Textile & Leather Review

ISSN 2623-6281 | www.tlr-journal.com | 10.31881/TLR

Blend of Fibres to Improve the Mechanical Properties of Needle-Punched Nonwovens for PM2.5 Air Filtration

Hanur Meku Yesuf, Hafeezullah Memon, Syed Rashedul Islam, Liu Jiawei, Desalegn Atalie, Xueping Zhang, Xiaohong Qin

How to cite: Yesuf HM, Memon H, Islam SR, Jiawei L, Atalie D, Zhang X, Qin X. Blend of Fibres to Improve the Mechanical Properties of Needle-Punched Nonwovens for PM2.5 Air Filtration. Textile & Leather Review. 2024; 7:235-264. https://doi.org/10.31881/TLR.2024.004

How to link: https://doi.org/10.31881/TLR.2024.004

Published: 16 February 2024

Blend of Fibres to Improve the Mechanical Properties of Needle-Punched Nonwovens for PM2.5 Air Filtration

Hanur Meku YESUF[1,2], Hafeezullah MEMON[3], Syed Rashedul ISLAM[4], Liu JIAWEI[1], Desalegn ATALIE[1,5], Xueping ZHANG[1*], Xiaohong QIN[1*]

[1]Key Laboratory of Textile Science & Technology, Ministry of Education, College of Textiles, Donghua University, Shanghai, 201620, China

[2]Ethiopian Institute of Textile and Fashion Technology, Bair Dar University, Bahir Dar, 6000, Ethiopia

[3]College of Textile Science and Engineering, Zhejiang Sci-Tech University, Hangzhou, 310018, China

[4]National Institute of Textile Engineering and Research (NITER), University of Dhaka, Dhaka, 1350, Bangladesh

[5]Xinjiang Technical Institute of Physics and Chemistry, CAS, University of Chinese Academy of Sciences, Xinjiang, 830011, China

*xhqin@dhu.edu.cn, xpzhang@dhu.edu.cn

Article

https://doi.org/10.31881/TLR.2024.004

Received 8 January 2024; Accepted 5 February 2024; Published 16 February 2024

ABSTRACT

This research investigated the innovative synthesis achieved through blending five distinct fibres (Polyacrylonitrile (PAN), Polyester (PET), Polylactic acid (PLA), Polypropylene (PP), and Polyphenylene sulfide (PPS)) in the production of needle-punched nonwoven fabrics tailored for air filtration applications. The study investigated the effects of needle-punched nonwovens made with up to five fibres on the physical and mechanical properties, addressing a gap in existing literature. The method involved manual and machine opening, blending, and carding of fibres, followed by producing three samples with different web arrangements (cross-laid web, parallel-laid web, and pre-needled parallel-lad web). The study employed standard test methods to characterize physical and mechanical properties. Results indicated that web arrangement and pre-needling significantly influenced various properties, with cross and parallel-laid web arrangements having minimal impact on thickness and bursting stretch. The parallel arrangement, whether pre-needled or not, showed no significant effect on GSM, fabric density, bursting strength, tear strength, abrasion resistance, and filtration efficiency. The highest abrasion resistance, lower pressure drop, highest fabric stiffness, moderate tensile strength, and higher bursting strength were observed in a cross-web arrangement. This study contributed valuable insights into the intricate interplay of fibre composition, web arrangement, and pre-needling in the design of advanced needle-punched nonwoven fabrics for air filtration. The findings provided a nuanced understanding of how these factors collectively impact the mechanical and physical characteristics of the material, paving the way for enhanced efficiency, durability, and versatility in air filtration applications.

KEYWORDS

blended-fibre, mechanical properties, pre-needling, web-arrangement, needle-punched nonwoven, air filtration

INTRODUCTION

Blending different types of fibres has been a common practice in the production of needle-punched nonwoven fabrics. Blending allows for the combination of different fibre properties to achieve the desired characteristics in the final product [1-4]. Fibre blend plays a crucial role in determining the mechanical properties of needle-punched nonwovens [5-7]. By carefully selecting and blending different types of fibres, it is possible to enhance specific properties such as tensile strength, tear strength, burst strength, abrasion resistance, and flexibility, thus tailoring the nonwoven fabric for various applications and performance requirements [1,4,8-15].

The fibre blend composition affects the tensile and tear strength of a needle-punched nonwoven by determining the inter-fibre bonding within the nonwoven structure [5,16,17]. By combining different types of fibres with varying characteristics, such as high-strength fibres and low-strength fibres, the overall tensile strength of the fabric can be enhanced or tailored to meet specific requirements. Certain fibres, such as high-tenacity fibres or fibres with good interlocking properties, can enhance tear resistance when blended appropriately. The fibre blend composition impacts burst strength by influencing the fabric's structural integrity and resistance to internal pressure [5,18,19]. Blending fibres with high tensile strength and good cohesion can improve the burst strength of needle-punched nonwovens. The fibre blend composition affects abrasion resistance by determining the fabric's surface properties, fibre strength, and inter-fibre cohesion [20-22]. Blending fibres with high abrasion resistance or adding abrasion-resistant finishes can enhance the overall durability of the nonwoven fabric. Fibre blend composition plays a role in determining the flexibility of needle-punched nonwovens [23,24]. By combining fibres with different bending properties or using fibres with good flexibility characteristics, the fabric's flexibility can be improved or modified.

Different scholars at different times have studied the development, properties, and parameter effects of needle-punched nonwoven fabric for different application areas. Some of the studies done on needle-punched nonwoven are presented in Table 1. The mechanical properties of needle-punched nonwoven materials play a crucial role in determining their filtration behaviour [13,25]. However, these properties come with certain limitations that can impact the overall performance of the material in filtration applications. Needle-punched nonwovens have limitations in tensile strength, especially if the fibres used are not inherently strong or if the needling process doesn't impart sufficient inter-fibre bonding. Roy and Ishtiaque [26,27] also noticed that higher punching and higher feeder speeds also give a higher number of breakages which results in lower tensile strength. Lower tensile strength can result in reduced durability, leading to potential issues during handling, installation, or exposure to airflows. It may also affect the integrity of the filter over time.

Needle-punched nonwovens may have limitations in resistance to bursting under certain conditions [19,28]. The resistance to bursting is a crucial aspect of the material's integrity during air filtration. Fibre breakage during manufacturing weakens the overall structure, compromising the nonwoven's ability to resist bursting when exposed to increased pressure during air filtration.

Table 1. Fibres, their blends and study properties of some needle-punched nonwovens

Fibre blend	Studied Properties	References
PAN and PAN/HAp	physical and mechanical properties of bone tissue regeneration	[29]
Polyester / Nylon / Kevlar	structural effect and property	[30]
Polyester / Palm	mechanical and ageing performances	[31]
polyester (HPET) / PP	mechanical properties	[5]
polyester / Bamboo	thermal resistance and the bursting strength	[32]
Recycled-PET / Kapok	thermal resistance and air permeability	[33]
Polyester/viscose	air permeability	[34]
Polyester/cotton	scraps to wrap preserved fruit	[35]
PET / Areca	building insulation applications	[3]
PLA/PP/Glass, PLA/PP/Hemp, PLA/Glass/Hemp, PP/Glass/ Hemp	noise-control performance	[36, 37]
PP/carbon	electromagnetic shielding effectiveness	[38]
Carbon /Polypropylene	mechanical Properties	[39]
PLA/TCF, PLA/flax, PLA/hemp, PP/TCF, PP/flax, PP/hemp	mechanical property (Triumfetta cordifolia fibre (TCF))	[40]
Jute / PP	sound reduction, water absorbency, thermal resistance and air permeability	[41-43]
Kapok/PP	Thermal Resistance	[44]
PP / Bamboo / PET, PP / Banana / PET, PP / Hemp / PET	acoustic properties	[45]
PP / Nettle	oil spill cleanup applications	[2]
Polyphenylene sulfide (PPS)	$PM_{2.5}$ filtration property, chemical resistance	[46],[47]
Polytetrafluoroethylene / PPS	Air filtration property	[48]

Needle-punched nonwovens may have limitations in resistance to abrasion, which can be a concern in applications where the filter comes into contact with particulate matter or experiences friction [49]. Poor abrasion resistance can lead to the shedding of fibres, compromising the filter's efficiency and potentially introducing particulate matter into the filtered air. The flexural rigidity of needle-punched nonwovens may be limited, especially if the fibres are not sufficiently stiff or if the structure lacks the necessary rigidity [49]. In applications where maintaining a specific shape or preventing sagging is crucial, limitations in flexural rigidity may lead to challenges in maintaining the desired filter geometry.

The nobility of this research work lies in the artful synthesis achieved through the blending of five distinct fibres. Among many fibres used for the production of needle-punched nonwovens Polyacrylonitrile (PAN), Polyester (PET), Polylactic acid (PLA), Polypropylene (PP) and Polyphenylene sulphide (PPS) are selected for this research work, i.e. the nobility of this research work. This innovative approach reflects a commitment to elevating the standards of nonwoven material design for air filtration. By intricately combining fibres with diverse characteristics, this research seeks to pioneer a new paradigm in filtration technology, aiming to enhance efficiency, durability, and versatility. The deliberate fusion of five fibres embodies a dedication to precision and optimization, showcasing a thoughtful and forward-thinking strategy in the pursuit of creating advanced needle-punched nonwoven fabrics. This noble endeavour not only signifies a significant leap forward in materials science but also underscores a genuine commitment to addressing the multifaceted challenges of air filtration with ingenuity and excellence.

PAN [50-53] fibres offer excellent strength and thermal stability. They can enhance the dimensional stability and durability of the nonwoven fabric. PAN fibres are known for their good resistance to chemicals and abrasion. PET [54-57] fibres are widely used in nonwoven applications due to their high tensile strength and excellent resilience. They provide good resistance to stretching and shrinkage. PET fibres offer high durability and are resistant to moisture, mildew, and most chemicals. PLA [58-61] fibres are derived from renewable resources, making them environmentally friendly. They offer good comfort, softness, and breathability. PLA fibres are biodegradable and have a lower carbon footprint compared to synthetic fibres. PP [62-65] fibres are lightweight and have high tensile strength. They provide excellent resistance to moisture, chemicals, and abrasion. PP fibres offer good thermal insulation properties. PPS [53,66-68] fibres have high chemical resistance and can withstand elevated temperatures. They provide excellent dimensional stability and resistance to creep. PPS fibres offer good electrical insulation properties.

