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Physical and Mechanical Analysis of Vegan Leather Reinforced with Natural Fibers

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Abstract

This study addresses the environmental and ethical issues associated with conventional animal leather and synthetic vegan leather by developing a sustainable plant-based alternative reinforced with natural fibers. The objective of this research is to fabricate and evaluate vegan leather using pineapple leaf fiber, banana stem fiber, and bamboo fiber with a natural latex binder. Non-woven mats were produced through a needle punching process and subsequently impregnated with latex using the vacuum infusion technique. The fabricated vegan leather composites were evaluated for physical properties including density, thickness, and hardness, as well as mechanical properties through tensile and tearing tests in accordance with ISO 13934 and ASTM D2261 standards. The results demonstrate that fiber type and matrix composition significantly influenced material performance. Cotton-based composites exhibited higher density and hardness, with composite leather densities ranging from approximately 882 to 1173 g/m², while polyester-based composites showed greater flexibility. Pineapple–cotton composites achieved the highest tensile strength of up to 6.81 MPa and superior tear resistance, whereas banana–polyester composites displayed the highest ductility with elongation at break reaching approximately 46.44%. Overall, the findings confirm that natural fiber-reinforced vegan leather produced using eco-friendly fabrication techniques possesses competitive physical and mechanical properties. Several key properties, including tensile strength, hardness, and density, were found to fall within reported ranges of commercial leather materials, making it a viable and sustainable alternative to conventional leather, with future work recommended to optimize fiber treatments, blending ratios, and long-term durability through advanced testing and life cycle assessment.

1. Introduction

The fashion and manufacturing industries have long relied on leather due to its durability, aesthetic appeal, and versatility; however, conventional leather production raises significant environmental and ethical concerns. Traditional animal-based leather manufacturing involves intensive livestock farming and hazardous tanning processes using chemicals such as chromium salts, which contribute to water and soil pollution, high energy and water consumption, deforestation, and greenhouse gas emissions [1,2]. In addition, increasing consumer awareness of animal welfare has further questioned the acceptability of traditional leather, driving demand for more ethical and sustainable alternatives. Although synthetic vegan leathers made from polyvinyl chloride (PVC) and polyurethane (PU) provide animal-free options, these petroleum-based materials are non-biodegradable and contribute to long-term environmental problems such as plastic waste and microplastic pollution [3]. Consequently, attention has shifted toward plant-based vegan leather derived from natural fibers such as bamboo, pineapple leaf fiber, and banana fiber, which are renewable, biodegradable, and widely available in tropical and subtropical regions. These cellulose-based fibers exhibit favorable mechanical properties, including good tensile strength and low density, making them suitable for bio-composite applications [4]. Pineapple leaf fiber has been successfully commercialized in products such as Piñatex®, while bamboo and banana fibers offer additional advantages in terms of mechanical performance, sustainability, and availability [5]. However, vegan leather produced using short fibers often suffers from weak inter-fiber bonding, reduced durability, and non-uniform surface characteristics, limiting its application in high-performance sectors such as fashion, automotive, and furniture industries [1]. Recent studies indicate that the use of long natural fibers, combined with fabrication techniques such as needle punching and vacuum infusion, can significantly improve fiber alignment, bonding efficiency, and mechanical performance. Therefore, this study focuses on the fabrication and characterization of vegan leather reinforced with long bamboo, pineapple, and banana fibers using a latex binder to develop a sustainable, eco-friendly, and high-quality alternative to conventional leather.

2. Material and Method

Pineapple leaf fiber, banana stem fiber, and bamboo fiber were used as reinforcement materials. The fibers were cleaned, dried, and cut prior to blending with cotton or polyester fibers at a ratio of 60:40. The blended fibers were fabricated into non-woven mats using a needle punching machine, where mechanical entanglement was achieved through repeated needle penetration. The non-woven mats were subsequently impregnated with latex resin using the vacuum infusion technique to ensure controlled resin flow, reduced air entrapment, and uniform fiber wetting. Physical characterization included density, thickness, and hardness measurements, while mechanical performance was evaluated through tensile and tearing tests using a Universal Testing Machine in accordance with ISO 13934 and ASTM D2261 standards.

