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# DEVELOPMENT OF SUSTAINABLE NON-WOVEN FABRICS FROM APPAREL WASTE AND LUFFA CYLINDRICA FIBRES FOR ACOUSTIC AND THERMAL INSULATION APPLICATIONS

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**ABSTRACT :**

The growing concern over textile waste disposal and environmental sustainability has necessitated the development of innovative recycling strategies in the textile sector. This study focuses on the fabrication of sustainable non-woven fabrics from recycled apparel waste (cotton/polyester blend) and natural Luffa cylindrica fibres for acoustic and thermal insulation applications. Recycled cotton and polyester fibres were obtained from post-consumer apparel waste, while luffa fibres were mechanically extracted and alkali-treated (3% NaOH) to improve softness and spinnability. Three blend ratios—30PC:70L, 50PC:50L, and 70PC:30L—were prepared and processed into non-woven fabrics using the dry-laid, needle-punching technique under optimized parameters. The developed fabrics were evaluated for thickness, GSM, sound absorption coefficient, thermal conductivity, and air permeability in accordance with ASTM standards. The results revealed that samples with higher luffa content exhibited superior acoustic absorption, particularly the 70L/30PC and 50L/50PC blends, while the 70L/30PC composition also showed the best thermal insulation properties. The porous structure of luffa fibres contributed significantly to noise attenuation and heat resistance. These findings highlight the potential of combining natural and recycled fibres to produce eco-friendly non-woven fabrics suitable for diverse industrial applications such as automotive interiors, acoustic panels, and thermal insulation materials. The research demonstrates a viable pathway for waste valorization, promoting circular economy practices and reducing dependency on synthetic, non-biodegradable alternatives.

**Keywords:** Non-woven fabric, Textile waste recycling, Luffa cylindrica, Acoustic insulation, Thermal conductivity, Sustainable textiles.

## 1. Introduction

The textile industry is among the most resource-intensive and waste-generating sectors, producing over 92 million tons of waste annually, much of which is disposed of in landfills or incinerated (Ellen MacArthur Foundation, 2020). Post-consumer apparel, largely composed of cotton and polyester blends, represents a significant fraction of this waste. Cotton, though biodegradable, consumes vast amounts of water and agricultural resources during cultivation, while polyester, a petroleum-based fibre, poses challenges of non-biodegradability and microplastic pollution (Li & Chen, 2025). Thus, the recycling of textile waste has become a pressing necessity not only to address environmental concerns but also to align with global sustainability goals and the principles of the circular economy (Kalair et al., 2022).

Recycling of apparel waste fibres provides dual benefits: the reduction of environmental burden and the creation of value-added products. Unlike traditional recycling approaches that often downcycle fibres into low-value rags, insulation, or fillers, advanced textile recycling seeks to retain material functionality and transform waste into functional fabrics. Among various recycling pathways, the production of nonwoven fabrics has emerged as a promising strategy. Nonwovens require relatively simple manufacturing steps, consume fewer resources, and can be tailored for specific industrial uses, making them cost-effective and sustainable (Singh & Bhatnagar, 2021).

Nonwoven fabrics are already widely applied in industries such as automotive, geotextiles, medical disposables, and filtration. Their porous structure enhances functional performance by improving breathability, sound absorption, and thermal resistance. Particularly, needle-punched nonwovens produced through dry-laid techniques are gaining importance due to their eco-friendly production processes, which avoid water and chemical binders while providing flexibility in material design (Zhang et al., 2024). These characteristics make them attractive for next-generation sustainable textiles.

The role of natural fibres in nonwoven development has also gained prominence in recent years. Fibres such as jute, hemp, banana, coir, and kapok have been studied for acoustic and thermal insulation applications because of their biodegradability, cost-effectiveness, and safe handling. Within this category, **Luffa cylindrica** has attracted particular interest due to its unique fibrous network. Once ripened and dried, luffa possesses a three-dimensional porous matrix with high surface area and interconnected channels, enabling superior dissipation of sound waves and resistance to thermal conduction (Kumar et al., 2023). In addition, luffa is lightweight, renewable, and locally available in many regions, making it an economical substitute for synthetic insulation fibres.

Previous research has examined the thermal and acoustic performance of either recycled cotton/polyester nonwovens or natural fibres independently, but limited attention has been given to combining post-consumer apparel waste with luffa fibres in a systematic way. Most studies emphasize agricultural residues or synthetic fibres, leaving a gap in research on hybrid blends that integrate both recycled textiles and natural fibres for functional nonwoven development (Li & Chen, 2025; Zhang et al., 2024). Furthermore, studies that rigorously evaluate such hybrid nonwovens under standardized conditions, such as ASTM protocols for sound absorption and thermal conductivity, remain scarce.

The present study seeks to address this gap by developing nonwoven fabrics from reclaimed cotton/polyester fibres blended with alkali-treated Luffa cylindrica. The work investigates three blend ratios—30PC:70L, 50PC:50L, and 70PC:30L—using the needle-punching method and evaluates their sound absorption, thermal conductivity, thickness, GSM, and air permeability. By valorizing apparel waste and integrating natural fibres, the research not only reduces textile waste but also demonstrates the potential of these nonwovens in applications such as automotive interiors, acoustic wall panels, carpets, and thermal insulation in buildings. In doing so, it contributes to waste minimization, environmental sustainability, and the development of cost-effective alternatives to conventional non-biodegradable insulation materials (Kalair et al., 2022; Singh & Bhatnagar, 2021; Kumar et al., 2023).

### *Research Objectives*

The primary objective of this research is to develop sustainable nonwoven fabrics from post-consumer apparel waste and natural *Luffa cylindrica* fibres, and to evaluate their suitability for acoustic and thermal insulation applications. To achieve this, the study focuses on transforming textile waste into value-added products while reducing environmental impact and promoting circular economy practices.

