et al., 2021; Debnath, 2010; Sengupta, 2010). Every methodological choice is discussed in depth, including theoretical rationale and alternatives (Wilson, 2007; Mao & Russell, 2015).

Results: A rigorous descriptive synthesis projects that layered nonwoven architectures with controlled porosity, increased thickness, graded density, and hybridization with luffa fibers will produce enhanced low- to mid-frequency absorption and improved transmission loss compared with homogeneous thin nonwovens (Koruk et al., 2021; Chen et al., 2019). Recycled polyester inclusion, when judiciously blended and needle-punched, boosts mechanical resilience and dimensional stability while maintaining acoustic porosity (Sharma & Goel, 2017; Debnath, 2017). Thermal insulation and air-permeability trade-offs are extensively described, offering practical design maps for acoustic-thermal multifunctional panels (Debnath, 2010; Santos et al., 2021).

Conclusions: Natural fibre-based nonwoven biocomposites represent a compelling class of sustainable acoustic materials. Optimizing fibre/resin ratio, thickness, and fibre orientation yields strong control over absorption spectra and transmission loss. Challenges remain in standardizing manufacturing at scale, ensuring consistent raw-material supply and quality, and balancing moisture sensitivity with long-term durability. The article proposes immediate research priorities and applied pathways to commercialization, arguing that cross-disciplinary collaborations and life-cycle assessments are critical for adoption (Rapp & Wiertz, 2019; IHS Markit, 2020).

Keywords: Nonwovens; natural fibers; luffa; sound absorption; needle-punched; recycled polyester; biocomposites

INTRODUCTION

The global demand for acoustic materials that are both effective and environmentally responsible has intensified due to escalating urban densities, regulatory pressures on noise exposure, and increasing consumer interest in sustainable building materials (Wilson, 2007; Rapp & Wiertz, 2019). Traditional acoustic absorbers such as mineral wool, foams, and dense synthetic fabrics, while acoustically effective, often present life-cycle and environmental challenges related to resource extraction, manufacturing energy, and end-of-life disposal (Santos et al., 2021). This backdrop fuels research into alternative materials that deliver comparable acoustic performance while reducing ecological footprint and enabling circularity (IHS Markit, 2020).

Natural fibers—such as jute, hemp, flax, and agricultural residues—offer intrinsic advantages: low embodied energy, biodegradability under certain conditions, renewability, and often favourable mechanical-to-weight performance ratios (Santos et al., 2021; Debnath, 2017). However, their acoustic performance depends critically on microstructural features (fibre diameter, micro-porosity), macro-architectural parameters (thickness, porosity, density gradients), and manufacturing processes (web formation, consolidation) (Mao & Russell, 2015; Kalebek & Babaarslan, 2016). Simultaneously, recycled synthetic fibres—particularly polyester from post-consumer or post-industrial streams—present an opportunity to combine mechanical robustness and circular economy principles when blended with natural fibres (Sharma & Goel, 2017). The use of agricultural by-products, such as luffa scraps—which are fibrous, porous sponge-like biological structures—has been specifically explored for their potential as sound-absorbing fillers and structures (Chen et al., 2019).

This work synthesizes the empirical and theoretical bases articulated in contemporary literature to propose an integrated approach to designing nonwoven biocomposites for acoustic applications. Specific attention is given to needle-punched nonwovens—a manufacturing class that yields mechanically coherent, porous structures suitable for acoustic absorption—due to their flexibility in fibre selection, thickness control, and minimal need for resins (Debnath, 2010; Sengupta, 2010). Needle-punching offers a pathway to engineer anisotropic fibre orientation and through-thickness reinforcement without extensive polymeric binders, aligning with sustainable product design objectives (Mao & Russell, 2015).

Problem Statement

Despite promising investigations into natural fibre and luffa-based acoustic materials, several gaps persist in systematic understanding: (1) the interplay between thickness, fibre/resin ratio, and fibre type on both sound absorption and transmission loss across the audible band remains incompletely mapped for nonwoven architectures (Koruk et al., 2021); (2) the performance consequences of blending recycled polyester with natural fibres in needle-punched webs—especially under varying compaction and needle-punch density—lack comprehensive descriptive frameworks (Sharma & Goel, 2017; Debnath, 2017); (3) relationships between acoustic performance and multifunctional criteria—thermal insulation, air permeability, compressive resilience—are often reported in isolation, hampering integrated panel design (Debnath, 2010). These gaps impede robust product design guidance for practitioners seeking sustainable acoustic materials.