2.1 Materials

Natural fiber derived from pineapple leaves, bamboo, and banana stems were selected for their biodegradable and renewable characteristics and their suitability for vegan leather applications. To ensure consistency and quality for composite fabrication, the raw fiber underwent preliminary processing, including washing, drying, and cutting to controlled lengths. According to the experimental design, the prepared natural fiber was blended with cotton and polyester fiber in predetermined ratios to enhance mechanical performance and optimize the structural integrity of the resulting non-woven composites. The fiber blends were then processed using a non-woven needle punching machine, where mechanical entanglement of the fiber produced cohesive non-woven fabric structures. These non-woven mats were subsequently impregnated with 250 mL of latex resin via the vacuum infusion technique, enabling controlled resin flow, reducing air entrapment, and ensuring uniform fiber wetting for the fabrication of vegan leather composites.. Figure 1 illustrates the three types of natural fiber used in this study and figure 2 illustrates the natural latex resin employed as the matrix binder for the fabrication of the vegan leather.

Figure 1 Type of fibers ; a) pineapple leaf fiber, b) banana stem fiber, c) bamboo fiber, d) polyester fiber, and e) cotton fiber.

Fig. 2 Natural latex resin

2.2 Fiber blending

To achieve the required mechanical and physical properties of the non-woven composites, polyester and cotton fibers were combined with natural fibers derived from pineapple leaves, bamboo, and banana stems. There are no surface treatment was applied to the natural fibers prior to the blending process. The fibers were used in their raw form to evaluate their inherent reinforcing capability and to maintain a more sustainable and environmentally friendly approach. The blending process began by feeding the opened fibers from storage onto a feeding apron using customized equipment equipped with an inclined apron, stripping roller, and fiber-adjusting roller. The feeding system operated at a power of 3 kW with a processing capacity of 60–160 kg/h. Subsequently, the fibers were processed using a carding machine operating at 13.25 kW with a capacity of 100–200 kg/h, which teased, blended, and aligned the fibers into a homogeneous and loose fiber web. This stage ensured uniform fiber distribution and proper alignment prior to the needle punching process. To optimize the structural integrity and performance of the composites for sustainable textile and vegan leather applications, several fiber blending ratios were prepared both manually and mechanically, such as 60% natural fiber with 40% polyester or cotton. The blending compositions used in the needle punching process are summarized in Table 1.

Table 1 Sample identification

Reinforcement specimen	Fiber sample				
	Banana stem fiber	Pineapple fiber	Bamboo fiber	Polyester fiber	Cotton fiber
BNP	60%			40%	
PP		60%		40%	
BMP			60%	40%	
BNC	60%				40%
PC		60%			40%
BMC			60%		40%

2.3 Needle punching process

The nonwoven fabrication process was conducted at the Nonwoven Laboratory, Universiti Tun Hussein Onn Malaysia (UTHM), Pagoh Campus, using a needle punching system to produce nonwoven fabrics from pineapple leaf fiber, banana stem fiber, and bamboo fiber for vegan leather applications. Prior to needle punching, all fibers underwent standardized preparation procedures, including cleaning, cutting to controlled lengths, and fiber opening using a NAP opener equipped with a 7.5 kW motor and 1.1 kW reducer, operating at a capacity of 150–300 kg/h to loosen and separate fiber bundles. The prepared fiber web was subsequently consolidated through needle punching, where barbed needles penetrated the web repeatedly at a frequency of 500–650 strokes per minute, mechanically entangling the fibers to form cohesive nonwoven fabrics with thicknesses ranging from 3 to 8 mm. Figure 3 shows illustrates the nonwoven needle punching machine employed for fabricating the nonwoven fiber mats.

Fig. 3 Nonwoven needle punching machine

2.4 Vacuum infusion

The vegan leather composites were fabricated using the vacuum infusion technique, an open-mold process that enables controlled resin flow and effective fiber impregnation. The mold was prepared by Bambosoidene Technology Sdn. Bhd at Universiti Tun Hussein Onn Malaysia (UTHM), Pagoh Campus. Prior to infusion, the nonwoven fiber mats were cut into uniform 1 ft × 1 ft sheets to ensure consistent thickness and fiber coverage. The fiber mats were placed on the mold surface and sealed to form an airtight system, after which a vacuum pump was applied to generate a pressure gradient while latex resin was introduced from the opposite end. A total of 250 ml of natural latex resin was used for each sample. Under vacuum, the resin was drawn uniformly through the fiber layers, ensuring complete wet-out and minimizing air entrapment, with a resin trap installed to protect the vacuum pump. After infusion, the mold was opened and the composite leather sheets were allowed to cure, producing uniform vegan leather samples suitable for subsequent testing. Figure 4 illustrates the vacuum infusion setup used in this research to impregnate the non-woven fiber mats with latex resin and form vegan leather composites.