Incorporating high-cost fibres like Polylactic acid (PLA) and Polyphenylene sulfide (PPS) in PM2.5 air filter needle-punched nonwoven materials is a strategic choice. PLA enhances filtration efficiency through fine fibres, aligning with sustainability goals, while PPS adds crucial high-temperature resistance for stability in demanding conditions. This optimization of mechanical properties, combined with Polyacrylonitrile (PAN), Polyester (PET), and Polypropylene (PP), creates a unique material, offering a competitive edge in markets with stringent performance criteria. Despite higher costs, the decision is justified by a careful cost-performance analysis, ensuring a balanced and cost-effective solution. The overall performance benefits, including enhanced filtration efficiency, durability, and sustainability, are weighed against the increased cost to ensure a balanced and cost-effective solution for the intended application.

Combining different types of fibres can create a diverse and effective filtration matrix. Each fibre type may contribute unique filtration properties, such as particle capture efficiency and the ability to trap different particle sizes. Blending fibres with varying diameters and surface characteristics can improve the nonwoven's ability to retain particles of different sizes. This is crucial in air filtration applications where a range of particle sizes needs to be captured. Blending fibres can help manage the pressure drop across the filter media. The combination of fibres with varying diameters and structures can create a filter with a balanced pressure drop, optimizing airflow without sacrificing filtration efficiency. Each fibre type has its own strength and durability characteristics. Blending fibres with different strengths can result in a nonwoven fabric that is both durable and resilient, maintaining its integrity over time in challenging filtration environments.

Blending fibres allows for tailoring the nonwoven material to be compatible with specific contaminants present in the air. This is important in applications where the filter needs to address diverse pollutants or contaminants. Blending fibres also allow for cost optimization by using a combination of more affordable fibres with those that provide specific performance benefits. This approach helps achieve the desired filtration properties without compromising on cost-effectiveness. However, the literature is silent about the effect of using up to five fibres on the physical and mechanical properties of needle-punched nonwovens. In the present work, an attempt has been made to evaluate the effect on the mechanical properties of five fibre blend needle-punched nonwoven fabric by varying the web arrangement.

EXPERIMENTAL

Materials

Five different fibres; Polyacrylonitrile (PAN), polyester (PET), Polylactic acid (PLA), polypropylene (PP) and Polyphenylene sulphide (PPS) staple fibres with different blend ratios were used for developing nonwoven fabrics. These fibres were from Nonwoven Research Laboratories at College of Textiles, Donghua University, China that were purchased from Suzhou Makeit Technology Co., Suzhou, China. The picture and details of fibres are shown in Figure 1 and Table 2.

Table 2. Basic properties of fibres

Parameters	Unit	Fibre type				
		PAN	PET	PLA	PP	PPS
Fibre Length	mm	38	38	51	51	51
Fibre Fineness	dtex	1.3	1.56	6.66	2.22	1.53
Fibre Strength	cN/dtex	5.62	5.42	0.44	2.83	6.31
Fibre Elongation	%	14.26	13.88	2.24	18.65	24.78

Figure 1. Fibres used

Sample preparation

The production line at Nonwoven Research Laboratories at the College of Textiles, Donghua University, China was used to produce the needle-punched nonwoven samples.

Nonwoven Web Preparation and Web Laying

PAN, PET, PLA, PP and PPS were opened and blended manually with equal proportions. Then the manually blended fibres were processed on the carding machine by keeping the feed roller, cylinder and doffer speeds constant. The fibre mass was placed evenly on the lattice of the carding machine. Carding is a dry-laid web formation technique with further opening, cleaning, blending, and fibre alignment. The feed basis weight of fibres was the same at 100 g for all single webs

Table 3. Combinations of blending ratio

Sample Code	Fibre blending combinations					Remarks
	PAN	PET	PLA	PP	PPS	
N0	20	20	20	20	20	Six webs laid down at a right angle alternatively one on top of the other
N1	20	20	20	20	20	Six webs laid down in a parallel manner one on top of the other
N2	20	20	20	20	20	Six webs pre-needling before and laid down in a parallel manner one on top of the other

For each sample, six webs were prepared in the blend ratio shown in and immediately after carding, the carded webs were laid down in different manners to produce three samples of needle-punched nonwoven. The final webs are prepared by laying individual webs in the order indicated in Figure 2. To further increase final web homogeneity for samples N1 and N2, web laying was carried out in the machine direction without altering the main fibre orientation. Fibres were predominately oriented in the longitudinal (machine) direction, making the final web anisotropic. As it is indicated in Table 3 under remarks, In the case of N0, Six carding webs laid down at a right angle alternatively one on top of the other before needling. In Figure 2, the red ➞ indicates the machine direction during carding, while blue ➞ indicates the machine direction during needling. About the needle punching machine, the six webs in the case of N0 are cross-laid at the right angle one from the other alternatively. It's a combination of parallel and cross. The carding parameters considered for the preparation of sample webs are feeder speed (0.77 rpm), cylinder speed (280 rpm) and doffer speed (7.01 rpm).

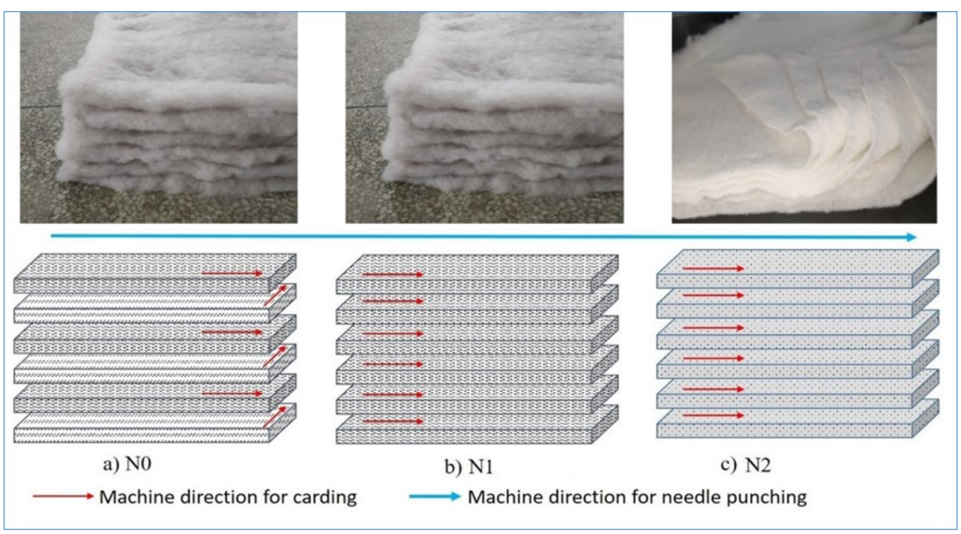

Figure 2. Nonwoven web laying arrangement

Needle Punching

The final webs were passed through in two consecutive machines. Sample webs were punched by pre-needling and final needling punch looms with a constant feeding speed, delivery speed, punch density and needle penetration depth as shown in Figure 3. In the first stage, after the laying of fibre webs into 3D fluffy layers, the web from carding was fed into a pre-needling punching loom to entangled six layers by using a conveyor and roller feeding system. It was a preliminary 3D web to compact slightly the fluffy mass of fibre webs by entangling the fibres. Pre-needling is used to minimize the thickness of the web.

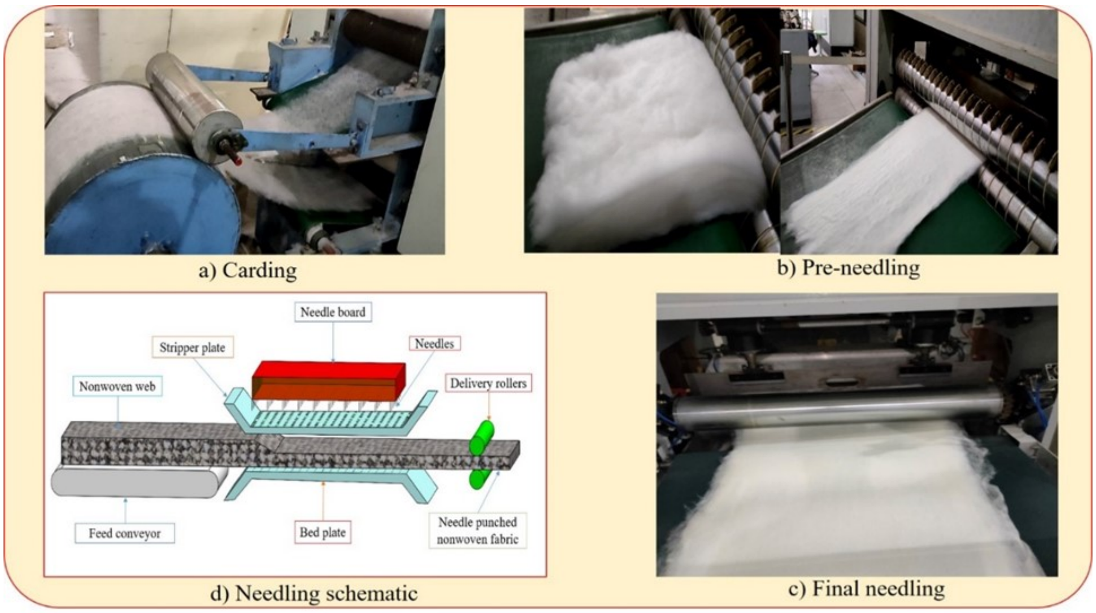

Figure 3. Needle punching process of the samples

Then, the pre-needled layered web of blended fibres was delivered to the main needle-punching loom, so that the more compressed nonwoven fabric could be developed. In this work, the samples pass through one time in the pre-needling punching loom and two times in the main needle punching loom for each side, a total of six needlings. For sample N2, six webs were pre-needled individually on each side before and laid down in a parallel manner one on top of the other. Again, after the laydown, it passed through one time in the pre-needling punching loom and two times in the main needle punching loom for each side, a total of eight needling. The punching parameters considered for the preparation of sample nonwoven fabrics during pre-needling are punch density (4800 punches/m²), needle penetration depth (5 mm)., feeding speed (1 m/min)., delivery speed (1 m/min) and needling frequency (200 punches per minute). The punching parameters during final needling are punch density (3200 punches/m²), needle penetration depth (8 mm), feeding speed (1 m/min), delivery speed (1 m/min) and needling frequency (150 punches per minute).