Literature Gap

While single studies have demonstrated specific performance benefits—luffa scrap-based mats with polyester fibers showing notable sound absorption (Chen et al., 2019) and jute/luffa biocomposites revealing thickness-dependent absorption and transmission loss (Koruk et al., 2021)—a comprehensive, methodologically explicit synthesis that ties fibre selection, web formation, needle-punch parameters, and hybridization strategies to a design space for acoustic-thermal multifunctional materials is absent. There is also a scarcity of consolidated procedural guidance that remains within sustainable material constraints—minimizing virgin polymer usage and relying on recycled or bio-based binders where necessary (Santos et al., 2021; Rapp & Wiertz, 2019). The current article addresses these lacunae by constructing a detailed, theoretically informed blueprint for material development and characterization grounded strictly in the cited literature.

METHODOLOGY

The methodology presented here is textually detailed and intended as a comprehensive, reproducible procedural framework for researchers and advanced practitioners seeking to produce and test sustainable sound-absorbing nonwoven biocomposites. Each step is accompanied by theoretical rationale, alternatives, and expected effects on acoustic and auxiliary properties. While not empirical in the sense of presenting new experimental data, this method synthesizes best-practice procedures and parameter interactions drawn from the literature, enabling immediate operationalization into laboratory or pilot production.

Fibre Selection and Pre-treatment

The selection of fibres is foundational. Natural fibres considered include jute and luffa (Koruk et al., 2021), while recycled polyester fibres (R-PET) are incorporated for mechanical resilience and binder substitution (Sharma & Goel, 2017). The decision matrix for fibre choice must weigh acoustic porosity (favouring coarse, porous natural fibres and luffa structures), mechanical cohesion (favoring synthetic fibres or inter-fibre entanglement), moisture sensitivity (a known issue for natural fibres), and availability/supply chain considerations (Santos et al., 2021; IHS Markit, 2020).

Pre-treatment protocols for natural fibres are critical to moderating moisture uptake, improving interfacial adhesion, and controlling microbial susceptibility. Chemical alkali treatments (e.g., NaOH washes), enzymatic treatments, or mild thermal drying can be considered. The literature indicates that careful pre-treatment can increase fibre surface fibrillation, thereby improving mechanical interlocking during needle-punching without relying on excessive resin content (Debnath, 2017). For luffa scraps, mechanical cleaning to remove residual pith and controlled sieving to achieve a size-consistent fraction are recommended to ensure reproducible web architecture (Chen et al., 2019). Recycled polyester fibres often require cleaning and de-bundling to avoid clumping during carding or airlaid processes—standard industry practice covered in nonwovens literature (Mao & Russell, 2015).

Fibre Blending Strategies

Hybridization is achieved by mass-proportion blending: pure natural fibre webs (100% jute or luffa) are compared with hybrid blends (e.g., 70:30 natural:R-PET; 50:50) in order to balance acoustic porosity and mechanical resilience (Sharma & Goel, 2017; Koruk et al., 2021). The aim is to identify blend windows where acoustic absorption remains high while mechanical properties and dimensional stability reach acceptable levels for handling and installation.

Three principal blending concepts are elaborated:

1. Homogeneous Mixing: Carding or airlaid blending where fibres are uniformly distributed. This is theoretically favourable for isotropic acoustic behaviour and uniform compressive response (Mao & Russell, 2015).

2. Layered Hybridization: Distinct layers—surface layers rich in recycled polyester for mechanical protection and core layers rich in luffa/jute for acoustic absorption—are stacked. This layered concept offers gradient density control and the potential to tune absorption peaks by layering materials of differing porosity and tortuosity (Koruk et al., 2021).

3. Interspersed Matrix: Luffa chunks or coarse fibres embedded within a matrix of finer jute and polymer fibres to create distributed cavity resonators and multi-scale porosity (Chen et al., 2019). This approach exploits luffa's natural sponge-like microstructure to produce broadband absorption across mid-low frequencies.

Web Formation Techniques

Three web formation approaches are delineated, each with theoretical advantages:

● **Carded Dry-laid:** Suitable for fine-to-medium fibres; provides good control over fibre orientation and web uniformity. Carding allows blending of natural and recycled fibres with consistent basis weight distribution (Mao & Russell, 2015).

● **Airlaid:** Particularly effective for shorter fibres, fluff, and high-porosity webs. Airlaid webs can incorporate luffa scraps and maintain open structures beneficial for sound absorption (Chen et al., 2019).

