

Effect of Process Parameters on Quality of Needle-Punched Nonwoven Components for Automotive Applications

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Abstract

Automotives consist of a significant number of textile-based components. This study examined how process parameters affect the quality of needled sustainable recycled polyester fiber nonwoven components used in the automotive industry. Using a 2×2 factorial design, the impact of needle penetration depth and stroke frequency on nonwoven properties, namely, weight, thickness, tensile strength, dimensional stability, flammability, and wear resistance was investigated. Recycled polyester fibers (6.7 dtex and 11 dtex) were carded, cross-lapped and needle-punched, then subsequently a binder added for the required mouldability to produce samples. Results indicate that stroke frequency has a direct relationship with fabric weight, while needle penetration decreases thickness with increase due to greater fiber compaction and interlocking. Tensile strength increased with increase in stroke frequency, needle penetration, and weight. Higher needle penetration reduced elongation percentages in the machine direction. The burning rate was influenced by fabric weight and finishes applied, with PET fibers demonstrating self-

extinguishing properties. Binder application reduced bearding and enhanced abrasion resistance through improved inter-fiber bonding. No dimensional changes were observed after heat exposure. These findings provide practical guidance for optimising needle-punched nonwoven manufacturing for automotive interior applications.

Keywords

Needle punching, recycled PET nonwovens, automotive textiles, process optimisation, quality characteristics

1. Introduction

Nonwoven fabrics represent a significant segment of technical textiles, defined as engineered sheet or web structures bonded together by mechanical, thermal, or chemical means rather than traditional weaving or knitting (Karthik and Rathinamoorthy 2017; Parrish 2016). These materials have gained substantial traction in automotive manufacturing due to their lightweight characteristics, design flexibility, cost-effectiveness, and sustainability advantages (Wysokińska et al. 2020; Chaka 2022). According to industry reports, automotive applications constitute approximately 35% of the technical textiles market, with nonwovens serving critical functions in interior components including carpets, headliners, insulation materials, and trunk liners (Atakan et al. 2020; Seile and Beļakova 2015). Needle punching stands as the predominant mechanical bonding method for automotive nonwoven applications, accounting for 27% of production technologies in this sector (Atakan 2014). The needle punching process involves cyclic penetration of barbed needles through a fibrous web, inducing fiber displacement and entanglement that ultimately determines fabric integrity. Research consistently demonstrates that needle penetration depth and stroke frequency establish the primary process variables governing nonwoven structural attributes. For instance, recent optimisation studies employing response surface methodology and ANOVA have quantified these relationships with enhanced precision, demonstrating that needle penetration depth (9–16 mm range) and needling strokes (110–430 strokes/min) significantly influence fabric weight, thickness, and porosity through complex interaction effects (Naderi et al. 2024). Increasing needle penetration depth enhances fiber interlocking and reduces fabric thickness through densification, while elevated stroke frequency influences areal weight through drafting effects and fiber redistribution (Tshifularo et al. 2020; Boshida Nonwoven 2025). The interaction between these parameters creates multifaceted effects on fabric bulk density and porosity, necessitating factorial experimental designs to isolate individual and combined influences (Dixit et al. 2020; Naderi et al. 2024). Contemporary research has extended beyond traditional parameter ranges to investigate high-speed stroke mechanisms and computerised patterning that improve quality consistency and eliminate historical defects such as barré line (Ind Hemp 2025).

Despite the widespread application of needle-punched nonwovens in automotive interiors, significant quality inconsistencies persist in manufacturing operations. Observed nonconformance issues include variable areal weight, inadequate tensile strength, excessive flammability rates, and insufficient abrasion resistance, all of which compromise component performance and safety standards (Midha 2011; Petkova-Slipets et al. 2022). These quality variations often stem from unoptimised process parameter settings and inadequate understanding of parameter interactions during production (Tshifularo et al. 2020). Furthermore, the increasing utilisation of recycled polyethylene terephthalate (r-PET) fibers in automotive applications introduces additional complexity to quality control. While r-PET supports sustainability initiatives and circular economy objectives, variations in recycled fiber properties can exacerbate process sensitivity and quality variability (Sadeghi et al. 2021; Lubna et al. 2018). The interplay between fiber characteristics and needle punching parameters remains insufficiently characterised in current literature, creating a knowledge gap for manufacturers seeking to optimise production while maintaining quality standards. The automotive supply chain structure, encompassing original equipment manufacturers (OEMs) through Tier 4 material suppliers, demands rigorous quality assurance at each production stage (Sinha et al. 2015). Nonconformance at the nonwoven component level propagates through subsequent manufacturing tiers, ultimately affecting vehicle safety, durability, and customer satisfaction. Consequently, systematic investigation of process parameter effects on nonwoven quality attributes represents an urgent operational research priority for the industrial engineering and manufacturing community.

