Investigation on Papaya and Bamboo Thermal Bonded Nonwovens for Thermal Insulation Applications

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Abstract: ***The rising need for thermal insulation materials has accelerated the utilization of agricultural waste and renewable natural fibers in nonwoven production. In this research, thermally bonded nonwoven fabrics were developed using agro-waste papaya fibers, blending with regenerated cellulosic fiber bamboo, binding with low melt PET fibers for thermal insulation applications. Transforming abandoned papaya biomass into a value- added structural material offers an eco-friendly strategy for managing garbage and reducing dependence on synthetic insulation products. The developed nonwoven fabrics were assessed for its physical and thermal characterizations. The binding indicated that the nonwovens exhibited promising insulation properties and light weight product suitable for automotive industry, building and technical textile applications.***

Keywords: Papaya, Bamboo fibers, thermal bonded nonwoven, thermal insulation.

1. Introduction

In technical textile applications, natural fibers are increasingly employed in automotive interior panels, filtration media, packaging materials, geotextiles, biomedical products, composites, protective textiles, and thermal and acoustic insulation products. (Duran et al., 2016). Their hollow cellular structure and inherent porosity enhance the entrapment of air, thereby improving thermal insulation performance while maintaining low material density. Furthermore, blending natural fibers with regenerated cellulosic fibers or low-melting polyester fibers improves processability, dimensional stability, durability, and functional performance.

Recent investigations have demonstrated that agricultural waste fibers can successfully replace conventional synthetic insulation materials in nonwoven structures without significantly compromising thermal performance. These developments support the transition toward sustainable and circular textile manufacturing (Periyasamy et al., 2023)

Natural fibres such as jute, kenaf, hemp, flax, bamboo, coconut coir, sisal, cotton, kapok, and agricultural residues have attracted significant interest owing to their low thermal conductivity (usually in the range of 0.03 to 0.06 W/m·K), low density, renewability, and lower environmental impact. The cellular structure of these fibres has lumens that effectively trap air. This is the main reason for the excellent thermal insulation performance of these fibres. Other factors that affect the insulation efficiency are fibre diameter, moisture content, density, porosity and fabrication technique. Porosity is one of the core parameters affecting the performance of thermal insulation materials. High porosity can reduce solid-phase heat conduction and increase the proportion of stagnant air, but excessively large pores will instead drive up convective heat transfer and weaken the thermal insulation effect. Therefore, pore size, pore distribution, and bulk density must be properly balanced to achieve excellent thermal insulation performance. (Ramful, 2026)

Nonwoven fabrics are engineered textile structures produced by bonding or interlocking fibers through mechanical, thermal, or chemical methods without the conventional processes of weaving or knitting. Owing to their lightweight structure, design flexibility, high porosity, and cost-effective production, nonwoven materials have become indispensable in technical textiles. (Russell et al., 2007) Their structural characteristics can be tailored by controlling fiber type, web formation technique, bonding process, thickness, and density, enabling their use in filtration, geotextiles, medical textiles, automotive interiors, packaging, protective clothing, and thermal insulation applications (Albrecht et al., 2003).

Thermal insulation materials reduce heat transfer between regions of different temperatures by minimizing conductive, convective, and radiative heat flow. In fibrous insulation systems, thermal resistance is largely governed by the amount of stagnant air trapped within the porous structure because air possesses a very low thermal conductivity of approximately 0.026 W/mK under ambient conditions. Therefore, highly porous fibrous assemblies generally exhibit lower thermal conductivity and better insulation efficiency (Siddiqui et al., 2018).

Bamboo fiber, a natural lignocellulosic fiber, is recognized for its high cellulose content, excellent moisture absorption, breathability, biodegradability, and favorable mechanical properties, making it a promising reinforcement material for sustainable textile and nonwoven applications. (Nayak & Padhye, 2015). The fiber possesses inherent antimicrobial activity, good thermal insulation, and ultraviolet (UV) protection, which contribute to improved wearer comfort and functional performance. Bamboo fibers are frequently blended with natural and regenerated cellulosic fibers, such as cotton, viscose, and modal, to enhance softness, dimensional stability, moisture management, and overall durability while maintaining the eco-friendly characteristics of the textile product (Jain et al., 2019)

Although numerous studies have explored the use of eco-friendly natural and regenerated cellulosic fibres nonwoven in technical application. Carica papaya stem bark parts an underutilized as an agricultural waste, but fiber exhibits commendable lignocellulosic properties and presents significant structural stability of nonwoven fabrics. Bamboo fibre offers superior softness, moisture control and thermal comfort properties. Low melt PET act as a proficient thermal bonding agent. The synergistic integration of these fibres is anticipated to produce lightweight, eco –friendly and thermally stabled nonwoven materials suitable for insulation applications.