● **Wet-laid:** Less commonly used for low-cost acoustic panels but useful when attempting to use finer cellulose fibres that can be dispersed in water. The wet-laid route often requires drying and can compact fibre networks, potentially reducing porosity if not carefully managed (Mao & Russell, 2015).

The method recommends piloting with carded dry-laid and airlaid processes due to their compatibility with varied fibre lengths and their capacity for producing high-porosity, needle-punchable webs.

Consolidation by Needle-Punching

Needle-punching is emphasized as the consolidation method of choice for creating mechanical coherence without heavy reliance on binders (Debnath, 2010). The parameters to control include:

● **Needle Density (Punches per cm^2):** Influences the degree of entanglement, thickness loss during consolidation, and porosity reduction. Low needle density retains porosity but reduces mechanical strength; conversely, high needle density increases strength at the expense of acoustic openness.

● **Needle Type and Bar Configuration:** Barb depth, diameter, and pattern determine fibre entanglement efficiency and through-thickness orientation. For hybrid webs with coarse luffa particles, needles with higher penetration energy may be required to achieve interlocking without damaging luffa structure.

● **Passes and Feed Rates:** The number of needle-punch passes allows stepwise consolidation, offering controlled densification to reach target air permeability and compressive resilience (Debnath, 2010).

The theoretical trade-off is explicit: increased mechanical integrity via denser needle-punching typically reduces open porosity and thus may shift absorption peaks to higher frequencies or reduce overall absorption coefficient in low-frequency ranges. The methodology calls for parametric testing across needle density gradients to map acoustic response.

Binder Selection and Minimal Resin Use

A central sustainability constraint is to minimize non-biodegradable binders. Two binder concepts are proposed:

● **Recycled Polyester as Mechanical Binder:** Utilizes the thermal softening behavior of polyester when locally heat-treated to form spot bonding without pervasive synthetic binder usage. This process must avoid complete melting that would fill pores.

● **Bio-based Binders:** Low-quantity biodegradable latexes or starch-based binders can be used sparingly for surface consolidation, particularly to improve edge strength or to provide a water-resistant facing layer. The literature suggests that minimal binder content (<5% by mass) can significantly improve durability without compromising acoustic porosity if applied as a thin surface film or discrete point bonding (Santos et al., 2021).

Thickness and Density Tuning

Thickness is a dominant variable for acoustic performance. Koruk et al. (2021) demonstrate a strong thickness dependence for both sound absorption and transmission loss. The methodological framework recommends producing samples across a thickness gradient (e.g., 10 mm to 60 mm) while maintaining consistent areal mass in some series to isolate thickness effects from density effects. Density manipulation is achieved by controlled compaction or controlled addition of mass via filler content.

Panel Finishing and Facings

For real-world application, finishing layers (perforated facings, fabric aesthetic faces) may be required. The methodology advocates testing both bare nonwoven faces and those with acoustically transparent facings to evaluate the influence of surface impedance on absorption curves. Theoretical guidance notes that thin facings can shift absorption peaks by modifying surface impedance and frictional losses at the interface (Sengupta, 2010).

Characterization Protocols

Sound absorption and transmission loss characterization are described in depth, following established laboratory approaches (Koruk et al., 2021; Chen et al., 2019). While explicit numerical procedures (e.g., ISO numbers) are not reproduced verbatim within this textual exposition, the conceptual protocols are described to enable replication:

● **Normal Incidence Sound Absorption Coefficient:** Measure absorption across a broad frequency range using an impedance tube methodology conceptually explained as capturing the ratio of absorbed to incident energy at normal incidence and identifying frequency-specific absorption peaks attributable to panel thickness and porosity.

● **Random Incidence/Room-Scale Absorption:** Laboratory reverberation room tests are discussed for assessing absorber performance in diffuse sound fields typical of practical rooms, describing how absorption coefficients measured under diffuse fields integrate scattering and edge effects.

● **Transmission Loss:** The methodology outlines measurement of reduction in transmitted sound through the panel using a source and receiver arrangement, with emphasis on the influence of panel mass, stiffness, and internal cavity resonance phenomena—particularly relevant for multilayered and luffa-containing composites (Koruk et al., 2021).

● Air Permeability and Porosity: Detailed conceptual descriptions of testing air flow resistance and porosity provide interpretive frameworks linking these parameters to viscous and thermal dissipation mechanisms responsible for sound absorption (Debnath, 2010).

● Compression and Resilience Testing: Compressive loading-unloading cycles are discussed to evaluate permanent set and resilience, crucial for panels used in furniture or resilient wall linings (Debnath, 2010).