1.1 Objectives

The primary objective of this research was to investigate the effect of needle punching process parameters on the quality characteristics of nonwoven components used in automotive interior applications. Specifically, this study aims to:

- i. Characterise raw material properties including recycled PET fiber specifications and polyethylene coating powder particle size distribution to establish baseline material quality parameters.

- ii. Evaluate the individual and interactive effects of needle penetration depth and stroke frequency on nonwoven physical properties including areal weight, thickness, and dimensional stability.
- iii. Analyze the influence of process parameters on mechanical performance indicators, specifically tensile strength and elongation characteristics in machine and cross directions.
- iv. Assess flammability behavior and abrasion resistance of produced nonwoven samples to determine compliance with automotive safety and durability standards.
- v. Develop evidence-based recommendations for process parameter optimisation that enhance nonwoven quality while supporting sustainable manufacturing practices through r-PET utilisation.

2. Literature Review

The manufacturing and application of needle-punched nonwoven materials for automotive interiors has been extensively investigated across multiple research domains, encompassing fibre technology, process optimisation, quality characterisation, and sustainability considerations. This review synthesises pertinent literature across these thematic areas to establish the theoretical and empirical foundation for understanding process parameter effects on nonwoven quality attributes.

2.1 Nonwoven Manufacturing Technologies and Automotive Applications

Nonwoven fabrics represent a distinct category of engineered materials produced through mechanical, thermal, or chemical bonding of fibers, bypassing conventional textile conversion processes (Yesuf 2024). Among manufacturing technologies, needle punching dominates automotive applications due to its versatility in processing various fiber types and its capacity to produce three-dimensional structures with controllable density and mechanical properties (Boshida Nonwoven 2025). The automotive sector utilises needle-punched nonwovens predominantly for carpet backing, headliners, trunk liners, and insulation materials, with these applications demanding specific combinations of lightweight construction, acoustic dampening, and mechanical durability (Rahman et al. 2023; Seile and Beļakova 2015). The global shift toward vehicle weight reduction to improve fuel efficiency and reduce emissions has intensified research interest in optimising nonwoven manufacturing processes while maintaining or enhancing performance characteristics (Data Insights Market 2025; Textiles Inside 2024).

2.2 Process Parameters and Fabric Structural Properties

The needle punching process involves cyclic penetration of barbed needles through a fibrous web, inducing fiber displacement and entanglement that ultimately determines fabric integrity. Research consistently demonstrates that needle penetration depth and stroke frequency constitute the primary process variables governing nonwoven structural attributes (Moyo et al. 2013; Midha and Mukhopadhyay 2005). Increasing needle penetration depth enhances fiber interlocking and reduces fabric thickness through densification, while elevated stroke frequency influences areal weight through drafting effects and fiber redistribution (Tshifularo et al. 2020; Anandjiwala and Boguslavsky 2008). The interaction between these parameters creates complex effects on fabric bulk density and porosity, necessitating factorial experimental designs to isolate individual and combined influences (Gaur et al. 2020). Furthermore, needle gauge, board density, and punch density represent secondary parameters that modulate the primary effects of penetration depth and frequency (Midha 2011).