Therefore, the investigator has undertaken this study to develop thermally bonded nonwoven fabrics using carica papaya, regenerated cellulosic fiber bamboo fiber and low melt PET fibers with different blend ratios and systematically evaluate their physical and thermal performance for sustainable thermal insulation applications

Research objectives

- To develop sustainable thermally bonded nonwoven fabrics using blends of papaya fiber, regenerated cellulosic bamboo fiber, and low-melt PET fiber.
- To optimize the fiber blend composition and thermal bonding process for the development of nonwoven fabrics.
- To evaluate the physical properties of the developed nonwoven fabrics.
- To investigate the thermal insulation properties of the developed nonwoven fabrics.

2. Materials and Methods

The Carica papaya plants were collected from Avalpoondurai, Erode, Tamil Nadu, India. Fiber extraction was carried out using the manual retting method. The extracted fibres were washed, dried, and cut to 2-inch staple lengths for the preparation of nonwoven fabrics. PET fibres (38 mm, 115°C, 3.6 cN/dtex, 40.10% elongation) were purchased from Coimbatore and bamboo fibres were procured from Pallava Textiles, Erode. Four nonwoven samples were prepared by manually blending, air-laying, needle-punching and hot-calendaring (120°C) papaya, modal and 20% low melt PET fibres. Fabrics were conditioned for 24 hours at Relative humidity 65%±2% and temperature 20°C±2°C. Thickness, areal density, and air permeability were measured according to ASTM standards. Bulk density was calculated as areal density divided by thickness, porosity was calculated using ASTM C 830-00. Thermal properties were characterized with C-Therm (ASTM D 7984) including conductivity (λ), resistance (R = T/λ), transmittance (U = 1/R), and effusivity, measured via instrument software.).

Table 1: Nomenclature of the samples

S. No	Sample Name	Sample Code
1	Thermal bonded Papaya 80%+ Low Melt PET 20%	TBPLP1
2	Thermal bonded Papaya 20% + Bamboo 60 % + Low Melt PET 20%	TBPBLP1
3	Thermal bonded Papaya 40% + Bamboo 40 % + Low Melt PET 20%	TBPBLP2
4	Thermal bonded Bamboo 80% + Low Melt PET 20%	TBBLP1

3. Results and Discussion

3.1 Physical properties of thermal bonded nonwoven fabrics

The physical properties of the developed thermal bonded nonwoven fabrics such as thickness, areal density, bulk density, porosity and air permeability is shown in Table-2

Table 2: Physical properties of the nonwoven fabrics

Sample	Thickness (mm)	Areal Density (g/m^2)	Bulk density (Kg/m3)	Porosity (%)	Air Permeability (cc/s/cm^2)
TBPLP1	4.604	615.27	133.6381	89.21	73.61
TBPBLP1	2.876	422.08	146.7594	86.78	59.72
TBPBLP2	3.041	383.56	126.1711	89.03	66.66
TBBLP1	1.898	320.72	168.9779	84.24	34.32

3.2 Thickness

The thickness of the developed thermal bonded nonwoven fabrics in different ratios are shown in Figure 1

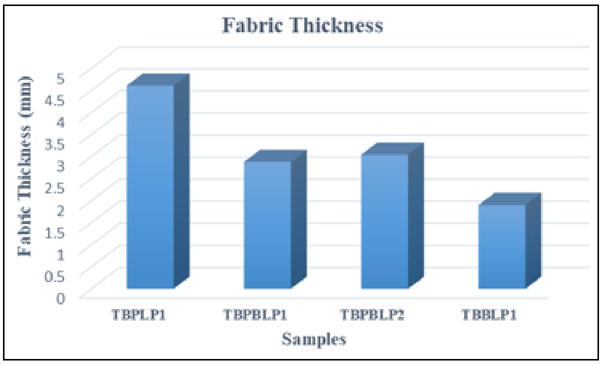

Figure 1: Fabric Thickness

An examination of thermal bonded nonwoven fabric thickness, data reveals significant diversity among the different samples, this parameter is inextricably linked to the bulk properties of cellulosic high percentage fibre content. The maximum measured thickness is 4.604 mm, sample TBPLP1 stands out and confirms the noticeable loftiness attained by papaya fibres and an open fibre structure. Contrastingly, TBBLP1 sample with the thickness of 1.898 mm, appears to have more compact fibres tightly packed, also PET or 80 percentage of bamboo, which restricts fibre expansion and limits air entrapment during the production stage

3.3 Areal Density

The Areal density of the developed thermal bonded nonwoven fabrics in different ratios are shown in Figure 2.