● Thermal Insulation Characterization: Given the multifunctional targets of many applications, the methodology outlines steady-state thermal resistance testing concepts, highlighting the interplay between porosity and thermal conductivity (Debnath, 2010; Santos et al., 2021).

● Microstructure and Morphology: Qualitative microscopy and descriptive morphological analysis are recommended to document fibre orientation, luffa particle distribution, and potential clogging of pores due to binders or thermal bonding.

Experimental Design Recommendations

The methodology culminates in a recommended experimental matrix that varies three primary axes: fibre blend ratios (natural:recycled), thickness/density combinations, and needle-punch intensity. A secondary matrix varies luffa inclusion fraction and binder strategy. The design fosters factorial interpretation of main effects and interactions, enabling robust mapping of design spaces.

RESULTS

The results section presents a theoretically consistent, literature-grounded description of anticipated outcomes across the experimental matrix. Since the current work synthesizes existing empirical results rather than report new measurements, the findings are framed as reasoned projections and integrated interpretations substantiated by the cited literature.

Acoustic Absorption Behavior

The synthesis reveals core patterns:

1. Thickness Dominance: Increased thickness systematically enhances low-frequency absorption and shifts the absorption curve toward lower frequencies (Koruk et al., 2021). This arises because thicker porous layers allow deeper penetration of incident sound waves before dissipation mechanisms dominate, thereby enabling more effective viscous and thermal losses at lower frequencies.

2. Fibre/Resin Ratio Effects: Higher proportions of natural porous fibres or luffa increase open porosity and tortuosity, improving mid-to-high-frequency absorption but sometimes reducing mechanical coherence unless compensated with polyester reinforcement or binders (Koruk et al., 2021; Chen et al., 2019). When resin or binder is increased, porosity decreases and absorption at low frequencies can be adversely affected due to tightened pore throats.

3. Layered vs. Homogeneous Architectures: Layered hybridization (polyester-rich surface with luffa-rich core) produces a composite impedance profile that can broaden absorption bandwidth. Surface layers protect the core and provide handling strength, while the porous core sustains viscous dissipation across frequencies (Koruk et al., 2021; Mao & Russell, 2015).

4. **Luffa Inclusion:** Luffa's intrinsic sponge-like structure introduces multi-scale porosity and localized

resonances when present as discrete chunks; this can lead to improved absorption in mid-low frequency bands, especially when combined with bulk porous matrices (Chen et al., 2019). However, excessive luffa fraction without mechanical reinforcement increases susceptibility to mechanical degradation and inconsistent panel behavior.

5. **Needle-Punching Trade-offs:** Denser needle-punching increases tensile and shear strength but reduces pore size and interconnectivity, thereby raising flow resistivity and sometimes enhancing absorption at higher frequencies while diminishing it at lower frequencies (Debnath, 2010). Optimal needle densities must be chosen to balance handling and acoustic objectives.

Transmission Loss Observations

Transmission loss is influenced by panel mass, stiffness, and internal cavity damping. Jute/luffa biocomposites show improved transmission loss with increased thickness and higher resin content that increases panel stiffness and mass (Koruk et al., 2021). Recycled polyester layers can contribute to mass and stiffness without dramatic increases in environmental burden when sourced from recycled streams (Sharma & Goel, 2017). However, increased mass and stiffness may be traded off against embodied energy and end-of-life recyclability—critical considerations in sustainable design (Santos et al., 2021).

Thermal and Air Permeability Interplay

Panels optimized for acoustic absorption often display increased thermal resistance due to trapped air pockets, but elevated open porosity can reduce thermal insulating performance if convective air movement becomes significant (Debnath, 2010). The methodology thus stresses achieving a careful compromise: maintaining high flow resistivity beneficial for sound absorption while designing panel facings or internal stratification to minimize convective heat transfer.

Mechanical and Durability Characteristics

Hybridization with recycled polyester and controlled binder application yield panels with acceptable compressive resilience and handling durability for most interior acoustic applications (Sharma & Goel, 2017; Debnath, 2017). However, natural fibre susceptibility to moisture and potential biological degradation remains a concern for humidity-prone environments; thus, surface treatments or moisture barriers may be necessary depending on intended application environments (Santos et al., 2021).

DISCUSSION

This section interprets the synthesized findings in the context of sustainable materials science, practical application constraints, and research priorities.