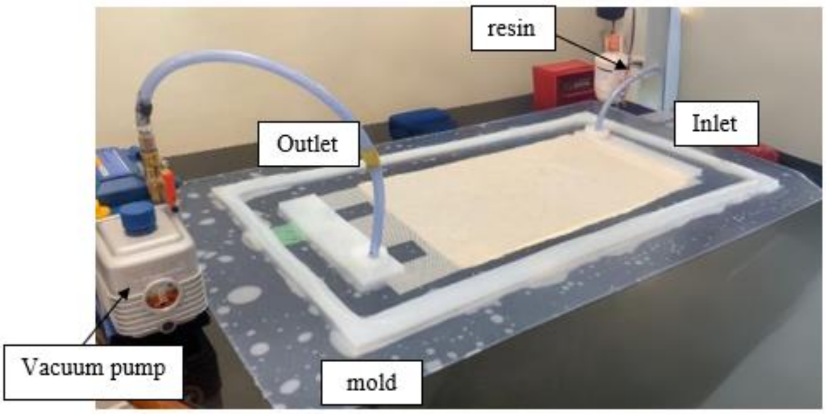
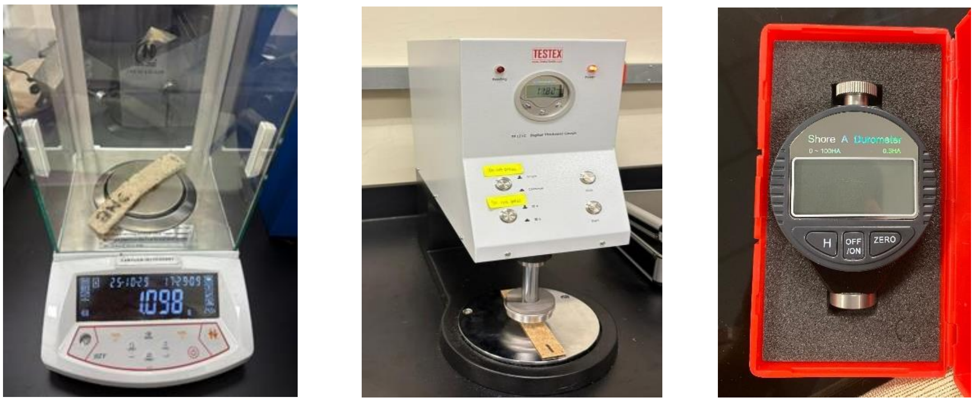


Fig. 4 Vacuum infusion setup

2.5 Physical test

Physical characterization of the vegan leather composites reinforced with bamboo, pineapple leaf, and banana stem fibers was conducted to evaluate their structural integrity and functional performance. Density was determined as mass per unit area by measuring sample mass and dimensions, with values expressed in g/m^2 to assess fiber packing and material uniformity. Thickness measurements were carried out in accordance with ISO 9073-2 using a digital thickness gauge under a presser foot load of 100 cN, and the average thickness was obtained from three measurement points for each specimen. Surface hardness was evaluated using a Shore A durometer following ASTM D2240 or ISO 48-4 standards, where indentation resistance was measured under a standardized load and reported as an average Shore hardness value. These physical tests provided essential insight into the compactness, durability, and suitability of the developed vegan leather composites for sustainable applications. Figure 5 shows the testing equipment employed for physical characterization.

$$Density\ (\rho) = \frac{Mass\ (g)}{Area\ (m^2)} \tag{1}$$

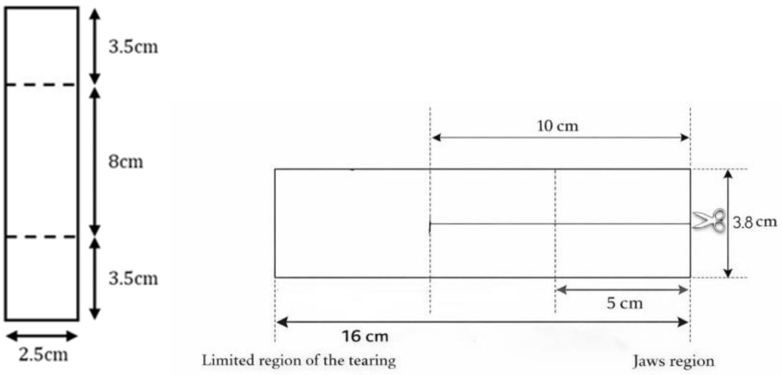


a) b) c)