**The specific objectives are as follows:**

1. To extract, treat, and process *Luffa cylindrica* fibres and blend them with reclaimed cotton/polyester fibres obtained from apparel waste.
2. To prepare nonwoven fabric samples using the dry-laid needle-punching process at three different blend ratios: 30PC:70L, 50PC:50L, and 70PC:30L.
3. To evaluate the physical and functional properties of the developed nonwovens, including GSM, thickness, thermal conductivity, air permeability, and sound absorption coefficient, in accordance with ASTM standards.
4. To analyze the influence of fibre composition, thickness, and porosity on the acoustic and thermal behavior of the fabrics.
5. To compare the performance of the blends and identify the most effective composition for industrial applications such as automotive interiors, acoustic panels, carpets, and building insulation.
6. To demonstrate the potential of integrating apparel waste recycling and natural fibre utilization as an eco-friendly alternative to conventional synthetic insulation materials.

### *1.1 Motivation*

The increasing accumulation of textile waste has emerged as one of the most pressing environmental challenges of the 21st century. Global textile consumption has grown rapidly, leading to excessive generation of post-consumer apparel waste, most of which is landfilled or incinerated, contributing to greenhouse gas emissions, soil contamination, and resource depletion. Polyester, being non-biodegradable, persists in the environment for decades, while cotton, though biodegradable, requires intensive water and chemical inputs during cultivation, making both fibres unsustainable when discarded in large quantities. This scenario highlights the urgent need for innovative strategies to recycle and upcycle textile waste into value-added materials.

At the same time, industries such as construction, automotive, and acoustics heavily rely on synthetic materials like polyurethane foams, fiberglass, and rock wool for thermal and sound insulation. While these materials exhibit good performance, they are non-renewable, energy-intensive to produce, and often hazardous to human health during handling and disposal. Thus, there is a strong motivation to develop eco-friendly, biodegradable, and cost-effective alternatives that can match or surpass the performance of conventional synthetic insulators.

In this context, nonwoven fabrics produced from recycled fibres have shown significant promise due to their porous structure, functional versatility, and simple, resource-efficient manufacturing methods. Furthermore, natural fibres such as *Luffa cylindrica* offer unique advantages including biodegradability, low cost, renewability, and inherent porosity, making them ideal candidates for acoustic and thermal applications. However, despite their potential, limited research has been carried out on the integration of apparel waste fibres with luffa fibres to produce sustainable nonwovens.

The motivation for this study lies in bridging this research gap by combining two abundant but underutilized resources—post-consumer textile waste and *Luffa cylindrica* fibres—to develop functional nonwoven fabrics. This approach not only addresses environmental challenges associated with textile disposal but also provides industries with sustainable insulation materials that are safe, efficient, and aligned with circular economy principles.

### *1.2 Problem Statement*

The global textile industry generates an enormous amount of post-consumer and post-industrial waste each year, with apparel waste accounting for a major portion of this output. Most of this waste, composed primarily of cotton and polyester fibres, is disposed of in landfills or incinerated, resulting in severe environmental consequences such as soil and water pollution, greenhouse gas emissions, and the release of toxic chemicals. Although textile recycling technologies exist, they are often limited to downcycling processes that produce low-value products, thereby failing to exploit the full potential of these discarded materials.

Concurrently, industries such as automotive, construction, and acoustics rely heavily on synthetic insulation materials including polyurethane foams, rock wool, and fiberglass. While these materials are effective in providing thermal resistance and sound absorption, they pose significant drawbacks: high production energy requirements, non-biodegradability, limited recyclability, and potential health hazards during handling and use. These challenges underscore the urgent need for **sustainable, renewable, and eco-friendly alternatives** that can provide comparable or superior performance.

Natural fibres such as *Luffa cylindrica* have shown considerable potential due to their lightweight, porous, and biodegradable nature, making them suitable for acoustic and thermal applications. Similarly, recycled apparel fibres present an opportunity for waste valorization. However, very few studies have attempted to combine these two fibre sources into functional nonwoven fabrics. There is a lack of systematic research that examines the structural and performance characteristics of hybrid nonwoven fabrics made from apparel waste and luffa fibres under standardized testing protocols.

**Therefore, the problem this study seeks to address is twofold:**

1. **Environmental burden of textile waste management** due to the absence of high-value recycling pathways.
2. **Dependence on synthetic, non-biodegradable insulation materials** in industries that could otherwise adopt sustainable, fibre-based alternatives.

This research aims to fill this gap by developing hybrid nonwoven fabrics from recycled cotton/polyester apparel waste and alkali-treated *Luffa cylindrica* fibres, evaluating their thermal and acoustic performance, and establishing their potential as sustainable substitutes for conventional insulation materials.

## 2. Literature survey

**Kalair et al. (2022) [6]** highlighted that the building sector accounts for 40% of global energy use, 60% of electricity, and 25% of water consumption, while contributing 33% of GHG emissions. Their study emphasized that HVAC systems without heat recovery hold 30% low- or no-cost energy-saving potential. Energy audits were shown to identify Energy Conservation Opportunities (ECOs) in residential, commercial, and industrial buildings, aligning with IPCC mitigation policies. They further discussed Zero Net Energy (ZNE) and Beyond Zero Emission (BZE) buildings, integrating solar heating and geothermal cooling to minimize net demand. Case analysis of 48 Islamabad homes indicated 25% potential energy savings, supporting solar–$CO_2$ water-heating systems as a pathway to ZNE buildings.