Interpretation of Acoustic Mechanisms

Sound absorption in porous media results from viscous friction, thermal exchanges, and microscopic inertial effects. The presented framework reiterates that porous natural fibres and luffa generate tortuous airflow paths where viscous friction converts acoustic energy to heat, while discrete luffa cavities can induce localized resonances and enhance broadband absorption (Chen et al., 2019; Koruk et al., 2021). Needle-punching modifies these mechanisms by altering pore connectivity and flow resistivity; thus, manufacturing becomes a direct tool for tuning acoustic impedance.

Balancing Performance and Sustainability

A central tension emerges between maximizing acoustic performance and preserving environmental credentials. Many high-performance acoustic treatments rely on synthetic foams or dense mineral solutions; nonwoven biocomposites sacrifice some absolute performance in exchange for reduced environmental impact and potential end-of-life circularity (Rapp & Wiertz, 2019; Santos et al., 2021). The literature-based projections indicate that well-designed hybrid nonwovens can achieve performance levels sufficient for many interior applications (e.g., offices, auditoria linings, vehicular interiors) while significantly reducing embodied carbon relative to fossil-derived alternatives.

Scope Limitations and Critical Considerations

Several significant limitations must be emphasized:

1. Material Variability: Natural fibres and agricultural by-products exhibit intrinsic variability due to cultivar, growing conditions, and processing. This variability complicates standardization and requires robust quality control procedures (Santos et al., 2021).

2. Moisture and Biological Stability: Natural fibre susceptibility to moisture uptake and biodegradation requires either stabilized formulations (through hydrophobic treatments) or application in controlled environments. This stability constraint is a limiting factor for external or high-humidity applications unless adequately mitigated (Debnath, 2017).

3. Scale-up and Manufacturing: Translating laboratory-scale needle-punching and airlaid processes to industrial-scale production demands investments in equipment, process control, and supply chain logistics—areas often overlooked in small-scale research studies. Economic analyses should accompany technical pilot studies to evaluate feasibility (IHS Markit, 2020).

4. End-of-Life Management: While biodegradability is an attractive attribute, hybridization with recycled PET and minimal binder usage complicates end-of-life decisions. Design for disassembly and selective recycling protocols must be developed to fully realize circularity (Santos et al., 2021; Rapp & Wiertz, 2019).

Recommendations for Future Research

The article identifies priority research directions:

- **Parametric Experimental Studies:** Factorial experimental campaigns are needed to quantify the interactions between thickness, flow resistivity, blended fibre ratios, needle-punching intensity, and luffa fraction across standardized acoustic testing regimes (Koruk et al., 2021).

- **Life-Cycle Assessment (LCA):** Comprehensive LCAs comparing biocomposite nonwovens to conventional foams and mineral wool across production, use, and end-of-life phases will help quantify trade-offs and inform policymaking (Rapp & Wiertz, 2019; IHS Markit, 2020).

- **Moisture Stabilization Strategies:** Research into low-impact hydrophobic surface treatments and bio-based preservatives that do not compromise biodegradability or recyclability is essential for broader application domains (Debnath, 2017).

- **Standardization and Industry Collaboration:** Development of performance standards and industrial specifications tailored to biobased nonwovens will accelerate adoption. Collaboration with industry bodies and standards organizations is necessary to codify test methods and acceptable material ranges (Mao & Russell, 2015).

● **Acoustic Modeling:** Computational models linking microstructural descriptors (pore size distribution, tortuosity) to acoustic properties would enable inverse design strategies where target absorption curves inform material architecture (Sengupta, 2010).

Application Pathways and Commercialization

Potential application pathways include interior wall panels, ceiling baffles, furniture liners, and automotive cabin liners. The design flexibility inherent to nonwovens—ease of cutting, shaping, and incorporation into composite sandwich panels—offers practical advantages for retrofit and bespoke acoustic solutions (Chapman, 2010; Wilson, 2007). Engagement with building certification systems and green procurement protocols will facilitate market entry for materials demonstrating reduced embodied environmental impacts.

CONCLUSION

This article integrates extant literature to deliver a comprehensive, actionable framework for the development of sound-absorbing nonwoven biocomposites grounded in sustainability principles. The convergence of natural fibres, luffa scraps, recycled polyester, and needle-punching technology presents a promising route toward acoustic materials that balance performance with ecological responsibility. Thickness and porosity emerge as primary design levers, with layered hybridization and controlled needle-punching offering pathways to tailor absorption and mechanical properties. Future work must prioritize experimental parametric studies, LCA, moisture-stability innovations, and standardization efforts. If these research avenues are pursued, nonwoven biocomposites could substantially contribute to sustainable noise mitigation strategies across multiple built-environment sectors.

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