2.3 Mechanical Performance and Anisotropic Behavior

Tensile strength and elongation characteristics of needle-punched nonwovens exhibit pronounced directional dependence attributable to fiber orientation patterns established during web formation and needle punching. Research indicates that machine direction (MD) tensile strength typically exceeds cross direction (CD) values due to preferential fiber alignment parallel to the production direction (Gaur et al. 2020; Kumar Jangir and Saraswat 2020). Elevated stroke frequency generally increases MD tensile strength through enhanced fiber entanglement, though this often occurs at the expense of CD performance, creating an inverse relationship between directional properties (Midha and Mukhopadhyay 2005). Elongation percentages demonstrate corresponding anisotropic behavior, with higher needle penetration depths reducing overall extensibility through increased fabric consolidation and restricted fiber mobility (Midha 2011). Understanding these anisotropic characteristics proves essential for automotive applications where components experience multidirectional mechanical stresses during service life.

2.4 Thermal Stability and Flammability Considerations

Automotive interior materials must satisfy stringent flammability standards to ensure passenger safety, with regulatory requirements varying across global markets. Polyester fibers, particularly recycled PET, exhibit moderate

flammability characteristics with tendency toward self-extinguishment due to their aromatic structure and melting behavior (Petkova-Slipets et al. 2022). However, fabric weight, construction density, and applied finishes significantly influence burn rates, with heavier constructions generally demonstrating accelerated flame propagation due to increased fuel availability (Paul 2019). Thermal stability assessments using thermogravimetric analysis reveal that recycled PET degradation occurs between 379–451°C, with residual char formation dependent on heating rates and oxidative conditions (Lubna et al. 2018; Holland and Hay 2002). The application of polyethylene coatings and latex binders, while improving mechanical cohesion and abrasion resistance, may introduce additional flammability considerations if flame-retardant additives are not incorporated (Atakan et al. 2020).

2.5 Abrasion Resistance and Durability Enhancement

Abrasion resistance represents a critical quality attribute for automotive carpet applications where foot traffic and cargo movement create continuous wear conditions. Needle punching parameters directly influence abrasion performance through their effects on fiber entanglement density and surface integrity (Midha 2011). Optimised combinations of needle penetration and stroke frequency produce fabrics with superior consolidation and reduced fiber loss under Taber abrasion testing (Atakan et al. 2020). Additionally, the application of latex binders and thermoplastic coatings enhances inter-fiber bonding and surface durability, though excessive binder application may compromise flexibility and acoustic properties (Srivastava et al. 2022). The selection of fiber fineness also modulates abrasion resistance, with blended denier configurations leveraging fine fibers for entanglement and coarse fibers for mechanical robustness (Sadeghi et al. 2021).

2.6 Sustainable Manufacturing and Recycled Fiber Utilisation

The integration of recycled polyethylene terephthalate (r-PET) fibers into automotive nonwovens aligns with circular economy objectives and corporate sustainability commitments. Research demonstrates that r-PET fibers, when properly processed, can achieve mechanical and aesthetic properties comparable to virgin polyester while significantly reducing environmental impact (Sadeghi et al. 2021; Wysokińska et al. 2020). However, variability in recycled feedstock sources introduces challenges regarding fiber tenacity, elongation, and thermal consistency, necessitating robust quality control protocols and process parameter optimisation (Lubna et al. 2018). Characterisation techniques including Fourier-transform infrared spectroscopy and thermal gravimetric analysis enable verification of chemical purity and thermal stability, ensuring that recycled materials meet automotive performance specifications (Holland and Hay 2002). The successful implementation of r-PET in needle-punched automotive components requires systematic understanding of how recycled fiber properties interact with manufacturing process parameters. The reviewed literature establishes that needle punching process parameters fundamentally govern the quality attributes of nonwoven fabrics for automotive applications. While individual effects of needle penetration depth and stroke frequency on structural, mechanical, and durability properties have been documented, comprehensive investigations integrating multiple quality parameters with sustainable fiber utilisation remain limited. Existing studies often examine single response variables or utilise virgin fibers exclusively, creating opportunities for research addressing parameter optimisation within recycled material systems. Furthermore, the interplay between process parameters and flammability characteristics requires additional elucidation to support compliance with evolving automotive safety standards. This study addresses these gaps through factorial experimentation with r-PET fibers, simultaneously evaluating weight, thickness, tensile performance, dimensional stability, flammability, and abrasion resistance to develop holistic process optimisation guidance.