Characterization

Standard Test Methods

All the tests followed a standard method, with all samples pre-conditioned for 24 hours at 20 ± 2°C and 65% relative humidity.

SEM Analysis

The scanning electron microscopy (SEM) was done with a Flex-SEM 1000, (SU1000, Hitachi Ltd. Japan). A gold layer using a vacuum sputter coater was used to coat all needle-punched fabric samples before analysis. SEM examined the morphology of fibres used and nonwoven fabric samples.

FTIR Test

The American Nicolet TM 5700 FT-IR spectrometer was used to carry out the Fourier transform infrared spectroscopy (FTIR) test. Based on the Attenuated Total Reflection (ATR) approach, spectra between 400 and 5000 cm^{-1} have been generated. FTIR tests were done at different areas of sample nonwovens and checked the uniformity and proper distribution of fibres during blending.

Thickness

The test was carried out according to the relevant provisions of GB/T 3820-1997 and ISO 5084:1996. Thickness gauge, capable of registering the distance between the bearing surface of the presser foot and the reference plate (to an accuracy of 0.01 mm).

GSM

The nonwoven fabric GSM was calculated as per ASTM 6242 standards, i.e., mass per unit area (areal density in grams per square meter). The specimen of the size 10 X 10 cm was cut randomly from different places and weighted in electronic balance with an accuracy of 0.001 g and an average of 10 readings was taken.

Density

Nonwoven fabric density, or bulk density, is the weight per unit volume of the nonwoven fabric (kg/m^3). It is determined by the following formula:

$$D = \frac{GSM}{T} \tag{1}$$

Where: D: Fabric density (kg/m^3); GSM: gram per square meter; T: thickness (mm)

Tensile Strength and Elongation

Constant-rate-of-extension (CRE) testing machine was used to carry out the test. The maximum force a nonwoven material can bear when it is stretched is known as its tensile strength. At the point of rupture, elongation at break or final elongation is represented as a percentage. The test was conducted in accordance with the pertinent GB/T 3923.1-2013 and ISO 13934-1:2013 standards. Until it ruptured, a fabric test specimen with the required dimensions was expanded steadily. Records are the maximum force, the elongation at maximum force, and, if necessary, the force and elongation at rupture.

Bursting Strength

Constant-rate-of-extension (CRE) testing machine was used to carry out the test. The nonwoven fabric is concurrently stretched in both directions at the same time when it is subjected to bursting force, and the cloth typically fails in the direction where its elongation is lowest. External stresses on nonwoven textiles can cause them to burst instead of rupture due to tensile stress. The test was carried out according to the relevant provisions of GB/T 19976-2005. A fabric was securely clamped in the ring sample holder of the fixed base. A polished steel ball traversing at a fixed speed was pressed against the specimen until failure occurred. The force required to cause failure was recorded as the bursting strength.

Tear Strength

Constant-rate-of-extension (CRE) testing machine was used to carry out the test. The test was carried out according to the relevant provisions of GB/T 3917.2-2009 and ISO 13937-2:2000. A rectangular test specimen was cut in the centre of the shorter edge to form a trouser shape. The legs of the trousers were gripped in the clamps of a recording tensile testing machine to form a straight line and pulled in the direction of the cut to tear the fabric. The force to continue the tear over a specified distance was recorded. The tear force was calculated from the force peaks of the autographic trace, or online by the electronic device.

Stiffness

Fabric stiffness was done based on ASTM D1388-96(2002) standard test method. The specimen was placed on the flat surface as a cantilever beam with a uniform load, and it was driven to move uniformly along the length direction by a driving mechanism. The inclined plane detection line contacted the sample when it was pushed out from the working platform and bent and sagged due to its weight. The extended length L was measured, and the bending length is also called the overhanging stiffness and the bending stiffness. According to the principle that the greater the bending stiffness, the harder it is to bend, it is used as a test index to evaluate the stiffness of the tested material.

Abrasion Resistance

The abrasion resistance test was done based on the GB/T48021-1997 standard test method for the stiffness of fabrics. The abrasion resistance of the samples was tested to have an idea about how the fabrics' rubbing properties would be. The number of abrasion cycles per specimen was 5000, the rotational speed was 56±0.6 rpm, the face diameter of the specimen was 32 mm, the specimen holder diameter was 38 mm and the pressure used was 12 kPa. Then the abrasion resistance is expressed based on the weight loss due to rubbing and calculated as follows:

$$\mathrm{Wl} = \frac{(\mathrm{Wb}-\mathrm{Wf})}{\mathrm{Wb}} \times 100 \tag{2}$$

Where: Wl: weight loss (%); Wb: Weight before abrasion (g); Wf: Weight after abrasion (g)

Filtration Testing

Filtration efficiency and pressure drop were examined using a U-Test automatic digital tester (Model: F003, Uti Intelligent Technology Co., Ltd., Suzhou, China) to assess dust filter ability. According to the ISO 29463 assessment system standard, NaCl particles of $PM_{2.5}$ were introduced to the filtering system at a constant air pressure flow rate of 32 l/min to stimulate dust. The tests were evaluated at 20 °C and 45% relative humidity. The moisture content of the fabric was determined using the ISO 939 standard. Then, filtration efficiency and dust holding capacity were calculated by the following formulas: [53]

$$F_e = \frac{D_c}{D_f} \text{ x } 100 \quad (3)$$

Where: Fe: Filtration efficiency (%); Dc: Dust collected; Df: Dust fed

RESULTS AND DISCUSSION

Scanning Electron Microscopy

Scanning electron microscopy (SEM) displayed the surface morphological structures of fibre used and needle-punched nonwoven fabrics. As depicted in Figure 4 (a-e), the image analysis revealed fibre crimp, which is added on synthetic fibre to improve the cohesion, bulkiness and web management before consolidation or bonding.

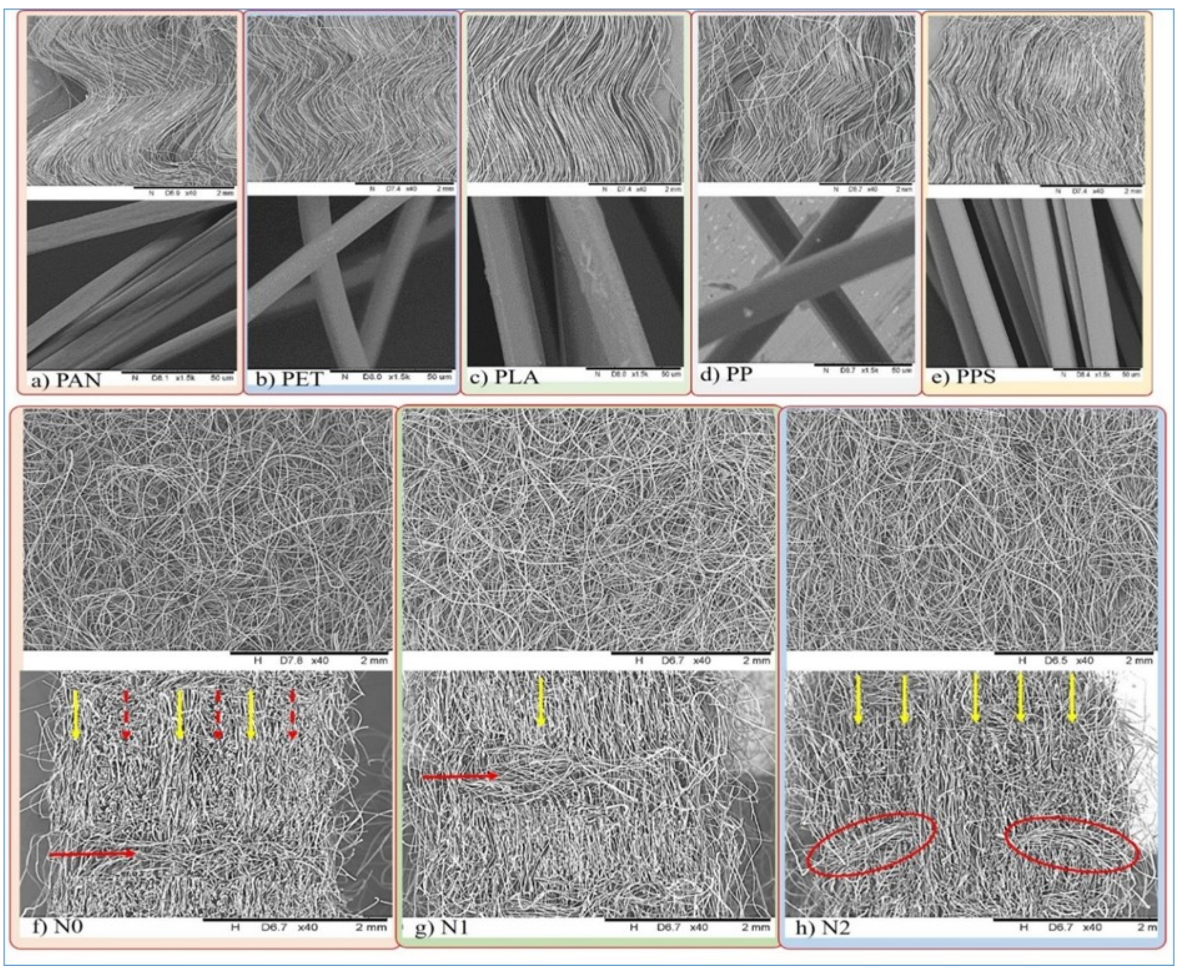

Figure 4. SEM of fibres used and surface morphology of blended fibre needle-punched fabric

The appearance and fineness of the fibre are also observed in Figure 4. SEM of the surface and cross-sectional view of needle-punched nonwoven fabrics are also shown in Figure 4 (f-h). The surface morphology of all fabrics is almost the same, whereas the cross-section view of the fabrics is different. In Figure 4 (f) sample N0, web laying was done in the machine direction (indicated by yellow line) and cross direction (indicated by red broken line) alternatively, so that the fibre surface is viewed in the longitudinal and fibres cross-section is viewed cross direction. The red line in a horizontal direction indicates the path of the needle and the direction of fibre alignment is changed due to up and up-and-down movement of the needle. In Figure 4 (g) sample N1, web laying was done in the machine direction (indicated by a yellow line) so that fibres were favourably lined up in the machine direction. Like N0, the red line in a horizontal direction indicates the path of the needle throughout the thickness of the fabric. In Figure 4 (g) sample N2, six webs were pre-needled individually on each side before and laid down in a parallel manner one on top of the other so that the joint places between individual webs are visible in the cross-section view (indicated by the yellow line). Unlike N0 and N1, the path of the needle throughout the thickness of the fabric is not continuous due to the pre-needling effect in the case of N2 (indicated by a red ellipse).