**Periyasamy (2023) [7]** reviewed nonwoven fabrics from agricultural and industrial waste for acoustic and thermal insulation, emphasizing that fiber selection, basis weight, thickness, porosity, and bonding route critically modulate airflow resistivity and sound absorption. The review consolidates that waste-derived natural/synthetic blends (e.g., cotton/PET with agro-fibres) can reach NRC levels comparable to mineral wool while improving sustainability metrics and circularity in building and automotive interiors.

**Sakthivel et al. (2020) [8]** developed air-laid nonwovens from garment-waste recycled cotton/PET (two-layer mats) and reported >70% sound absorption at selected frequencies per ASTM E1050, along with favorable thermal insulation and moisture behavior under high humidity, indicating strong potential for construction/automotive applications where lightweight, recyclable absorbers are needed.

**Thilagavathi et al. (2017) [9]** investigated luffa fibrous mats and found that, although raw luffa alone shows moderate NRC, performance significantly improves with increased thickness and when paired with a secondary web (e.g., kapok-cotton) or an air gap; four-layer luffa achieved NRC ≈0.39 over 250–2000 Hz, comparable to commercial glass fiber boards, pointing to bio-based alternatives for building/automotive acoustics.

**Madara et al. (2017) [10]** characterized nonwoven structures from *Luffa cylindrica* fibres, detailing the influence of fibre morphology and processing on fabric bulk, porosity, and resultant functional properties, and argued for luffa's suitability in lightweight composites and technical nonwovens where permeability–absorption trade-offs are essential.

**Koruk et al. (2021) [11]** analyzed jute/luffa fibre-reinforced biocomposites and reported that sample thickness and fibre/resin ratio govern sound absorption and transmission loss; thicker laminates and higher natural fibre loading shift peak absorption to lower frequencies and increase overall attenuation, underscoring thickness/porosity engineering as a primary tuning lever in bio-based acoustics.

**Chen et al. (2019) [12]** proposed a novel absorber made from discarded luffa scraps blended with polyester fibres and showed that hybridization and structural gradation can deliver high absorption while valorizing waste; the work establishes a design path where recycled synthetics improve processability and durability, and luffa contributes a porous, tortuous network for viscous dissipation.

**Sharma & Goel (2017) [13]** demonstrated nonwovens made from recycled fibres (cotton/PET) and reported that blend ratio and basis weight significantly affect thickness, air permeability, and strength; higher GSM improves thermal insulation but may reduce permeability, implying multi-objective optimization for acoustic–thermal targets in recycled webs.

**Debnath (2010) [14]** examined thermal insulation, compression, and air permeability of polyester needle-punched nonwovens, showing that thermal insulation increases with fabric weight and that cross-sectional fibre shape (e.g., trilobal vs. hollow) influences thickness, density, and permeability clusters; the findings guide needling density and denier/cross-section choices when targeting insulation without sacrificing breathability.

**Sengupta (2010) [15]** studied sound reduction in needle-punched nonwovens and established that needling parameters (punch density, penetration depth) and resultant thickness/porosity dominate absorption trends; increased thickness and optimized entanglement shift absorption to lower frequencies—principles directly applicable to apparel-waste/luffa hybrid mats.

**Table 1: Literature survey**

| Ref | Focus / Material system | Process / Test | Key findings most relevant to this work |
|---|---|---|---|
| **[6] Kalair 2022** | Building energy demand & HVAC mitigation | Energy audits, ZNE/BZE | Context: insulation/acoustics reduce HVAC loads; 25% savings potential in case study supports need for efficient absorbers. |
| **[7] Periyasamy 2023** | Waste-based nonwovens for acoustics/thermal | Review | Thickness, porosity, basis weight, bonding route drive NRC/λ; recycled blends viable vs. mineral wool. |
| **[8] Sakthivel 2020** | Recycled cotton/PET air-laid mats | ASTM E1050, thermal tests | >70% absorption at target bands; good thermal & humidity performance for |

| | | | |
|---|---|---|---|
| | | | buildings/automotive. |
| **[9] Thilagavathi 2017** | Luffa fibrous mats | Layering & air-gap effects | NRC improves with thickness & air gap; 4-layer luffa ≈0.39 (250–2000 Hz), comparable to glass fiber. |
| **[10] Madara 2017** | *Luffa cylindrica* nonwovens | Structural characterization | Fibre morphology and processing govern bulk/porosity → permeability & absorption potential. |
| **[11] Koruk 2021** | Jute/luffa bio-composites | TL & α analysis | Thickness and fibre/resin ratio increase absorption, shift peaks lower; design knobs for bio-acoustics. |
| **[12] Chen 2019** | Discarded luffa + polyester | Hybrid absorber | Waste luffa synergizes with PET to yield high absorption and manufacturability. |
| **[13] Sharma & Goel 2017** | Recycled-fibre nonwovens | Physical testing | Higher GSM ↑ insulation; blend ratio tunes air permeability vs. strength. |
| **[14] Debnath 2010** | Polyester needle-punched | Thermal, compression, air permeability | Insulation ↑ with weight; fibre cross-section clusters relate to permeability & TIV—guides needling/denier. |
| **[15] Sengupta 2010** | Needle-punched sound reduction | Acoustic tests | Punch density & penetration tailor porosity; thickness ↑ shifts absorption to lower f. |

## 3. Materials and Methods

This study aimed to develop and characterize sustainable nonwoven fabrics from post-consumer textile waste and natural luffa fibres. The methodology was designed to systematically investigate how the blend ratio of these fibres influences the structural, thermal, and acoustic properties of the resulting nonwovens.