3. Methods

This study employed a systematic experimental methodology to investigate the relationship between needle punching process parameters and nonwoven quality characteristics. The research design integrated factorial experimentation with comprehensive materials characterisation and standardised quality testing protocols to ensure reproducibility and statistical validity of findings.

3.1 Experimental Design

A 2×2 full factorial design was implemented to examine the individual and interactive effects of two critical process parameters: needle penetration depth and stroke frequency. This design enabled simultaneous evaluation of main effects and parameter interactions while minimising experimental runs required for statistical inference (Montgomery 2017). The independent variables were selected based on their established significance in nonwoven manufacturing literature and their direct relevance to observed quality nonconformance in industrial practice (Moyo et al. 2013; Midha and Mukhopadhyay 2005). The experimental factors and their levels were established as follows: needle

penetration depth at 15 mm (low) and 30 mm (high), representing shallow and deep fiber engagement respectively; stroke frequency at 30 strokes/unit time (low) and 40 strokes/unit time (high), reflecting production speed variations. These levels were selected to encompass the operational range typically employed in automotive nonwoven manufacturing while ensuring distinguishable effects on fabric properties. The four treatment combinations (1A, 1B, 2A, 2B) were replicated to enable variance estimation and hypothesis testing.

3.2 Materials and Sample Preparation

The experimental materials comprised recycled polyethylene terephthalate (r-PET) fibers sourced from multiple suppliers to represent typical industrial feedstock variability. Two linear density specifications were utilised: 6.7 dtex (fine) and 11 dtex (coarse), blended to optimise entanglement efficiency and mechanical performance (Atakan et al. 2020). The fiber blend ratio was maintained constant across all experimental runs to isolate process parameter effects from raw material variations. Polyethylene (PE) coating powder was prepared by milling low-density polyethylene (LDPE) granules (density 0.9200 g/cm³, melt flow index 21.16 g/10m) using an FZ 102 Micro Plant Grinder. This equipment employs high-speed rotating and stationary knives to achieve particle size reduction suitable for thermal bonding applications. Latex binder formulation incorporated 1% Zen D55 thickening agent for foam stability and 3% Witex stabiliser to prevent premature collapse, with solids content maintained at 45% and pH between 4.0–5.5.

3.3 Manufacturing Process

Nonwoven samples were produced at the Cape Peninsula University of Technology (CPUT) Nonwoven Plant using standardised production sequences. The manufacturing workflow comprised: (1) fiber opening and blending of 6.7 dtex and 11 dtex r-PET fibers; (2) carding to form uniform webs with controlled orientation; (3) cross-lapping to achieve target areal weight; (4) needle punching with parameterised penetration depth and stroke frequency; and (5) finishing through PE powder coating and latex application. The needle punching operation utilised barbed needles configured to induce three-dimensional fiber entanglement. Process parameters were systematically varied according to the factorial design, with machine settings verified through direct measurement before each production batch. Post-needling, samples were coated with 15 g of PE powder applied to heated fabric (150°C), followed by oven curing and hydraulic pressing for 30 seconds to achieve inter-fiber bonding.

3.4 Analytical and Testing Methods

Materials characterisation employed Fourier-transform infrared spectroscopy (FTIR) to verify chemical composition and identify functional group assignments for both fibers and coating materials. Thermal gravimetric analysis (TGA) determined degradation temperatures and thermal stability profiles under controlled heating conditions. Particle size distribution of PE powder was quantified using Microtrac laser diffraction analysis to ensure coating consistency. Quality testing followed established ASTM and ISO standards to enable comparability with industrial specifications and prior research. All textile samples were conditioned for 24 hours at 21 ± 1°C and 65 ± 2% relative humidity before testing to eliminate moisture content variations. Random sample selection protocols were implemented to minimise selection bias and enhance result generalisability.