Fourier Transform Infrared Spectroscopy

Figure 5 shows the FTIR result of blended fibre needle-punched nonwoven fabric and the chemical structure of fibres. PAN fibres' FTIR spectra show a variety of peaks attributable to the presence of CH_2, CN, C=O, and C-H bonds. The C-H bonds in CH, CH_2 and CH_3 have a relationship to the absorption peaks between 2926 and 2935 cm^{-1}. Another peak is seen between 2243 and 2246 cm^{-1}, and it is connected to the presence of nitrile (C-N) bonds, proving the existence of the nitrile group in the polyacrylonitrile chain. The presence of comonomers causes the absorption peaks in the ranges of 1730-1737 cm^{-1} and 1170 cm^{-1}, which are connected to C=O or C-O bonds. Resonant C-O bonds are associated with absorption in the 1593–1628 cm^{-1} region.

The vibration of the CH_2, CH_3, and CH bonds in the PET structure resulted in FTIR spectra of PET fibres having peaks at about 2900 cm^{-1}. In the chemical structure of PET, the conjugated ester group was identified by the stretching of the C=O bond at a peak of 1715 cm^{-1}. C=C stretching, attributed to benzene vibration, was seen at a peak 1050 cm^{-1} wavelength. 1780 and 1680 cm^{-1} for the C=O stretch and 3600–3000 cm^{-1} for the O–H stretch are the regions of interest for PLA. The maxima in the graph that correspond to the PLA's C=O stretching and C-O-C stretching are located at around 1750 and 1180 cm^{-1}, respectively.

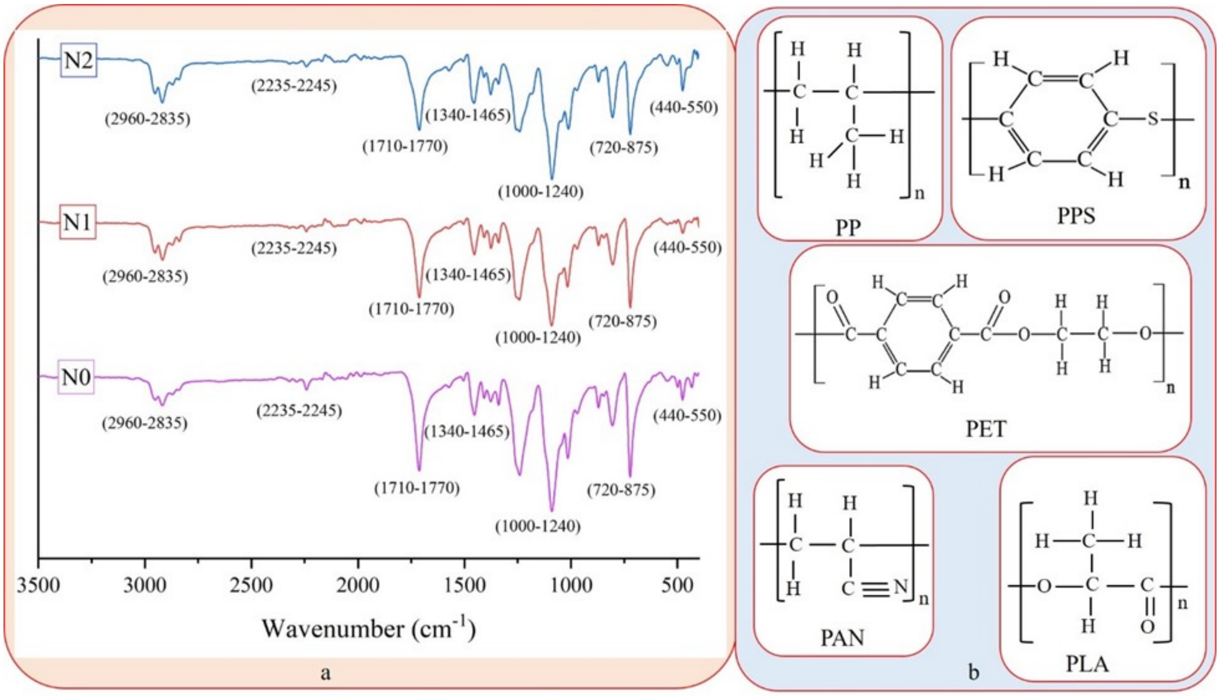

Figure 5. a) FTIR result of blended fibre needle punched nonwoven fabric, b) Chemical structure of fibres

PP has CH_3 stretching peaks at 2956 cm^{-1}, CH_2 stretching peaks at 2921 and 2840 cm^{-1}, and the methyl group umbrella mode at 1377 cm^{-1}. In one unit of the PP molecule chain, there are three atoms of carbon, in the form of different groups: $-CH_2$, -CH- and $–CH_3$. The C-H stretching vibration of a benzene ring was identified as the source of the PPS raw material's absorption band peak at 3063 cm-1. The peaks at 1090 and 1072 cm^{-1} were attributed to S-C6H4-S's C-S bond stretching, while those at 1572, 1470, and 1385 cm^{-1} were assigned to S-C_6H_4-S's benzene ring stretching. The C-H bending modes were ascribed to the peaks at 1008 and 804 cm^{-1}.

Physical Properties

From Table 4, N2 shows a greater fabric thickness. This is because of pre needling, the fibre is not pressed down during the final needling. The individual pre-needled webs create voids when laid down together, resulting in a higher thickness for the final nonwoven compared to the others. On the other side, N0 shows a lower thickness. The individual webs are laid down at a right angle on top of the others alternatively. The fibres are aligned in both machine and cross direction. Due to this the web is not exposed to tension and is drafted in the machine's direction because of the delivery rollers. Similarly, it is drafted in the cross direction due to the pressing of the top needle plate. So that the fibres are forced to go downward with the needle resulting in a reduced thickness. N1 shows a lower thickness than N2 and a higher thickness than N0. There are no voids between the webs, so it is pressed more and results in less thickness than N2. However, there is a tendency to draft due to the parallel arrangement of all webs in the nonwoven structure, so N1 shows a slightly higher thickness than N0.

Table 4. Physical properties of sample needle punched nonwovens

Physical properties	Samples		
	N0	N1	N2
Thickness (mm)	3.85	4.17	4.63
GSM	467.36	379.29	386.52
Fabric density (kg/m^3)	121.34	90.96	83.40
fibre packing density	0.148402	0.111273	0.101876

The GSM of N0 is higher than N1 and N2. This is because there is less drafting, and all the fibres are entangled together in their position. In this case, a more compacted and dense fabric can be produced, leading to less thickness, higher GSM, and greater fabric density. On the other hand, N2 shows less GSM. This is because the web was drafted two times during the pre-needing and final needling. So that high thickness, less GSM and density of nonwoven fabric is achieved. A certain web weight produces less fabric weight when there is a greater needling density. The drafting and spreading of fibres during punching, which increases with the number of needles, is what causes the decrease in fabric weight. The web is drawn through the needling zone between the bed plate and the stripper plate, resulting in an increase in length that may contribute to the decrease in fabric weight. When the needles are removed, they tend to pull the fibres back up, and the forces of recovery cause the web to spread.

Even with the same blend ratio, the different fibre lay directions and pre-needling processes in cross-laid, parallel-laid, and parallel-laid pre-needled needle-punched fabrics can lead to variations in GSM due to changes in fibre distribution, needle penetration, and overall fabric density. In the cross-laid fabric, fibres may be arranged in a more interlocked or crisscross pattern during the carding and web-laying process. Needles might penetrate the fabric at different angles due to the crisscrossing fibres, affecting the depth of entanglement, and potentially influencing GSM. This arrangement could result in a denser and more compact fabric structure, leading to a higher GSM. In the parallel-laid fabric, fibres are aligned more in the same direction, which might lead to a less dense structure compared to the cross-laid fabric. Needles might follow the same paths depending on the initial fibre alignment, potentially leading to more drafted fibre webs. This could result in a lower GSM as there may be more open spaces or voids within the fabric. In parallel Laid Pre-Needled Fabric, pre-needling involves partial entanglement of fibres before the final needling process. This pre-needling could lead to more drafted fibre webs because of passing through the machine multiple times, affecting the overall fabric density and GSM. A higher fibre packing density generally indicates a more compact and closely packed arrangement of fibres.

Mechanical Properties

Bursting Strength and Bursting Stretch

The bursting properties of sample needle-punched nonwovens are presented in Figure 6. The bursting strength of N0 is higher than the others. This is due to the perpendicular arrangement of the webs. The fibres are arranged in both directions so that the fabric can resist the bursting load applied in all directions. The other reason is that N0 has the highest density of the others, which means the fibres are entangled and create a strong cohesion force between them. So that they can resist the bursting load. Similarly, to resist the highest bursting load the fabric stretched more.