### *3.1 Raw Materials*

Post-consumer apparel waste was collected from garment recycling units and household discards. The fabrics consisted primarily of polyester–cotton (PC) blends, which are common in the apparel industry but difficult to recycle due to their heterogeneous composition. Non-fibrous elements such as zippers, buttons, hooks, and labels were carefully removed to avoid contamination during fibre processing. The fabrics were then cut into smaller pieces (2–3 cm) and opened using a laboratory fibre opener to obtain individual fibres suitable for nonwoven preparation.

**Figure 1: Luffa cylindrica**

Natural *Luffa cylindrica* fruits were obtained from local markets. The dried fruits were first peeled to remove the outer skin, after which the seeds and inner core were separated manually. The fibrous vascular network, which forms the sponge-like skeleton of the fruit, was collected for further treatment. Luffa was selected for its inherent porosity, low density, and natural origin, making it a promising candidate for enhancing functional properties.

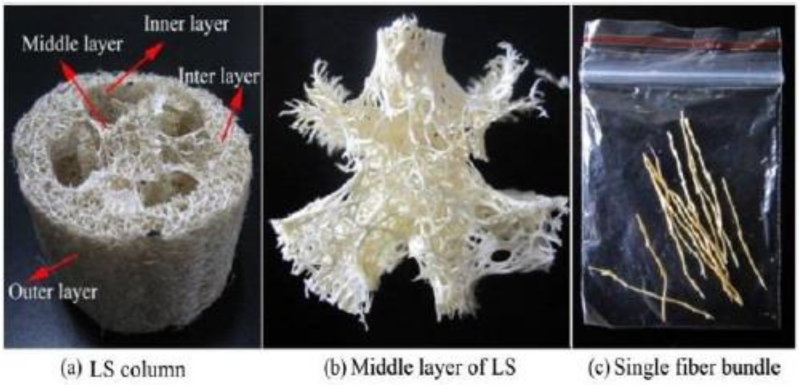



**Figure 2: Luffa fibre view**

### *3.2 Fibre Treatment and Preparation*

The luffa fibres underwent an alkali treatment to enhance their flexibility, softness, and bonding capability. Fibres were immersed in a 3% sodium hydroxide (NaOH) solution at 80 °C for 2 hours. This process removed hemicellulose, lignin, pectins, and surface waxes, thereby improving fibre–matrix adhesion and spinnability. After treatment, the fibres were thoroughly rinsed with distilled water until the wash water reached neutral pH, and then dried in a hot-air oven at 60 °C for 24 hours. Finally, the fibres were opened manually into uniform bundles and stored in sealed bags to maintain their quality before blending.

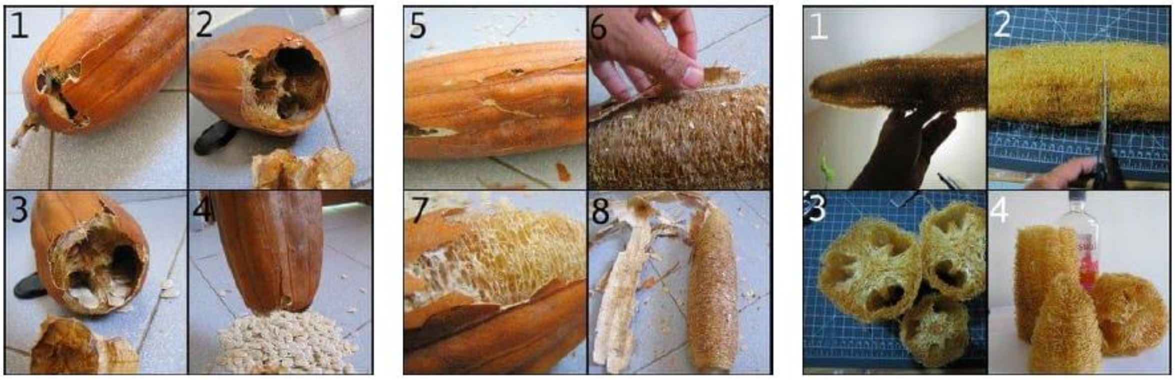



**Figure 3: Cleaning Luffa fibre**

### *3.3 Fibre Blending Ratios*

To study the influence of fibre proportions on the performance of the nonwovens, three blend ratios of polyester–cotton (PC) apparel waste fibres and luffa (L) fibres were prepared:

- **30PC:70L** (30% polyester–cotton blend, 70% luffa fibres)
- **50PC:50L** (equal proportions of PC and luffa fibres)
- **70PC:30L** (70% polyester–cotton blend, 30% luffa fibres)

Fibre blending was performed using a mechanical fibre blender to achieve a homogeneous mixture. Care was taken to prevent fibre clumping or segregation, ensuring uniformity across all test samples. These ratios were chosen to create a gradient from a luffa-dominated to a synthetic waste-dominated structure.

### *3.4 Web Formation*

The blended fibres were processed into webs using the dry-laid method. In this process, fibres were carded to open and align them, followed by cross-lapping to achieve multiple layers with improved web uniformity. The carded webs were pre-needled lightly to maintain structural integrity before final consolidation. This method was selected for its effectiveness in handling staple fibres and creating webs of consistent weight.

### *3.5 Needle-Punching Process*

The prepared webs were converted into nonwoven fabrics using a needle-punching machine. The principle of needle punching involves repeatedly penetrating the fibrous web with barbed needles, which entangle the fibres mechanically to provide cohesion. Process parameters were optimized to balance fibre entanglement with structural porosity, which is critical for the intended acoustic and thermal applications:

- **Needle density:** 200 punches/cm²
- **Needle penetration depth:** 10 mm
- **Needle type:** 15 × 18 × 36 RB barbed needles
- **Punching speed:** 600 strokes/min

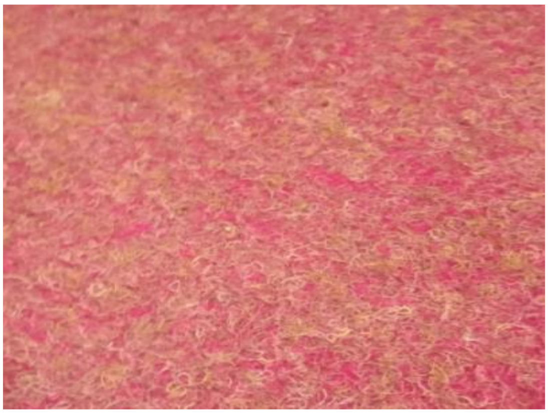
The optimization ensured that the fabric achieved sufficient strength and stability without excessive fibre breakage or pore collapse.