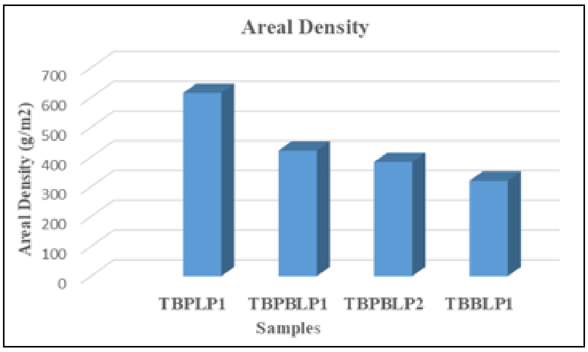

Figure 2: Areal Density

Areal density reflects the mass per unit area and is vital for figuring out the weight and mechanical parameters of nonwoven fabrics. An enhanced areal density often denotes the denser and potentially stronger material. The areal density of the thermal bonded nonwoven fabrics encompasses from 320.72 to 615 g/m^2. Among all samples, TBPLP1 exhibited the highest areal density (615.27g/m^2) signifying a more substantial fabric structure. The other aspect TBBLP1 revealing the lowest value (320.72 g/m^2), leading a lighter and presumably more flexible fabric. The variances can be derived by difference in fibre packing and fibre diameter among the samples

3.4 Bulk density

The bulk density of the developed thermal bonded nonwoven fabrics in different ratios are shown in Figure 3

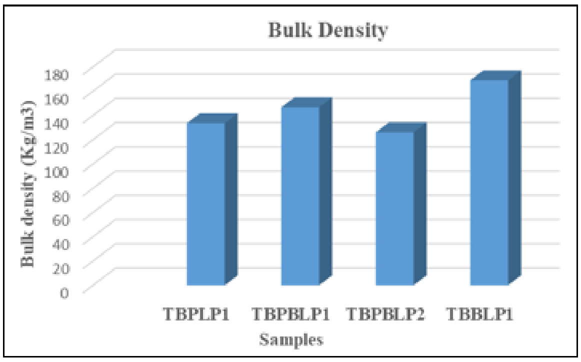

Figure 3: Bulk Density

Bulk density shows a broad range from 126.17 kg/m^3 (TBPBLP2) to 168.98 kg/m^3 (TBBLP1), which is a key metric for evaluating the stiffness and rigidity of nonwoven fabrics. The sample TBBLP1 obviously has high density, suggests that despite its thickness, the fibres are packed with minima voids, increasing the total density of fabric. Conversely TBPBLP2, with the lowest bulk density, because of more gaps between the fibres, makes the material more flexible and softer

3.5 Porosity

The porosity of the developed thermal bonded nonwoven fabrics in different ratios are shown in Figure 4

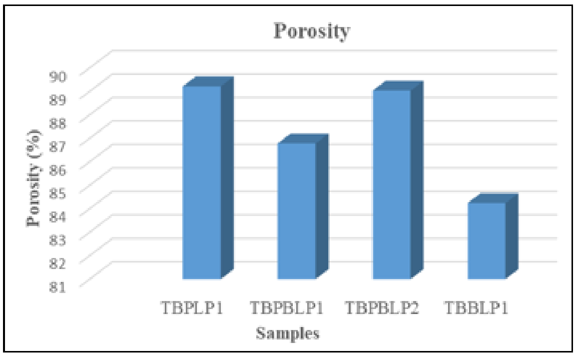

Figure 4: Porosity

Porosity offers a window into the microstructural openness of the nonwoven fabrics, closely related to their acoustic and thermal properties. TBPLP1 and TBPBLP2 exhibit the highest porosity percentages (89.21% and 89.03%) correspondingly. It shows a large number of interconnected voids and air channels in fabric structure. The trapped air acts as a superior thermal barrier. Such high porosity is beneficial for insulation applications. TBBLP1 has a significantly lower porosity of 84.24 % with less voluminous structure.