Fig. 5 a) Weight balance, b) thickness gauge, c) Shore durometer

2.6 Mechanical test

Tensile and tearing properties of the non-woven vegan leather composites were evaluated using a Universal Testing Machine (UTM). Tensile testing was conducted in accordance with ISO 13934-1 (strip method), where specimens measuring 150 mm × 25 mm were subjected to uniaxial loading at a crosshead speed of 100 mm/min until failure, and the maximum breaking force and elongation were recorded. A 100 N load-capacity UTM equipped with pneumatic grips was used to prevent specimen slippage, and all tests were performed at room temperature. Tearing resistance was assessed following ASTM D2261, with specimens conditioned according to ASTM D1776 and cut to dimensions of 160 mm × 40 mm with a gauge length of 100 mm. The tests were carried out at a crosshead speed of 100 mm/min, applying tensile force until tear propagation occurred. Tearing strength was calculated using T=F/A, where F is the maximum tearing force (N) and A is the specimen width (m), providing a standardized measure of the material's strength, flexibility, and durability for vegan leather applications. Figure 6 shows the dimensions of tensile and tearing test samples.



a) b)

Fig. 6 a) Tensile sample dimension b) tearing sample dimension

3. Result Analysis

The six fabricated non-woven vegan leather composites bamboo cotton (BMC), pineapple cotton (PC), banana cotton (BNC), bamboo polyester (BMP), pineapple polyester (PP), and banana polyester (BNP) were systematically evaluated through physical and mechanical testing to investigate the influence of natural fiber type and blend composition on their structural and functional performance. Physical characterization, including density, thickness, and hardness measurements, provided insight into fiber packing, material uniformity, and surface resistance, which are critical parameters for vegan leather applications. Mechanical evaluation through tensile and tearing tests assessed tensile strength, elongation behavior, and resistance to tear propagation, offering a comprehensive understanding of the durability and reliability of the composites under applied loads. The results were summarized in comparative tables and figures, allowing clear identification of performance trends among the different fiber blends and facilitating interpretation of the effects of material composition and processing behavior on the final properties.

3.1 Physical analysis

The average density values of the non-woven composites leather produced from different natural fiber and matrix combinations are shown in Table 2, revealing clear variation depending on fiber composition. Pineapple cotton non-woven (PC N) exhibited the highest density at 851 g/m², indicating a compact and closely packed fiber structure. In contrast, bamboo cotton non-woven (BMC N) recorded the lowest density of 223 g/m², suggesting a looser fiber arrangement with lower mass per unit area. Banana cotton non-woven (BNC N) and banana polyester non-woven (BNP N) showed moderate density values of 297 g/m² and 356 g/m², respectively, reflecting intermediate levels of fiber packing and consolidation. Pineapple polyester non-woven (PP N) and bamboo polyester non-woven (BMP N) displayed comparatively lower densities of 286 g/m² and 251 g/m², indicating lighter web structures. Overall, the low standard deviation values indicate good measurement consistency, while cotton-based non-wovens generally demonstrated higher density than polyester-based counterparts, highlighting the influence of matrix type on fiber packing and mass distribution.

Table 2 Average density of non-woven with different type of fiber

Designation name	Density (g/m^2)	
	AVG	SD
PC N	851.63	54.56
BMC N	223.68	29.87
BNC N	297.55	20.41
PP N	286.88	24.48
BMP N	251.09	16.35
BNP N	356.32	33.57

Table 3 shows the density, thickness, and hardness of the composite vegan leathers, highlighting clear variations influenced by fiber type and blend composition. A substantial increase in density was observed for all composite leathers compared with their corresponding non-woven materials, indicating effective resin impregnation and improved fiber consolidation. Pineapple cotton (PC) exhibited the highest density 4.40 g, reflecting a compact structure with strong fiber–matrix bonding, followed by banana cotton (BNC) at 4.23 g. Banana polyester (BNP) recorded a moderate density of 3.40 g, while bamboo cotton (BMC) and bamboo polyester (BMP) showed similar values of 3.51 g, indicating consistent but moderate consolidation. Pineapple polyester (PP) presented the lowest density 3.31 g with the lowest standard deviation, demonstrating excellent material uniformity despite reduced compactness. Overall, cotton-based composites consistently showed higher density than polyester-based composites, confirming the stronger contribution of cotton fibers to material compactness.