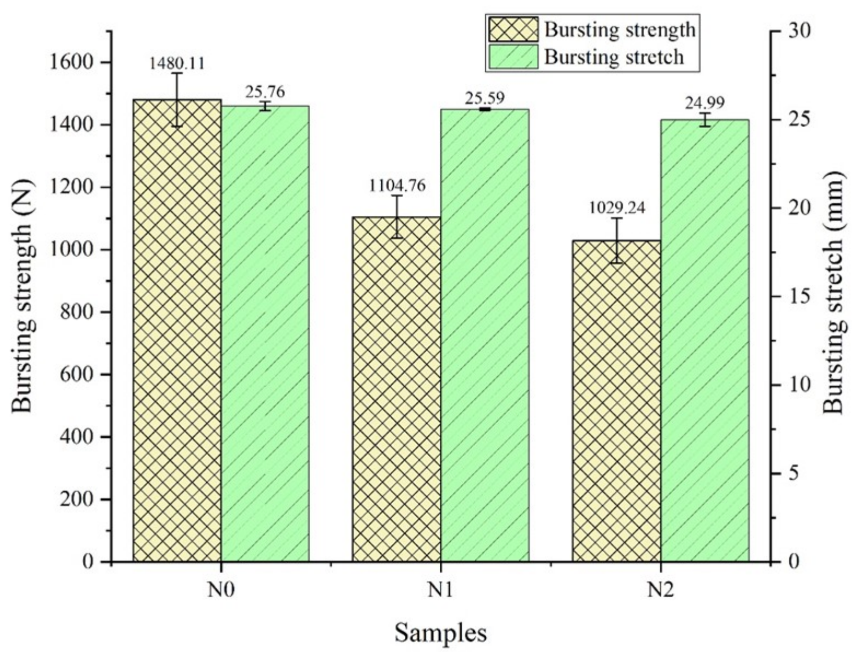

Figure 6. Bursting properties of sample needle punched nonwovens

N2 shows the lowest bursting strength. The subsequent needling of the web during pre-needling and final needling breakage of fibre has occurred. Due to this fibre breakage, the bursting strength of N2 becomes low. The total needling of N2 is eight whereas N0 and N1 are six. The GSM of N2 is low. It means it has less number of fibres in the fabric, which also affects the bursting of sample N2.

Tensile Strength and Breaking Elongation

Regarding the tensile characteristics of the textiles, the orientation of fibres in the web becomes especially significant. The tensile properties of sample needle-punched nonwovens are shown in Figure 7. The tensile strength of N1 is highest in the machine direction. This is because of the parallel arrangement of fibre webs. The fibres aligned in the machine direction, resulting from the carding process, have the opportunity to share the exposure of tensile load on the fabric. N2 shows the lowest tensile Strength in the machine direction, even if the webs are arranged in a parallel way. This is because of the subsequent needling of webs during pre-needling and final needling and fibre breakage would occur. So this fibre breakage reduces the tensile strength of sample N2.

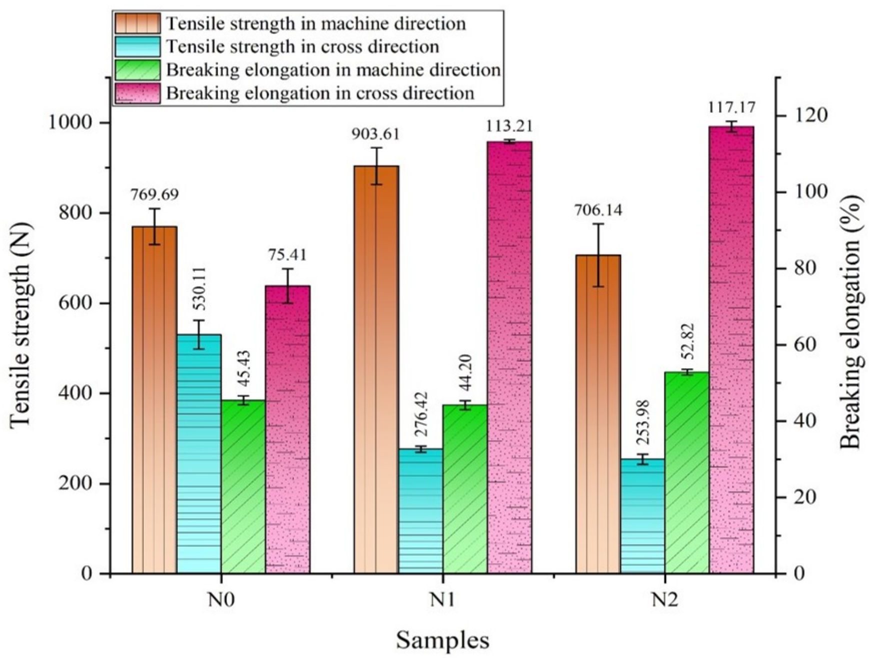

Figure 7. Tensile properties of sample needle punched nonwovens

N0 exhibits a moderate tensile strength attributed to the perpendicular arrangement of webs. In the machine direction, N0 demonstrates lower tensile strength than N1 but higher than N2. This lower strength in the machine direction compared to N1 is due to half of the fibres being oriented in the cross-direction. Notably, the decision not to pre-needle N0 results in reduced fibre breakage, contributing to a higher tensile strength in the machine direction compared to N2. Even with N0, tensile strength in the machine direction is higher because of the sliding of the fibres and resulting draft in the cross direction during needling, the tensile strength is also reduced relatively. N2 shows the highest braking elongation in the machine direction. This is due to the slippage of the pre-needle web layers because the entanglement between the pre-needle webs is less. When the webs are pre-needled, the number of non-entangled fibres is minimized. So for the final needling, the entanglement of the fibres between the webs is less. N1 shows less breaking elongation in the machine direction. When the tensile load is applied parallel to the axis of the fibres, the effect of the load is distributed on the length and has less elongation. N0 shows less elongation than N2 and higher elongations than N1. The proportional arrangement of fibre webs in both directions reduces the elongation in the machine direction. But as compared to N1, N2 elongates more because less number of fibres are aligned in the direction.

Stiffness and Abrasion Resistance

The stiffness and abrasion resistance of sample needle-punched nonwovens are presented in Figure 8. The fabric stiffness of N0 is expected to be influenced by the cross-web arrangement and high fabric density. N0 exhibits the highest fabric stiffness, attributed to its cross-web arrangement and high fabric density. Cross-web arrangement contributes to anisotropic properties, potentially impacting stiffness in both machine and cross directions. High fabric density generally leads to increased stiffness due to a more compact structure. The significant stiffness values in both machine and cross directions suggest a rigid and dense structure, making it well-suited for applications requiring robust mechanical properties.

The fabric stiffness of N1 is influenced by the parallel arrangement and medium fabric density. N1 displays moderate fabric stiffness, influenced by the parallel arrangement and a medium fabric density. Parallel arrangement may result in stiffness being more predominant in the direction of the aligned fibres. The stiffness is notably higher in the machine direction, indicating that the aligned fibres contribute to the overall rigidity of the fabric. Medium fabric density suggests a balance between compactness and openness, affecting overall stiffness.

https://doi.org/10.31881/TLR.2024.004

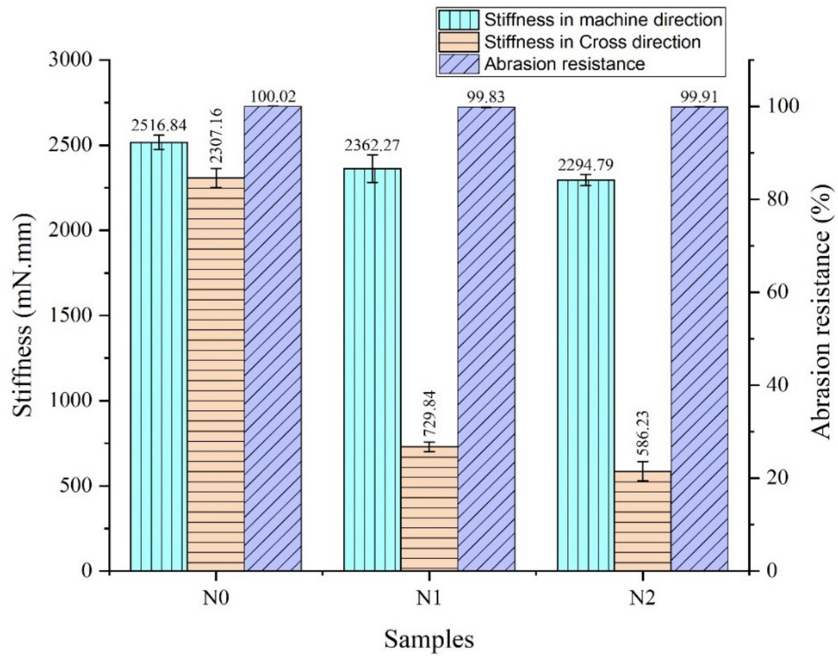

Figure 8. Stiffness and abrasion resistance of sample needle-punched nonwovens

The fabric stiffness of N2 is influenced by the pre-needling process, parallel arrangement, and relatively less fabric density. N2 shows relatively lower fabric stiffness compared to N0 and N1. Pre-needling may impact the fibre entanglement and overall compactness of the fabric. However the combination of parallel arrangement and less fabric density results in a fabric with moderate stiffness. While it maintains a certain level of stiffness, it may offer advantages in terms of flexibility and drape.

The fabric abrasion resistance analysis highlights the impact of arrangement, fabric density, and pre-needling on the ability of needle-punched nonwoven fabrics to resist wear and abrasion. N0 exhibits the highest abrasion resistance among the three samples. The combination of cross-web arrangement and high fabric density contributes to a robust structure that withstands abrasion effectively, making it suitable for applications requiring high durability. N1 demonstrates moderate abrasion resistance, influenced by the parallel arrangement and a medium fabric density. N2 shows relatively lower abrasion resistance compared to N0 but slightly higher than N1. The pre-needling, parallel arrangement and less fabric density contribute to a fabric that can still withstand abrasion well, offering a balance between flexibility and durability. N2, with pre-needling and parallel arrangement, provides a good balance between flexibility and abrasion resistance. However, the difference is not significant between the samples. All samples show good abrasion resistance. This is because of the fibre strength, excellent cohesion between the fibres and high entanglement of the fibres, providing options tailored to specific durability requirements.