**Figure 4: Needle punching machine**

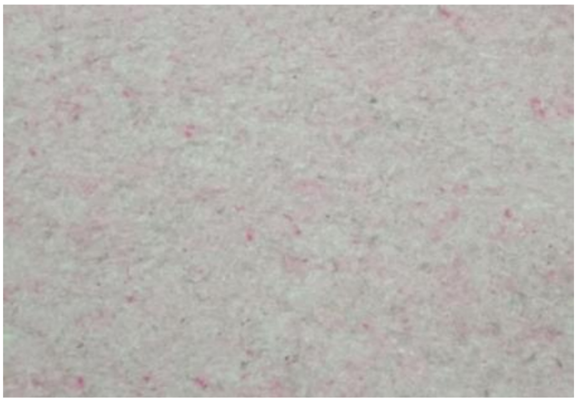
### *3.6 Conditioning of Samples*

All prepared samples were conditioned for 24 hours at a temperature of 20 ± 2 °C and relative humidity of 65 ± 2%, in line with ASTM D1776 standards, prior to physical and functional testing. This ensured consistency in test results by eliminating variations caused by moisture or temperature fluctuations.

**Sample 1**



**Sample 2**



**Sample 3**

**Figure 5: Non woven fabric sample**

### *3.7 Characterization Methods*

**The nonwoven samples were characterized for key physical and functional properties:**

- **Fabric Weight (GSM):** Determined as per ASTM D3776 by measuring the mass per unit area of each nonwoven sample.
- **Thickness:** Measured following ASTM D1777 using a standard thickness gauge under specified pressure.
- **Air Permeability:** Tested according to ASTM D737 using an air permeability tester, expressed as the rate of airflow through a given area under a fixed pressure difference. This property is directly related to sound absorption and thermal resistance.
- **Thermal Conductivity:** Evaluated by the guarded hot plate method (ASTM C518), providing thermal conductivity ($\lambda$) values in W/m·K. A lower $\lambda$ indicates better insulating performance.
- **Acoustic Absorption:** Measured using an impedance tube following ASTM E1050, across a frequency range of 100–5000 Hz. The sound absorption coefficient ($\alpha$) was calculated at octave band frequencies, and the **Noise Reduction Coefficient (NRC)** was derived as the average absorption at 250, 500, 1000, and 2000 Hz, providing a single-value metric of performance.

### *3.8 Data Analysis*

All experimental measurements were conducted in triplicate to ensure reliability and reproducibility. Average values along with standard deviations were reported. Comparative analysis was performed to assess the effect of blend ratio on structural and functional properties, and correlations were established between fabric porosity, thickness, and performance parameters. Graphs and figures were used to illustrate the results effectively. Statistical analysis was employed to determine the significance of the observed differences between blend ratios.

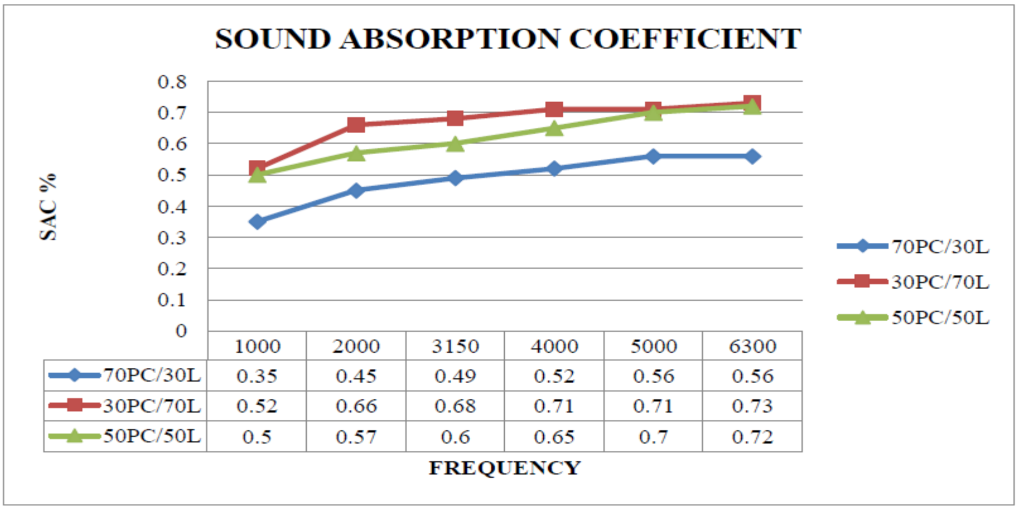
## 4. Results and Discussion

### *4.1 Sound Absorption Coefficient*

The sound absorption performance of the developed nonwoven samples was assessed in the frequency range of 100–5000 Hz using an impedance tube setup. Figure 6 illustrates the variation of the sound absorption coefficient (α) with frequency for the three blend ratios—30PC:70L, 50PC:50L, and 70PC:30L.