Thickness measurements also varied significantly among the composites. Bamboo cotton (BMC) recorded the lowest thickness 2.12 mm, while banana polyester (BNP) exhibited the highest thickness 4.16 mm, suggesting enhanced bulk formation and rigidity. Bamboo polyester (BMP) showed a high thickness 3.99 mm with the greatest uniformity, indicating well-controlled fiber distribution during processing. Banana cotton (BNC) displayed moderate thickness 3.09 mm, whereas pineapple polyester (PP) and pineapple cotton (PC) recorded thinner profiles of 2.96 mm and 2.41 mm, respectively. In general, banana- and bamboo-based composites produced thicker structures than pineapple-based composites, while polyester-blended composites demonstrated superior thickness uniformity.

Hardness results revealed clear differences in surface resistance and rigidity. Bamboo cotton (BMC) showed the highest hardness 71.00 HA, followed closely by pineapple cotton (PC) at 70.10 HA and pineapple polyester (PP) at 70.90 HA. Banana cotton (BNC) exhibited slightly lower hardness 68.70 HA, indicating moderate surface stiffness. In contrast, bamboo polyester (BMP) and banana polyester (BNP) displayed substantially lower hardness values of 30.50 HA and 36.90 HA, respectively, reflecting softer and more compressible surfaces. Overall, cotton-reinforced composite leathers consistently exhibited higher hardness than polyester-reinforced composites, highlighting their suitability for vegan leather applications requiring enhanced surface durability and wear resistance.

Table 3 Average physical performance of vegan leather with different type of fiber

Designation name	Density (g/m^2)		Thickness (mm)		Hardness (HA)	
	AVG	SD	AVG	SD	AVG	SD
PC	1173.92	114.52	2.41	0.07	70.10	3.41
BMC	935.63	76.81	2.12	0.07	71.00	3.33
BNC	1127.84	88.47	3.09	0.12	68.70	4.40
PP	882.93	19.91	2.96	0.04	70.90	5.36
BMP	936.59	67.22	3.99	0.04	30.50	4.35
BNP	1060.32	91.37	4.16	0.16	36.90	6.18

The fiber weight fraction varied significantly among the six composite materials, which directly influenced their mechanical and aesthetic properties. As shown in Table 4, bamboo cotton (BMC) exhibited the highest fiber fraction of 76.10 wt% and the lowest matrix fraction of 23.90 wt%, indicating a fiber-dominant structure with strong reinforcement potential. Banana cotton (BNC) and bamboo polyester (BMP) also showed high fiber fractions of 73.60 wt% and 73.20 wt%, respectively, suggesting effective fiber incorporation and improved load transfer efficiency. Moderate fiber fractions were observed in pineapple polyester (67.50 wt%) and banana polyester (66.40 wt%), reflecting a more balanced fiber–matrix distribution. In contrast, pineapple cotton (PC) showed the lowest fiber fraction of 27.40 wt% and the highest matrix fraction of 72.60 wt%, indicating a matrix-rich composite structure. In general, composites with higher fiber fractions are expected to exhibit increased stiffness, tensile strength, and load-bearing capacity due to the greater role of fibers in carrying applied loads, whereas matrix-rich composites such as PC may provide improved flexibility, smoother surface finish, and better resin impregnation, contributing to enhanced softness and aesthetic qualities. These variations in composition are likely influenced by differences in fiber morphology, packing density, and wettability during fabrication, and they play a crucial role in controlling the density, thickness, hardness, and overall performance of composite leathers for specific end-use applications.

Table 4 Fiber fraction (wt%)

Designation name	Fiber fraction (wt%)	Matrix fraction(wt%)
PC	27.40	72.60
BMC	76.10	23.90
BNC	73.60	26.40
PP	67.50	32.50
BMP	73.20	26.80
BNP	66.40	33.60