Tear Strength

The tear strength values provided in Figure 9 for different needle-punched nonwoven air filters (N0, N1, and N2) in both directions provide insights into their mechanical properties. The arrangement of fibres significantly influences tear strength. In the machine direction N0, arranged in a cross-web configuration, has the highest tear strength among the three filters. This is due to the presence of fibres in the cross direction resisting the nonwoven from tearing. N1, arranged in a parallel configuration, exhibits a slightly lower tear strength compared to N0. This is because of the presence of fewer fibres arranged in the cross direction and it is easy to slip in the direction of applied force. N2, pre-needled and parallel arranged, demonstrates the lowest tear strength among the three, attributed to the absence of fibres arranged in the cross direction and the breakage of fibres during pre-needling. In the cross direction N0, arranged in a cross-web configuration, has a measurable and less tear strength than N1 and N2. N1 and N2, both arranged in a parallel configuration, did not tear under the testing conditions in the cross direction due to the presence of many fibres in the machine direction to resist the nonwoven from tearing.

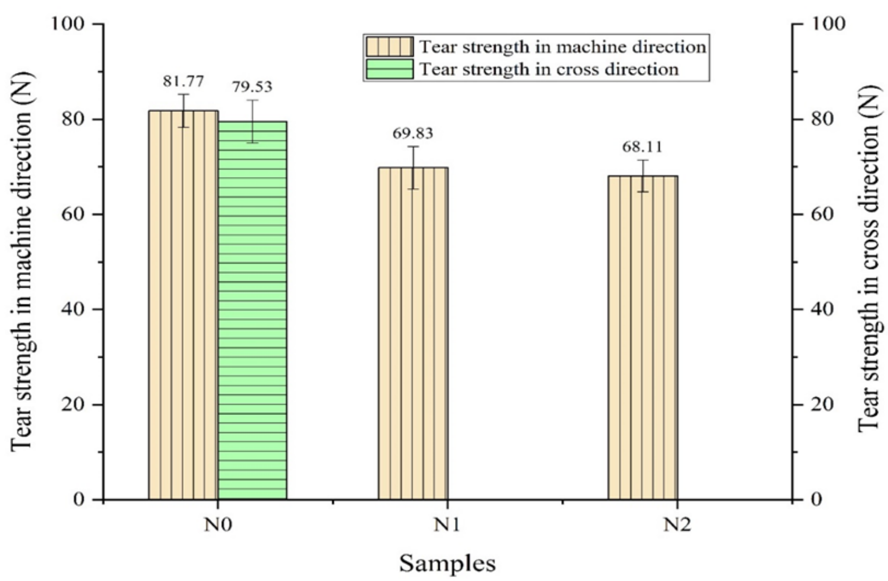

Figure 9. Tear strength of sample needle punched nonwovens

Filtration Efficiency and Pressure Drop

The air filtration efficiency values provided in Table 5 for different needle-punched nonwoven air filters (N0, N1, and N2) indicate the percentage of $PM_{2.5}$ captured by the filters during air filtration and pressure drop. The fabric density of N0 (arranged in a cross-web pattern) is the highest among the samples. In contrast, N1 (arranged in a parallel fashion) and N2 (pre-needled and parallel arranged) have a lower density. Interestingly, the filtration efficiency data (98.41%, 98.12%, and 98.10% for N0, N1, and N2, respectively) indicates that fabric density alone does not dictate filtration performance. While N0 has the highest density, N1 and N2, with lower densities, demonstrate comparable filtration efficiencies.

Air permeability, a measure of how easily air passes through a fabric, shows a trend of increasing values from N0 to N2. Higher air permeability is associated with lower pressure drop, indicating that the parallel arrangement in N1 and N2 facilitates efficient airflow. The pressure drop values (75.80 Pa, 68.12 Pa, and 66.69 Pa for N0, N1, and N2, respectively) corroborate this observation, emphasizing the influence of fabric structure on airflow resistance. This trend suggests that the parallel arrangement and pre-needling techniques contribute to a more favourable airflow resistance, resulting in lower pressure drops compared to the cross-web arrangement. Porosity, which represents the void space within a fabric, follows a similar trend as air permeability, increasing from N0 to N2. The higher porosity in N2 aligns with its lower pressure drop and enhanced airflow characteristics.

Table 5. Filtration efficiency and pressure drop of needle-punched nonwoven samples

	N0	N1	N2
Fabric density (kg/m^3)	121.34	90.96	83.40
Porosity (%)	89.96	92.47	93.11
Air Permeability ($m^3/m^2/hr$)	1722.25	1784.61	1830.26
Filtration Efficiency (%)	98.41	98.12	98.10
Pressure drop (Pa)	75.80	68.12	66.69

Fabric properties, including density, arrangement, porosity, and air permeability, are essential in optimizing the performance of nonwoven fabrics for filtration applications. The balanced blending of diverse fibres further contributes to achieving the desired filtration efficiency while maintaining acceptable pressure drop levels. The filtration efficiency results reveal consistently high performance across all samples above 98%, indicating their excellent performance in capturing airborne $PM_{2.5}$ particles with low-pressure drops.

Statistical Comparison Test Results between Samples

The summarized test results of the needle-punched nonwoven fabric in

Table 6 samples show that the mechanical properties of N0 are better than N1 and N2. The effects of web arrangement and pre-needling are statistically significant on the physical and mechanical properties of needle-punched nonwoven samples. The mean comparison between samples in physical and mechanical properties is indicated by the Tukey test. The pressure drop, thickness and bursting stretch mean difference between samples N0 and N1 is not significant at 0.05 level. This shows that the cross and parallel web arrangement does not affect the pressure drop, thickness and bursting stretch of needle-punched samples. The GSM, fabric density, bursting strength, tear strength in machine direction, abrasion resistance, pressure drop and filtration efficiency mean difference between N1 and N2 is not significant at 0.05 level. This indicates that the parallel arrangement of webs whether pre-needled or not has no effect on GSM, fabric density, bursting strength, tear strength in machine direction, abrasion resistance, pressure drop and filtration efficiency of samples. The abrasion resistance means the difference between N0-N2 is not significant at 0.05 level. This shows that cross-web arrangement and pre-needled parallel web arrangement have no difference in the effect of abrasion resistance of the samples. As depicted in Table 6, a statistically significant distinction (p-value ⩽ 0.05) in Filtration Efficiency % (p=0.000) among the samples was noted at a 0.05 significance level.

Table 6. Tested properties comparison between samples

S/N	Tested Properties	N0	N1	N2	P-value	Tukey Test		
						Sig N0-N1	Sig N0-N2	Sig N1-N2
1	Thickness(mm)	3.85	4.17	4.63	2.38036E-5	0	1	1
2	GSM	467.36	379.29	386.52	1.29847E-9	1	1	0
3	Fabric density (Kg/m^3)	122.04	91.51	83.78	4.64934E-9	1	1	0
4	Bursting strength (N)	1480.15	1104.76	1029.24	2.73115E-13	1	1	0
5	Bursting stretch (mm)	25.76	25.59	24.99	1.33571E-6	0	1	1
6	Tensile strength (N) in machine direction	769.69	903.61	706.14	1.50243E-8	1	1	1
7	Breaking elongation (%) in machine direction	45.43	44.20	52.82	1.11022E-16	1	1	1
8	Tensile strength (N) in cross direction	530.11	276.42	253.98	0.000	1	1	1
9	Breaking elongation (%) in cross-direction	75.41	113.21	117.17	0.000	1	1	1
10	Tear strength (N) in machine direction	81.77	69.83	68.11	1.31566E-8	1	1	0
11	Tear strength (N) in cross direction	79.53	No tear	No tear	-	-	-	-

S/N	Tested Properties	N0	N1	N2	P-value	Tukey Test Sig N0-N1	Sig N0-N2	Sig N1-N2
12	Stiffness (mN.mm) in Machine direction	2516.84	2362.27	2294.79	0.000	1	1	1
13	Stiffness (mN.mm) in cross-direction	2307.16	729.84	586.23	0.000	1	1	1
14	Abrasion resistance (%)	100.00	99.83	99.91	0.00762	1	0	0
15	Filtration efficiency (%)	98.41	98.12	98.10	0.000	1	1	0
16	Pressure drop (Pa)	75.80	68.12	66.69	0.01877	0	1	0

- P-value < 0.05 indicates that the difference of the means is significant at 0.05 level.
- Sig equals 1 indicates that the difference of the means is significant at 0.05 level.
- Sig equals 0 indicates that the difference of the means is not significant at 0.05 level.

CONCLUSION

The blending of diverse fibres stands as a cornerstone in the production of needle-punched nonwoven fabrics, offering a pathway to tailor mechanical properties for optimal performance. The careful consideration of fibre composition plays a pivotal role in determining crucial attributes such as tensile strength, tear resistance, burst strength, abrasion resistance, and flexibility. Recognizing the inherent limitations in mechanical properties is imperative, especially as they directly impact the filtration behaviour of needle-punched nonwovens. Challenges such as reduced tensile strength may pose durability concerns during handling, while limitations in abrasion resistance can compromise the overall efficiency by contributing to fibre shedding. The sample laid down at the right angle provided better mechanical properties; like tensile of 769.69 N, bursting of 1480.15 N, stiffness of 2516.84 mN.mm, abrasion resistance of up to 100%) and filtration efficiency of more than 98%. Whereas, samples laid down in parallel and pre-needled webs provided moderate mechanical properties and a filtration efficiency of more than 98%. The pressure drop of the samples in all cases was 66.69-75.80 Pa and possible to say it was very low.