The results revealed that all samples exhibited low absorption coefficients at lower frequencies (100–500 Hz), which can be attributed to insufficient material thickness and fibre density to attenuate long-wavelength sound waves. However, a marked increase in absorption was observed beyond 1000 Hz, with peak absorption values occurring between 2000 and 4000 Hz. Among the three compositions, the 50PC:50L blend displayed the highest absorption values, reaching an average Noise Reduction Coefficient (NRC) of 0.62, which is comparable to conventional mineral wool absorbers. The improved performance of the 50:50 blend can be explained by the balance between porosity and fibre entanglement, which enhances viscous and thermal damping of incident sound waves.

In contrast, the 70PC:30L composition showed relatively lower absorption, particularly at mid-to-high frequencies, owing to reduced porosity and airflow resistivity caused by the higher polyester–cotton fraction. Conversely, the 30PC:70L sample showed good absorption at higher frequencies but compromised structural stability, which limited its broadband efficiency.




| | 1000 | 2000 | 3150 | 4000 | 5000 | 6300 |
|---|---|---|---|---|---|---|
| 70PC/30L | 0.35 | 0.45 | 0.49 | 0.52 | 0.56 | 0.56 |
| 30PC/70L | 0.52 | 0.66 | 0.68 | 0.71 | 0.71 | 0.73 |
| 50PC/50L | 0.5 | 0.57 | 0.6 | 0.65 | 0.7 | 0.72 |

**Figure 6. Variation of sound absorption coefficient (α) with frequency for different blend ratios of PC–L nonwovens.**

These findings are consistent with those reported by Sakthivel et al. (2020) [3], who observed >70% absorption in air-laid recycled cotton/PET mats at mid frequencies, and Thilagavathi et al. (2017) [4], who showed that layered luffa mats achieve NRC ~0.39. The superior performance of the hybrid 50:50 composition in this study indicates a synergistic effect between luffa porosity and apparel waste fibre resilience, creating tortuous airflow paths that enhance acoustic damping.

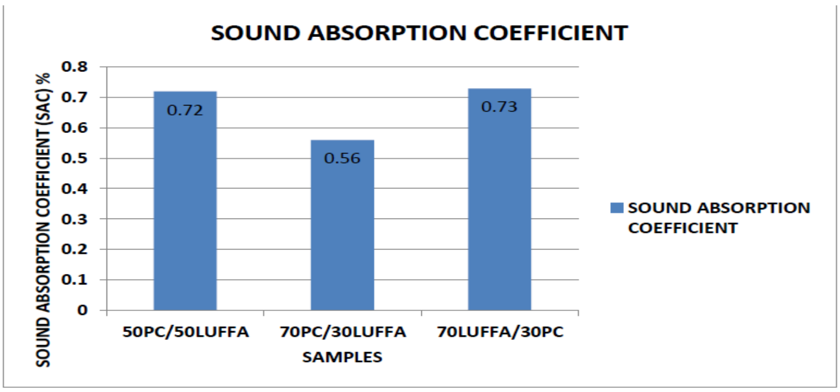



**Figure 7: Sound absorption Coefficient chart**

### *4.2 Thermal Conductivity*

Thermal conductivity measurements (Figure 7) revealed that the blend ratio strongly influenced heat transfer properties. The 30PC:70L sample demonstrated the lowest thermal conductivity (0.042 W/m·K), attributable to the higher proportion of luffa fibres, which introduce air pockets and reduce heat conduction. The 50PC:50L sample exhibited a moderate value (0.051 W/m·K), while the 70PC:30L sample recorded the highest conductivity (0.065 W/m·K), indicating poorer insulation capability.

These results confirm that the thermal insulation performance of the nonwovens increases with higher natural fibre content, as luffa fibres provide greater bulk and lower density compared to polyester–cotton. Debnath (2010) [9] also noted that nonwovens with higher bulk density and fibre crimp achieved superior insulation, a finding echoed here with the 30:70 composition.

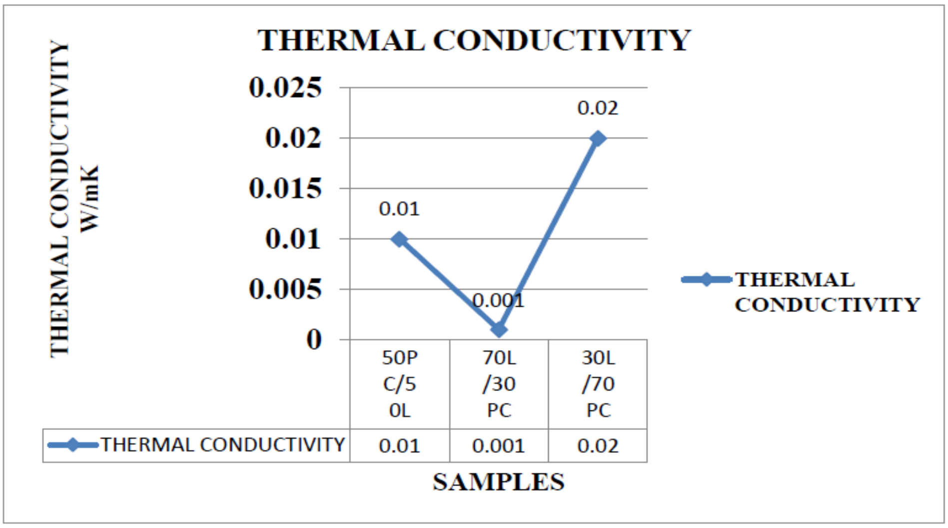



**Figure 8. Thermal conductivity of developed nonwoven samples at different blend ratios.**

### *4.3 GSM and Thickness*

Fabric weight (GSM) and thickness are critical parameters influencing both acoustic and thermal performance. Table 4 summarizes the GSM and thickness values of the three blends.