3.2 Tensile performance

The tensile properties of the composite leathers showed pronounced variation depending on fiber type and blend composition, as reflected in both the numerical results and load extension behavior. Pineapple cotton (PC) exhibited the highest tensile performance, achieving an average maximum load of 410 N and a tensile stress of 6.81 MPa, but with limited elongation 15.73%, indicating high stiffness and low ductility. Banana cotton (BNC) and pineapple polyester (PP) demonstrated moderate tensile strength, with average loads of 177 N and 165 N, respectively, and stresses of approximately 2.26 MPa; however, PP showed significantly greater elongation 29.66% compared to BNC 13.70%, reflecting its more ductile polymer-rich structure. Bamboo cotton (BMC) and banana polyester (BNP) exhibited comparable tensile loads of around 130 N, while showing higher extensibility, with strains of 25.98% and 46.44%, respectively. Bamboo polyester (BMP) recorded the lowest tensile strength 61.12 N, 0.61 MPa but the highest elongation 48.74%, indicating very high ductility despite weak load-bearing capacity. The corresponding load–extension curves further confirm that cotton-based composites generally provide higher tensile strength, whereas polyester-based composites favor ductility, demonstrating that fiber type primarily governs strength while matrix type controls deformation behavior in the composite leathers.

Table 5 Average tensile test performance

Designation name	Load, N		Stress,Mpa		Strain at max	
	Average	STDV	Average	STDV	Average	STDV
PC	410.44	64.25	6.81	1.07	15.73	2.16
PP	165.49	12.62	2.24	0.17	29.66	6.76
BNC	177.07	18.24	2.29	0.24	13.70	2.01
BNP	132.72	10.33	1.28	0.10	46.44	8.07
BMC	129.57	27.27	2.44	0.51	25.98	5.62
BMP	61.12	14.55	0.61	0.15	48.74	13.85

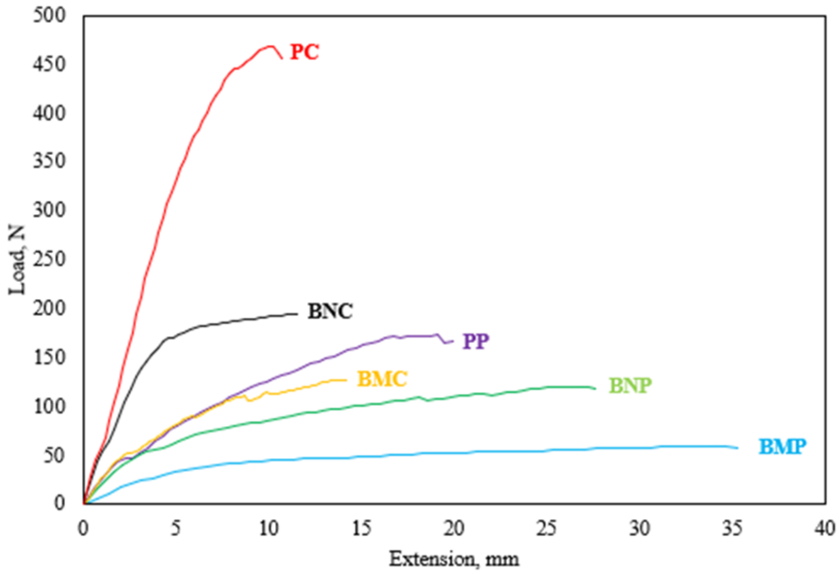


Fig. 7 Load-extension tensile behavior

The average tensile stress results presented in Figure 7 reveal distinct differences in the tensile performance of the composite leathers. Pineapple cotton (PC) exhibited the highest average tensile stress of approximately 6.81 MPa, indicating superior stiffness and strong fiber matrix interaction that enabled the composite to withstand high tensile loads prior to fracture. The relatively larger standard deviation observed for PC suggests some specimen-to-specimen variability, likely due to natural fiber heterogeneity or slight differences in fiber alignment during fabrication. Pineapple polyester (PP) and banana cotton (BNC) displayed moderate tensile stress values of approximately 2.26 MPa, accompanied by small standard deviations, indicating consistent tensile behavior and a more uniform material structure. Bamboo cotton (BMC) showed a slightly higher average stress of about 2.44 MPa; however, its larger error bar indicates increased variability, possibly resulting from uneven fiber dispersion or non-uniform interfacial bonding. In contrast, banana polyester (BNP) and bamboo polyester (BMP) recorded the lowest tensile stress values of approximately 1.28 MPa and 0.61 MPa, respectively, with minimal variation, confirming their consistently low load-bearing capacity. Overall, these results demonstrate that cotton-based composite leathers provide superior resistance to tensile stress compared with polyester-based counterparts, with PC exhibiting the highest mechanical robustness, while BMP shows the poorest structural resistance.