3.6 Air permeability

The air permeability of the developed thermal bonded nonwoven fabrics in different ratios are shown in Figure 5

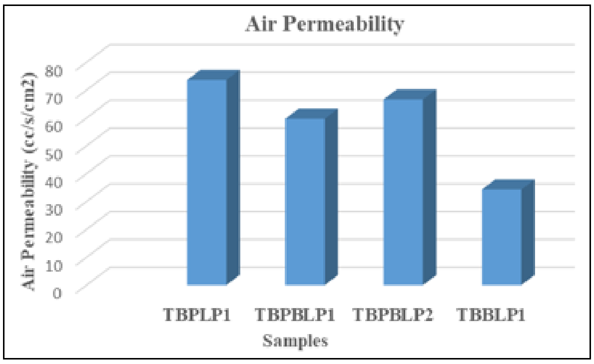

Figure 5: Air permeability

Thermal bonded nonwovens TBPLP1, achieves the maximum air permeability at 73.61 cc/s/cm^2, due to high thickness and porosity to achieve the maximum air circulation. On the other aspect, sample TBBLP1 denotes low air permeability (34.32cc/s/cm^2) that mirrors its compactness and reduced void content, which may be beneficial for filtering application where limited airflow is the top concern. The intermediate permeability values of TBPBLP1 and TBPBLP2 samples shows the nuanced influence of both fibre selection and fibre blending ratios

4. Testing of Thermal Properties

Table 3 shows the thermal properties of thermal bonded nonwoven samples, which comprise thermal conductivity, thermal resistance, thermal transmittance and thermal effusivity. Nonwoven fabrics are made from different blending ratios with the same fibers but the fabric thickness values are varied to investigate the influence of thermal insulation properties

Table: 3 Characterization of Thermal properties

Sample	Thermal Conductivity (W/ (mK)	Thermal Resistance (m2K)/W	Thermal transmittance W(m2K)	Thermal effusivity (Ws^(1/2) / Km^2)
TBPLP1	0.03869	0.1189	8.4040	72.2010
TBPBLP1	0.03820	0.0752	13.2811	69.5885
TBPBLP2	0.03702	0.0821	12.1730	63.1812
TBBLP1	0.04044	0.0469	21.3098	81.2743

4.1 Thermal Conductivity

The thermal conductivity of the developed thermal bonded nonwoven fabrics in different ratios are shown in Figure 6

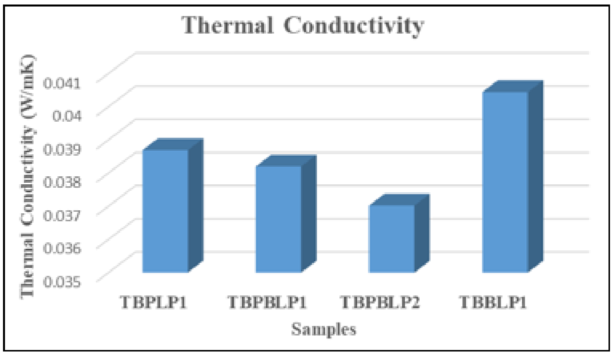

Figure 6: Thermal Conductivity

Thermal conductivity is a crucial parameter, characterizing the capability of the material to conduct heat. Among the examined samples, TBBLP1 recorded highest thermal conductivity at 0.04044 W/(Mk). This result shows that bamboo nonwoven is naturally capable of effective heat transfer owing to its microstructural features, such as more aligned, very less porous fibre matrix formation. In comparison, TBPBLP2 attained least thermal conductivity of 0.03702 W/(Mk). Suggesting that balanced proportion of papaya and bamboo fibres combined with low melt PET inhibits heat transmission more effectively. It is noticed that with increasing papaya fibre blending ratio the thermal conductivity of fabric tends to decrease.