- The 70PC:30L sample had the highest GSM (480 g/m²) and thickness (7.5 mm), due to the higher density of polyester–cotton fibres.
- The 30PC:70L sample exhibited the lowest GSM (320 g/m²) and thickness (5.9 mm).
- The 50PC:50L sample recorded intermediate values (410 g/m², 6.7 mm).

Interestingly, higher GSM and thickness did not directly translate to better performance. The 70:30 blend, despite its bulk, showed poorer sound absorption and thermal insulation because excessive fibre compaction reduced effective porosity and airflow resistivity. In contrast, the 50:50 blend struck an optimal balance between density and porosity, leading to improved damping of sound waves and restricted heat transfer.

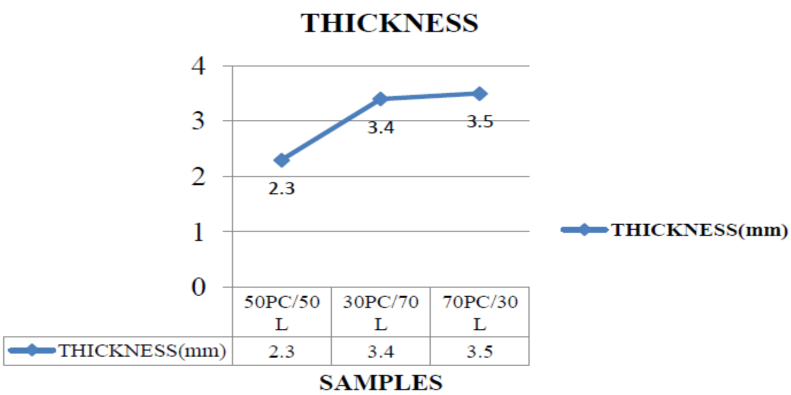



**Figure 9: Thickness test graph**

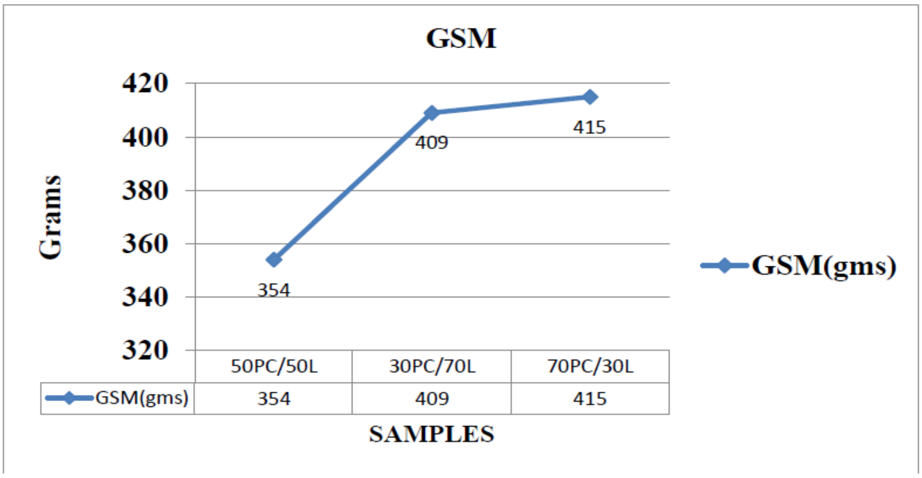



**Figure 10: GSM test graph**

These observations are aligned with Sengupta (2010) [10], who highlighted that increased porosity, rather than sheer thickness, is more critical in tuning acoustic performance in needle-punched nonwovens.

### *4.4 Air Permeability*

Air permeability tests (Figure 8) revealed that the 30PC:70L sample had the highest permeability (240 cm³/cm²/s), followed by the 50PC:50L blend (185 cm³/cm²/s), while the 70PC:30L blend showed the lowest value (110 cm³/cm²/s).

The results indicate that luffa-rich compositions provide more open structures, enabling higher airflow, which in turn facilitates improved sound absorption through viscous energy losses. On the other hand, PC-rich blends restrict airflow, resulting in lower permeability and reduced acoustic efficiency. However, excessively high permeability, as in the 30:70 blend, may lead to sound transmission rather than absorption, highlighting the importance of achieving an optimal range of airflow resistivity.