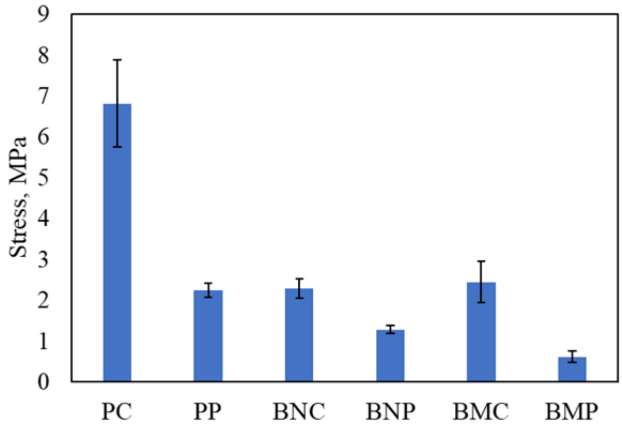


Fig.8 Average tensile stress

3.3 Tearing performance

The tearing performance of the composite leathers exhibited distinct variations depending on fiber type and blend composition. Pineapple cotton (PC) demonstrated the highest tearing resistance, recording an average tearing load of 136.31 N, which indicates strong resistance to tear initiation; however, its moderate maximum strain of 40.04% and the sharp load drops observed in the tearing curve suggest a more brittle failure once tearing began. Pineapple polyester (PP) showed moderate tearing strength 94.09 N with higher elongation 48.51%, reflected by a smoother load extension curve, indicating a more ductile tearing response. Banana cotton (BNC) exhibited lower tearing resistance 67.42 N but high extensibility 63.19%, allowing greater deformation before failure. Banana polyester (BNP) achieved the most balanced tearing performance, combining a high tearing load of 90.68 N with the highest strain at maximum extension 68.36%, and its smooth, steadily rising curve confirms stable tear propagation and excellent ductility. In contrast, bamboo cotton (BMC) and bamboo polyester (BMP) recorded the lowest tearing loads of 46.73 N and 36.37 N, respectively, yet both displayed high strain values exceeding 55%, indicating materials that deform extensively but possess limited tear resistance. Overall, the results show that PC provides the strongest but more brittle tear resistance, BNP offers the best combination of strength and ductility, PP exhibits stable ductile behavior, and bamboo-based composites are highly extensible but mechanically weak during tearing.

Table 6 Average tearing test performance

Designation name	Load, N		Strain at max	
	Average	STDV	Average	STDV
PC	136.31	20.57	40.04	3.68
PP	94.09	9.81	48.51	10.43
BNC	67.42	14.57	63.19	17.47
BNP	90.68	22.42	68.36	12.41
BMC	46.73	1.51	55.98	8.87
BMP	36.37	9.33	58.58	17.12