Furthermore, this innovative synthesis of PAN, PET, PLA, PP, and PPS fibres marks a pioneering stride in filtration technology, promising advancements in efficiency, durability, and versatility. The unique properties offered by each fibre contribute to the development of an advanced filtration structure. Manufactured Needle punched samples also provide a filtration efficiency of $PM_{2.5\ of}$ more than 98% and a very low-pressure drop of 66.69-75.80 Pa. The combination of these fibres not only optimized particle capture and pressure drop but also underscored a visionary approach in materials science. Needle-punched nonwovens, boasting shorter processing times, cost-effectiveness, and the ability to yield fabrics with distinctive properties, emerge as a promising avenue for filter fabric manufacturing, further strengthened by the blending of five carefully selected fibres. The arrangement of the fibre web and the pre-needling process emerge as crucial factors, particularly in samples with a cross-laid web arrangement, showcasing superior fabric density, bursting strength, tensile strength, stiffness, and abrasion resistance—attributed that position these fabrics as optimal solutions for applications demanding exceptional mechanical properties.

REFERENCES

[1] Ferdousi US, Fayez K, Irtifa S. Non-woven. In: Rahman MM, Mashud M, Rahman MM, editors. Advanced Technology in Textiles: Fibre to Apparel. Springer; 2023. p. 233-255. https://doi.org/10.1007/978-981-99-2142-3_8

[2] Brindha R, Thilagavathi G, Viju S. Development of nettle–polypropylene-blended needle-punched nonwoven fabrics for oil spill cleanup applications. Journal of Natural Fibers. 2019; 17(10):1439-1453. https://doi.org/10.1080/15440478.2019.1578717

[3] Muthukumar N, Thilagavathi G. Development of areca husk fiber/low melt PET needle punched nonwovens for building insulation applications. Materials Today: Proceedings. 2023. https://doi.org/10.1016/j.matpr.2023.05.325

[4] Zhang Y, Lin JH, Cheng DH, Li X, Wang HY, Lu YH, Lou CW. A Study on Tencel/LMPET-TPU/Triclosan Laminated Membranes: Excellent Water Resistance and Antimicrobial Ability. Membranes. 2023; 13(8):703. https://doi.org/10.3390/membranes13080703

[5] Li J-H, Shiu B-C, Lou C-W, Hsieh J-C, Hsing W-H, Lin J-H. Mechanical properties of needle-punched/thermally treated non-woven fabrics produced from recycled materials. The Journal of The Textile Institute. 2021; 112(1):23-29. https://doi.gov/10.1080/00405000.2020.1747169

[6] Han M, Zhou C, Bi Q. Residual mechanical properties of needle-punched carbon/carbon composites after oxidation. Composites Communications. 2021; 28:100966. https://doi.org/10.1016/j.coco.2021.100966

[7] Sharma A, Choudhary M, Agarwal P, Biswas S, Patnaik A. Effect of micro-sized marble dust on mechanical and thermo-mechanical properties of needle-punched nonwoven jute fiber reinforced polymer composites. Polymer Composites. 2021; 42(2):881-898. https://doi.org/10.1002/pc.25873

[8] Venkataraman D, Shabani E, Park JH. Advancement of Nonwoven Fabrics in Personal Protective Equipment. Materials. 2023; 16(11):3964. https://doi.org/10.3390/ma16113964

[9] Fu Y, Li C, Xue M, Cao Y, Zhang W, Li D. Liquid handling properties of carboxymethyl modified chitosan nonwovens for medical dressings. Journal of Molecular Structure. 2023; 1292:136118. https://doi.org/10.1016/j.molstruc.2023.136118

[10] Konstantinova N, Erofeev O. Development of Materials for Upholstered Furniture Elements of Reduced Fire Hazard. Fibre Chemistry. 2022; 54(4):258-262. https://doi.org/10.1007/s10692-023-10389-8

[11] Zhang X, Wang Y, Liu W, Jin X. Needle-punched electret air filters (NEAFs) with high filtration efficiency, low filtration resistance, and superior dust holding capacity. Separation and Purification Technology. 2022; 282:120146. https://doi.org/10.1016/j.seppur.2021.120146

[12] Yakovleva O, Sashina E, Nabieva I. Needle punched nonwoven silk waste material with antifungal properties for air filtration. Journal of Natural Fibers. 2022; 19(17):15367-15376. https://doi.org/10.1080/15440478.2022.2125921

[13] Chauhan VK, Singh JP, Debnath S. Investigation on filtration properties of polyester needle-punched dust filter. The Journal of the Textile Institute. 2020; 111(6):897-905. https://doi.org/10.1080/00405000.2019.1676993

[14] Qadir MB, Jalalah M, Shoukat MU, Ahmad A, Khaliq Z, Nazir A, Anjum MN, Rahman A, Khan MQ, Tahir R, Faisal M, Alsaiari M, Irfan M, Alsareii SA, Harraz FA. Nonwoven/Nanomembrane Composite Functional Sweat Pads. Membranes. 2022; 12(12):1230. https://doi.org/10.3390/membranes12121230

[15] Aly NM. Fire protective textiles. In: ul-Islam S, Majumdar A, Butola B, editors. Advances in Healthcare and Protective Textiles. Woodhead Publishing; 2023. p. 203-258. https://doi.org/10.1016/B978-0-323-91188-7.00007-8

[16] Çinçik E, Koç E. The effect of blend ratio and process parameters on tensile properties of polyester/viscose blended needle-punched nonwovens. Fibers and Polymers. 2013; 14(6):1040-1049. https://doi.org/10.1007/s12221-013-1040-4

[17] Leshchenko T, Chernousova N, Dedov A, Komarova LY, Nazarov V. Mechanical Properties of Moistened Needle-Punched Nonwoven Fabric Based on Blend of Fibers with Various Linear Densities. Fibre Chemistry. 2023. https://doi.org/10.1007/s10692-023-10400-2

[18] Chauhan VK, Debnath S, Singh B. Optimizing bursting behavior of calendered needle-punched polyester fabrics. The Journal of The Textile Institute. 2022; 113(5):779-788. https://doi.org/10.1080/00405000.2021.1905301

[19] Koç E, Çinçik E. An investigation on bursting strength of polyester/viscose blended needle-punched

nonwovens. Textile Research Journal. 2012; 82(16):1621-1634. https://doi.org/10.1177/0040517511429608

[20] Patnaik PK, Swain PTR, Biswas S. Investigation of mechanical and abrasive wear behavior of blast furnace slag-filled needle-punched nonwoven viscose fabric epoxy hybrid composites. Polymer Composites. 2019; 40(6):2335-2345. https://doi.org/10.1002/pc.25090

[21] Mohammed H, Sukumar N. Water Penetration and Abrasion Resistance of Functional Nonwoven Fabrics Produced Using Recycled Cotton and Acrylic Fibers. Journal of Natural Fibers. 2022; 19(15):10001-10014. https://doi.org/10.1080/15440478.2021.1993476

[22] Gonca A, Tercan M. An Ivestigation on Abrasion Resistance And Bending Rigidity of Recycled Nonwovens Including Blanket Trimmings. Textile and Apparel. 2023; 33(2):176-184. https://doi.org/10.32710/tekstilvekonfeksiyon.938931

[23] Anuar NIS, Zakaria S, Gan S, Chia CH, Wang C, Harun J. Comparison of the morphological and mechanical properties of oil Palm EFB fibres and kenaf fibres in nonwoven reinforced composites. Industrial Crops and Products. 2019; 127:55-65. https://doi.org/10.1016/j.indcrop.2018.09.056

[24] Tshifularo C, Anandjiwala R, Patnaik A. Effect of process parameters on properties of polypropylene and kenaf fibres needle-punched nonwoven geotextiles. Indian Journal of Fibre & Textile Research. 2020; 45(3):274-285. https://doi.org/10.56042/ijftr.v45i3.25951

[25] Thilagavathi G, Muthukumar N, Neelakrishnan S, Egappan RS. Development of polyester needle-punched nonwoven fabrics for filter press applications. Journal of Industrial Textiles. 2019; 48(10):1566-1579. https://doi.org/10.1177/1528083718769929

[26] Roy R, Ishtiaque SM. Influence of Punching Parameters on Fibre Orientation and Related Physical and Mechanical Properties of Needle Punched Nonwoven. Fibers and Polymers. 2019; 20(1):191-198. https://doi.org/10.1007/s12221-019-8784-4

[27] Roy R, Ishtiaque SM, Dixit P. Impact of fibre orientation on thickness and tensile strength of needle-punched nonwoven: Optimization of carding parameters. Journal of Industrial Textiles. 2020; 51(3_suppl):4801S-4817S. https://doi.org/10.1177/1528083720910706

[28] Miao M, Glassey HE, Rastogi M. An Experimental Study of the Needled Nonwoven Process: Part III: Fiber Damage Due to Needling. Textile Research Journal. 2004; 74(6):485-490. https://doi.org/10.1177/004051750407400604

[29] Rajzer I, Grzybowska-Pietras J, Janicki J. Fabrication of bioactive carbon nonwovens for bone tissue regeneration. Fibres & Textiles in Eastern Europe. 2011; 19(84):66-72.