4.2 Thermal Resistance

The thermal resistance of the developed thermal bonded nonwoven fabrics in different ratios are shown in Figure 7

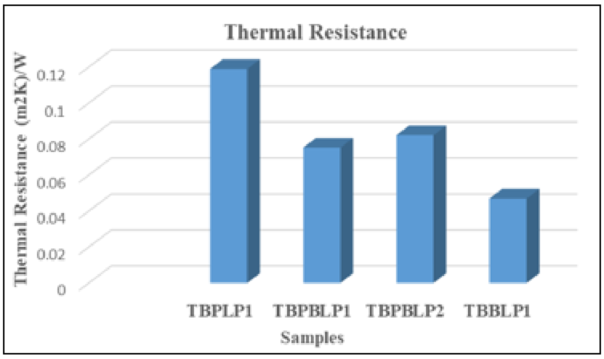

Figure 7: Thermal Resistance

Thermal resistance quantifies the materials capacity to resist heat flow, directly reflecting its insulation efficiency. TBPLP1(0.1189 m^{2}K/W) displayed the highest thermal resistance. Since the high resistance value can be attributed by the papaya fibre dominance, which are likely to a more tortuous path to make heat flow more convoluted, ultimately produced high resistance rating. TBPBLP2 reported the minimum thermal resistance 0.0469 m^{2}K/W, highlighting bamboo's heat transmission sensitivity.

4.3 Thermal Transmittance

The thermal transmittance of the developed thermal bonded nonwoven fabrics in different ratios are shown in Figure 8

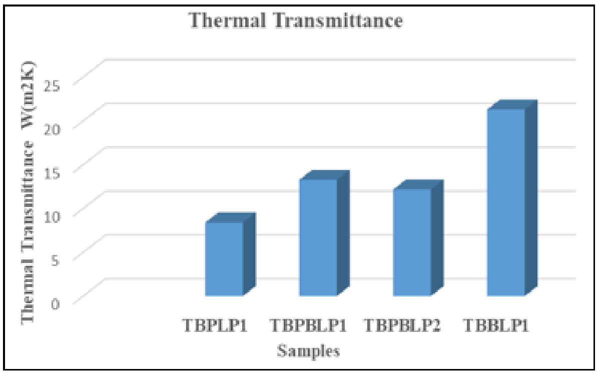

Figure 8: Thermal Transmittance

Thermal Transmittance often known as U –Value, that describes speed of heat transmission through a substance, where diminished values signify superior insulating abilities. TBPLP1 showing the lowest thermal transmittance at 8.4.40W/(m^{2}K) it indicate that least permeability to heat flow, making it highly suitable for applications requiring strong thermal barriers. However, TBBLP1 registered the highest thermal transmittance at 21.3098 W/(m^{2}K), confirming its diminished insulating efficiency and elevated higher heat transfer rate. TBPBLP1 and TBPBLP2 showed comparatively average transmittance levels.

4.4 Thermal Effusivity

The thermal effusivity of the developed thermal bonded nonwoven fabrics in different ratios are shown in Figure 9

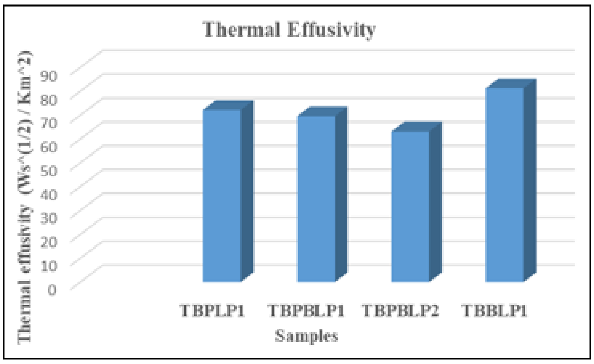

Figure 9: Thermal Effusivity

Thermal effusivity determines the fabric's ability to exchange heat with its environment, affecting the perceived warmth or coolness of a nonwoven upon touch. TBBLP1 possessed the most notable thermal effusivity at 81.2743 (Ws^(1/2) / Km^2), indicating a rapid rate of heat absorption and release, which can result in a cooler touch sensation. Sample TBPBLP2 had the lowest effusivity at 63.1812

(Ws^(1/2) / Km^2), reflecting a slower heat exchange rate and a warmer touch feel.

5. Conclusion

This investigation successfully developed thermal bonded nonwoven fabrics from agro –waste papaya fibre, bamboo fibres and low melt PET fibres for thermal insulation applications. Among the produced samples the papaya fibre nonwoven produced a bulkier and less dense with improved air entrapment, resulting in enhanced thermal insulation performance. By lowering reliance on traditional synthetic insulation materials, the proposed light weight nonwoven fabrics offers great potential use in automobile interiors, architectural insulation and other sustainable thermal insulation applications.

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