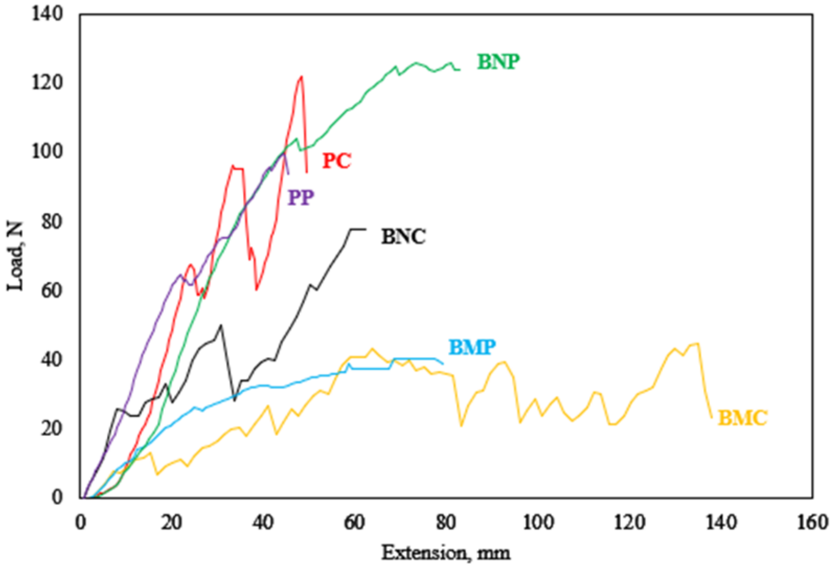


Fig. 9 Load-extension tearing behavior

The average tearing load results presented in Figure 10 reveal clear differences in the tearing performance of the composite leathers. Pineapple cotton (PC) exhibited the highest average tearing load of approximately 135 N, indicating superior resistance to tear initiation and strong fiber matrix interaction that enabled the composite to withstand higher tearing forces prior to failure. The relatively larger error bar observed for PC suggests some variability between specimens, likely resulting from natural fiber heterogeneity or slight differences in fiber orientation during fabrication. Pineapple polyester (PP) and banana polyester (BNP) demonstrated moderate tearing loads of approximately 95 N and 90 N, respectively; PP showed lower variability, indicating more consistent tear resistance, whereas the larger error bar for BNP reflects reduced uniformity in internal structure or bonding quality. Banana cotton (BNC) recorded a lower average tearing load of around 67 N with moderate variability, indicating reduced resistance to tear propagation. Bamboo cotton (BMC) and bamboo polyester (BMP) exhibited the lowest tearing loads, approximately 47 N and 37 N, respectively, with relatively small error bars, confirming consistently weak tear resistance across samples. Overall, these results indicate that PC provides the highest tear resistance, PP and BNP exhibit moderate tearing performance, and bamboo-based composites demonstrate the weakest resistance to tearing.

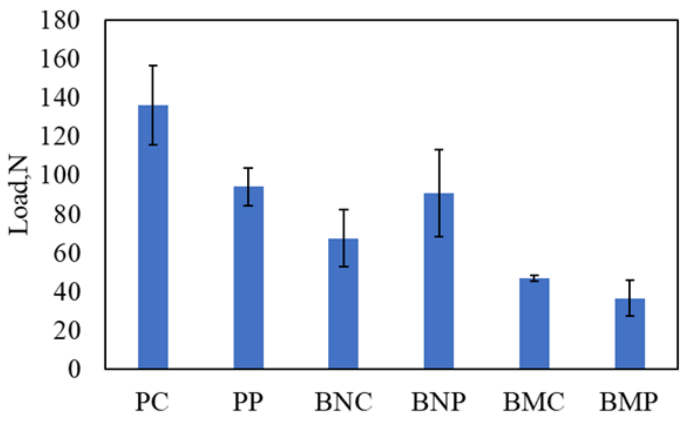


Fig. 10 Average tearing load

4. Conclusion

This study was successfully conducted in accordance with the defined objectives, focusing on the development and evaluation of vegan leather reinforced with natural fibers. Agricultural waste fibers pineapple leaf fiber, banana stem fiber, and bamboo fiber were effectively utilized as reinforcement materials, while cotton and polyester fibers served as blending matrices. The fabrication process, combining non-woven needle punching with vacuum infusion using a latex binder, was successfully implemented, resulting in six distinct composite leather variants (PC, PP, BNC, BNP, BMC, and BMP) with consistent dimensions and acceptable surface quality. Physical characterization confirmed that fiber type and matrix selection significantly influenced density, thickness, and hardness, with cotton-based composites generally exhibiting higher compactness and surface resistance, while polyester-based composites demonstrated improved uniformity and flexibility. Mechanical evaluation revealed that pineapple cotton (PC) provided the highest tensile and tear resistance, whereas banana polyester (BNP) and bamboo polyester (BMP) exhibited greater elongation, indicating superior ductility. Overall, the results demonstrate that natural fiber type primarily governs strength, while matrix type strongly influences deformation behavior. This study confirms that plant-based non-woven composites reinforced with agricultural waste fibers have strong potential as sustainable alternatives to conventional leather, supporting environmentally friendly material development and effective waste valorization.

Based on the findings of this study, several recommendations are proposed for future research and development. Future studies should investigate chemical or surface treatments, such as alkaline or enzymatic treatments, to enhance fiber–matrix interfacial bonding and further improve mechanical performance. In addition, exploring different fiber blending ratios is recommended to optimize strength, flexibility, and surface characteristics for specific applications, including footwear, upholstery, and fashion accessories. Further performance evaluations, such as abrasion resistance, water absorption, UV resistance, and ageing behavior, should also be conducted to assess long-term durability and service performance. Future work may consider the use of fully bio-based matrices to further enhance the biodegradability and sustainability of vegan leather composites. Finally, conducting a life cycle assessment (LCA) is strongly recommended to quantitatively evaluate the environmental benefits of the developed vegan leather in comparison with conventional animal-based and synthetic leather materials.

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