[30] Lin TR, Lin TA, Lin M-C, Lin Y-Y, Lou C-W, Lin J-H. Using recycled high-strength polyester and Kevlar® wastes to reinforce sandwich-structured nonwoven fabric: Structural effect and property evaluation. Journal of Cleaner Production. 2020; 267:121899. https://doi.org/10.1016/j.jclepro.2020.121899

[31] Azmami O, Sajid L, Boukhriss A, Majid S, El Ahmadi Z, Benayada A, Gmouh S. Mechanical and aging performances of Palm/ Wool and Palm/ Polyester nonwovens coated by waterborne polyurethane for automotive interiors. Industrial Crops and Products. 2021; 170:113681. https://doi.org/10.1016/j.indcrop.2021.113681

[32] Mohd Tahir AA-h, Abdul Rashid AH, Nasir SH, Ahmad M, Nor Anuwar AA. Thermal resistance and bursting strength analysis of multilayer needle-punched bamboo/polyester nonwoven batt. The Journal of The Textile Institute. 2022; 114(7):974-985. https://doi.org/10.1080/00405000.2022.2105069

[33] Jabbar A, Ali MA, Shahzad A, Naeem MS, Javed Z, Qadir MB, Rehman K, Irfan M, Ahmad Z. Development of Kapok/Recycled-PET Blended Needle-Punched Thermal Waddings. Journal of Natural Fibers. 2020; 19(3):1024-1032. https://doi.org/10.1080/15440478.2020.1784816

[34] Çinçik E, Koç E. An analysis on air permeability of polyester/viscose blended needle-punched nonwovens. Textile Research Journal. 2012; 82(5):430-442. https://doi.org/10.1177/0040517511414977

[35] Khojitmate S, M OT, Kwankhao B. A needle-punched nonwoven experiment using cotton and polyester scraps to wrap preserved fruit. Heliyon. 2022; 8(11):e11288. https://doi.org/10.1016/j.heliyon.2022.e11288

[36] Yilmaz ND, Banks-Lee P, Powell NB, Michielsen S. Effects of porosity, fiber size, and layering sequence on sound absorption performance of needle-punched nonwovens. Journal of Applied Polymer Science. 2011; 121(5):3056-3069. https://doi.org/10.1002/app.33312

[37] Yilmaz ND, Michielsen S, Banks-Lee P, Powell NB. Effects of material and treatment parameters on noise-control performance of compressed three-layered multifiber needle-punched nonwovens. Journal of Applied Polymer Science. 2011; 123(4):2095-2106. https://doi.org/10.1002/app.34712

[38] Ozen MS, Sancak E. Investigation of electromagnetic shielding effectiveness of needle punched nonwoven fabrics with staple polypropylene and carbon fibres. The Journal of The Textile Institute. 2015; 107(2):249-257. https://doi.org/10.1080/00405000.2015.1024943

[39] Shao Y, Matsushita M, Yang Y, Ohtani A, Zhao D, Liu R, Yang Y. Effect of the Carding Process and Reinforcement Method of Carbon Fiber/Polypropylene Fiber Nonwoven Fabrics on the Anisotropic

Mechanical Properties of Hot-Pressed Composites. Fibers and Polymers. 2020; 21(5):1115-1125. https://doi.org/10.1007/s12221-020-9622-4

[40] Mewoli A, Segovia C, Soppie AG, Ebanda FB, Njom AE, Ateba A, Brosse N. Investigation of the performance of needle-punched nonwoven fabrics using Triumfetta cordifolia and thermoplastic fibers, compared to other commercial bast fibers used in preformed biosourced composites. Heliyon. 2023; 9(7):e17888. https://doi.org/10.1016/j.heliyon.2023.e17888

[41] Debnath S, Madhusoothanan M. Water absorbency of jute—polypropylene blended needle-punched nonwoven. Journal of Industrial Textiles. 2010; 39(3):215-231. https://doi.org/10.1177/1528083709347121

[42] Debnath S. Thermal resistance and air permeability of jute-polypropylene blended needle-punched nonwoven. NIScPR Online Periodicals Repository. 2011; 32(2):122-131. Available from: https://nopr.niscpr.res.in/handle/123456789/11887

[43] Sengupta S. Sound reduction by needle-punched nonwoven fabrics. NIScPR Online Periodicals Repository. 2010; 35(3):237-242. Available from: https://nopr.niscpr.res.in/handle/123456789/10222

[44] Thenmozhi R, Thilagavathi G. Investigations on Kapok/Polypropylene Needle Punched Nonwoven for Thermal Resistance Applications. Journal of Natural Fibers. 2023; 20(1):2146247. https://doi.org/10.1080/15440478.2022.2146247

[45] Islam S, Mominul Alam SM. Investigation of the acoustic properties of needle punched nonwoven produced of blend with sustainable fibers. International Journal of Clothing Science and Technology. 2018; 30(3):444-458. https://doi.org/10.1108/ijcst-01-2018-0012

[46] Zhu R, Zheng J, Ni B, Zhang P. Exploration of PM2.5 filtration property of filter bag for environment protection. IOP Conference Series: Earth and Environmental Science. 2017; 69(1):012040. https://doi.org/10.1088/1755-1315/69/1/012040

[47] Wenjun D, Ruquan Z, Ying W. Chemical resistance of polyphenylene sulfide needle. In: Kim PYH, editor. Advances in Engineering Research. Proceedings of the 2016 International Forum on Energy, Environment and Sustainable Development. 16-17 April 2016. Shenzhen, China: China: Atlantis Press; 2016. p. 648-651. https://doi.org/10.2991/ifeesd-16.2016.117

[48] Wang Y, Xu Y, Wang D, Zhang Y, Zhang X, Liu J, Zhao Y, Huang C, Jin X. Polytetrafluoroethylene/Polyphenylene Sulfide Needle-Punched Triboelectric Air Filter for Efficient Particulate Matter Removal. ACS Appl Mater Interfaces. 2019; 11(51):48437-48449. https://doi.org/10.1021/acsami.9b18341

[49] Kumar Midha V. Study of stiffness and abrasion resistance of needle-punched nonwoven blankets. The Journal of the Textile Institute. 2011; 102(2):126-130. https://doi.org/10.1080/00405000903561430

[50] Dang W, Liu J, Wang X, Yan K, Zhang A, Yang J, Chen L, Liang J. Structural Transformation of Polyacrylonitrile (PAN) Fibers during Rapid Thermal Pretreatment in Nitrogen Atmosphere. Polymers. 2020; 12(1):63. https://doi.org/10.3390/polym12010063

[51] Adegbola T, Agboola O, Fayomi O. Review of polyacrylonitrile blends and application in manufacturing technology: recycling and environmental impact. Results in Engineering. 2020; 7:100144. https://doi.org/10.1016/j.rineng.2020.100144

[52] Ge Y, Fu Z, Deng Y, Zhang M, Zhang H. The effects of chemical reaction on the microstructure and mechanical properties of polyacrylonitrile (PAN) precursor fibers. Journal of Materials science. 2019; 54(19):12592-12604. https://doi.org/10.1007/s10853-019-03781-5

[53] Maduna L. Development of spunlaced nonwoven filters from PAN, PPS and PI fibres for industrial use [dissertation]. South Africa: Nelson Mandela University; 2018. 179 p. Available from: https://core.ac.uk/download/pdf/224301116.pdf.

[54] Ketema A, Worku A. Review on intermolecular forces between dyes used for polyester dyeing and polyester fiber. Journal of Chemistry. 2020; 2020:1-7. https://doi.org/10.1155/2020/6628404

[55] Palacios-Mateo C, van der Meer Y, Seide G. Analysis of the polyester clothing value chain to identify key intervention points for sustainability. Environmental Sciences Europe. 2021; 33(1):2. https://doi.org/10.1186/s12302-020-00447-x

[56] Selonen S, Dolar A, Jemec Kokalj A, Skalar T, Parramon Dolcet L, Hurley R, van Gestel CAM. Exploring the impacts of plastics in soil - The effects of polyester textile fibers on soil invertebrates. Science of The Total Environment. 2020; 700:134451. https://doi.org/10.1016/j.scitotenv.2019.134451

[57] Zaghloul MYM, Zaghloul MMY, Zaghloul MMY. Developments in polyester composite materials–An in-depth review on natural fibres and nano fillers. Composite Structures. 2021; 278:114698. https://doi.org/10.1016/j.compstruct.2021.114698

[58] Jem KJ, Tan B. The development and challenges of poly (lactic acid) and poly (glycolic acid). Advanced Industrial and Engineering Polymer Research. 2020; 3(2):60-70. https://doi.org/10.1016/j.aiepr.2020.01.002

[59] Yang HJ, Kim YK, Son JA, Choi IS, Lim SK. Preparation of modified polylactic acid fiber containing anti-hydrolysis agents. Journal of Applied Polymer Science. 2023; 140(38):e54436. https://doi.org/10.1002/app.54436

[60] Zhou L, Ke K, Yang M-B, Yang W. Recent progress on chemical modification of cellulose for high mechanical-performance Poly (lactic acid)/Cellulose composite: A review. Composites Communications. 2021; 23:100548. https://doi.org/10.1016/j.coco.2020.100548

[61] Yang Y, Zhang M, Ju Z, Tam PY, Hua T, Younas MW, Kamrul H, Hu H. Poly(lactic acid) fibers, yarns and fabrics: Manufacturing, properties and applications. Textile Research Journal. 2020; 91(13-14):1641-1669. https://doi.org/10.1177/0040517520984101

[62] Eidan J, Rasoolan I, Rezaeian A, Poorveis D. Residual mechanical properties of polypropylene fiber-reinforced concrete after heating. Construction and Building Materials. 2019; 198:195-206. https://doi.org/10.1016/j.conbuildmat.2018.11.209

[63] Wang D, Ju Y, Shen H, Xu L. Mechanical properties of high performance concrete reinforced with basalt fiber and polypropylene fiber. Construction and Building Materials. 2019; 197:464-473. https://doi.org/10.1016/j.conbuildmat.2018.11.181

[64] Wang J, Dai Q, Si R, Guo S. Mechanical, durability, and microstructural properties of macro synthetic polypropylene (PP) fiber-reinforced rubber concrete. Journal of Cleaner Production. 2019; 234:1351-1364. https://doi.org/10.1016/j.jclepro.2019.06.272

[65] Yoo D-Y, Banthia N. Impact resistance of fiber-reinforced concrete–A review. Cement and Concrete Composites. 2019; 104:103389. https://doi.org/10.1016/j.cemconcomp.2019.103389

[66] Yu Y, Xiong S, Huang H, Zhao L, Nie K, Chen S, Xu J, Yin X, Wang H, Wang L. Fabrication and application of poly (phenylene sulfide) ultrafine fiber. Reactive and Functional Polymers. 2020; 150:104539. https://doi.org/10.1016/j.reactfunctpolym.2020.104539

[67] Chen G, Mohanty AK, Misra M. Progress in research and applications of Polyphenylene Sulfide blends and composites with carbons. Composites Part B: Engineering. 2021; 209:108553. https://doi.org/10.1016/j.compositesb.2020.108553

[68] Chukov D, Nematulloev S, Zadorozhnyy M, Tcherdyntsev V, Stepashkin A, Zherebtsov D. Structure, mechanical and thermal properties of polyphenylene sulfide and polysulfone impregnated carbon fiber composites. Polymers. 2019; 11(4):684. https://doi.org/10.3390/polym11040684