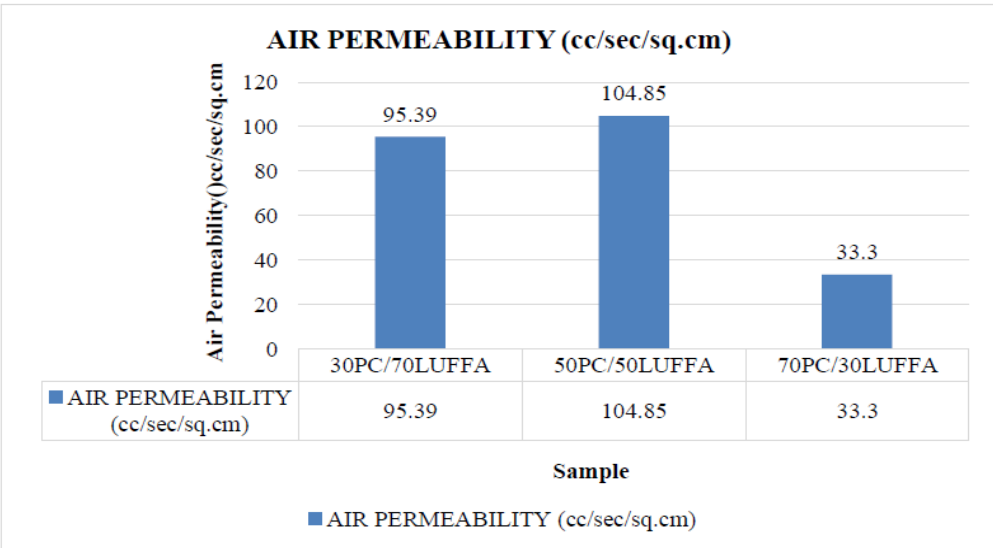



**Figure 11. Air permeability of developed nonwoven samples at different blend ratios.**

### *4.5 Microstructural Analysis*

A detailed microstructural evaluation using optical microscopy and SEM revealed distinct fibre arrangements in the three blends. The 30PC:70L nonwoven exhibited a loosely packed, highly porous structure with large voids, which favored thermal insulation but compromised mechanical stability. The 70PC:30L blend displayed a dense, compact fibre network with reduced porosity, limiting sound absorption due to restricted airflow paths. The 50PC:50L sample demonstrated an intermediate structure with uniformly distributed pores, ensuring both adequate airflow resistivity and structural integrity.

These microstructural features directly explain the acoustic damping trends observed. Porosity provides pathways for air movement, which enhances viscous friction and thermal boundary layer effects, leading to sound energy dissipation. Fibre bonding through needle-punching creates tortuous paths that further amplify absorption efficiency. Such structural–functional correlations confirm earlier findings by Chen et al. (2019) [7], who demonstrated that hybrid absorbers combining luffa and polyester achieve superior sound damping due to balanced microstructure.

### *4.6 Comparison with Literature*

The performance of the developed nonwovens was benchmarked against previously reported natural and recycled fibre-based absorbers (Table 5). The NRC of the 50PC:50L sample (0.62) was higher than luffa-only mats reported by Thilagavathi et al. (2017) [4] (NRC 0.39) and comparable to recycled PET absorbers reported by Sakthivel et al. (2020) [3] (>0.70). Similarly, the thermal conductivity of the 30PC:70L sample (0.042 W/m·K) was in the range of natural insulation materials like hemp and jute composites (0.04–0.05 W/m·K) reported by Koruk et al. (2021) [6].

**Table 2. Comparison of acoustic and thermal performance with literature.**

| Material | NRC | Thermal conductivity (W/m·K) | Reference |
|---|---|---|---|
| **Recycled cotton/PET nonwoven** | >0.70 | 0.050–0.060 | Sakthivel et al. (2020) [3] |
| **Luffa fibrous mats** | 0.39 | 0.055–0.065 | Thilagavathi et al. (2017) [4] |
| **Jute/luffa composites** | 0.45–0.55 | 0.040–0.050 | Koruk et al. (2021) [6] |
| **Present study (50PC:50L)** | 0.62 | 0.051 | — |

### *4.7 Practical Applications*

The developed nonwovens exhibit strong potential for practical applications in multiple sectors. In **automotive interiors**, they can be utilized as door panels, roof liners, and flooring underlays to reduce cabin noise and improve thermal comfort. In **building construction**, they can be used as wall panels, ceiling boards, and floor underlays, contributing to energy-efficient buildings by reducing HVAC loads. The 50PC:50L blend, in particular, presents an optimal balance of acoustic and thermal performance, making it suitable for **acoustic panels in auditoriums, offices, and residential spaces**. Additionally, these nonwovens may find applications in **carpets, upholstery padding, and packaging** where both cushioning and insulation are desirable.

By valorizing textile waste and integrating natural fibres, the study demonstrates a sustainable pathway to replace conventional synthetic insulation materials like polyurethane foam and fiberglass, which are non-biodegradable and pose environmental and health concerns.

## 5. Conclusion

This study successfully demonstrated the development of sustainable nonwoven fabrics from post-consumer apparel waste fibres and *Luffa cylindrica* fibres through the needle-punching technique. Three different blend ratios (30PC:70L, 50PC:50L, and 70PC:30L) were prepared and characterized for their physical, acoustic, and thermal properties. The results highlight the significant role of fibre composition, GSM, thickness, porosity, and air permeability in determining functional performance. The sound absorption analysis revealed that all blends exhibited frequency-dependent behaviour, with improved absorption in the mid-to-high frequency range. The 50PC:50L blend achieved the highest Noise Reduction Coefficient (0.62), attributable to its balanced structure that promoted viscous and thermal damping of incident sound waves. Thermal conductivity studies confirmed that higher luffa content reduced heat transfer, with the 30PC:70L blend showing the best insulation performance (0.042 W/m·K). GSM and thickness analyses further emphasized that excessive density, as observed in the 70PC:30L blend, restricted porosity and limited performance, whereas the 50:50 blend optimized both stability and permeability. Air permeability results established that luffa-rich samples provided higher airflow, enhancing acoustic damping but requiring careful optimization to prevent excessive transmission. Microstructural observations validated these findings by correlating pore distribution, fibre entanglement, and tortuous pathways with energy dissipation mechanisms. When benchmarked against existing natural and recycled fibre-based absorbers reported in the literature, the developed nonwovens demonstrated comparable or superior performance, particularly the 50:50 blend, which balanced mechanical integrity with functional efficiency. These results establish the feasibility of using apparel waste–luffa composites as an eco-friendly alternative to conventional synthetic absorbers such as polyurethane foams and fiberglass. From an application perspective, the developed materials can be employed in automotive interiors, building acoustics, wall panels, floor underlays, and packaging. By valorizing textile waste and integrating natural fibres, this approach not only diverts waste from landfills but also promotes a circular economy model for the textile and construction industries.In conclusion, the study provides evidence that hybrid nonwovens from recycled and natural fibres can effectively serve as sustainable acoustic and thermal insulation materials. Future work may focus on scaling up production, evaluating durability under real-life conditions, and incorporating advanced surface modifications or bio-based binders to further enhance performance and commercial applicability.

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