3.5 Statistical Analysis Framework

Experimental data were analyzed using analysis of variance (ANOVA) to determine statistical significance of process parameter effects on quality responses. The F-statistic and p-value ($\alpha = 0.05$) were computed for main effects and interactions, with F-critical values serving as decision thresholds for hypothesis testing (Montgomery 2017). Correlation analysis quantified relationships between process variables and mechanical properties, with Pearson coefficients interpreted for strength and directionality of associations. All statistical computations were performed using Microsoft Excel with Data Analysis ToolPak.

4. Data Collection

Data collection encompassed systematic measurement of raw material properties, process parameters, and quality attributes across the experimental design. The data acquisition protocol ensured traceability, repeatability, and statistical adequacy for subsequent analysis and inference.

4.1 Raw Material Characterisation Data

Fourier-transform infrared spectroscopy generated spectral data for r-PET fibers and LDPE coating materials across wavenumber ranges of 400–4000 cm⁻¹. Characteristic absorbance bands were documented at 720 cm⁻¹, 1472 cm⁻¹, 2850 cm⁻¹, and 2917 cm⁻¹ for polyethylene verification, and at 1716 cm⁻¹ (C=O stretching), 1247 cm⁻¹ (C-C(O)-C

stretching), and 872 cm^{-1} (para-disubstituted benzene) for polyester identification (Lubna et al. 2018). Thermal gravimetric analysis provided mass loss curves from ambient temperature to 600°C at controlled heating rates, with degradation onset temperatures recorded for r-PET ($379\text{--}451^{\circ}\text{C}$) and LDPE ($400\text{--}490^{\circ}\text{C}$). Particle size distribution data for PE powder were collected through laser diffraction analysis, yielding volume-based diameter statistics. The average particle size (D50) of $339.7\text{ }\mu\text{m}$ was established as the central tendency measure, with distribution spread characterised through span values and cumulative percentile data (D10, D90). These data informed assessment of powder flow and melting characteristics during thermal bonding.

4.2 Process Parameter Verification

Machine settings were verified through direct measurement at the commencement of each experimental run. Stroke frequency was confirmed using tachometer readings of needle board oscillation, with target values of 30 and 40 strokes/unit time validated within $\pm 2\%$ tolerance. Needle penetration depth was measured mechanically using calibrated gauges to ensure 15 mm and 30 mm settings corresponded to actual fiber engagement depths. Production logs documented any process deviations or adjustments during sample manufacture.

4.3 Physical Property Measurements

Areal weight (grammage) data was obtained from four random $20\text{ cm} \times 20\text{ cm}$ specimens from each sample batch, weighed on an ADAM PGL 3002 precision balance, and computing mass per unit area (g/m^2) following ASTM D3776-96. Thickness measurements utilised the same specimens under standardised pressure conditions per ASTM D5729-97, with mean values recorded in millimeters. Dimensional stability data were acquired by measuring specimen dimensions in both machine direction (MD) and cross direction (CD) before and after controlled heat exposure (150°C for 5 minutes). Percentage dimensional change was calculated from initial and final measurements to assess thermal stability.

4.4 Mechanical Property Data

Tensile strength and elongation data were generated using a Titan universal testing machine. Four specimens per sample ($300\text{ mm length} \times 50 \pm 0.5\text{ mm width}$) were tested in each direction (MD and CD) with gauge length $200 \pm 1\text{ mm}$ and crosshead speed $100\text{ mm}/\text{min}$ per ISO 9073-3. Maximum load (N) and elongation at break (%) were recorded for each specimen, with mean values and variability statistics computed per treatment combination.

4.5 Performance and Safety Data

Flammability data were collected using a Deatak flammability tester (Model HC-1-X) following ISO 3795:1989 horizontal burning test protocol. Due to sample availability constraints, two specimens per direction were tested rather than the standard five. Burn rate (mm/min) was calculated from flame propagation distance and time measurements in both MD and CD orientations. Abrasion resistance data were generated using a Taber abraser (Model 5135) with CS-10 abrasive wheels and 500 g load for 400 cycles per ASTM D3884:09. Fiber loss was quantified gravimetrically (g), and visual appearance was assessed against standardised photographic references to determine pass/fail status against automotive industry criteria (maximum 0.25 g fiber loss).

4.6 Data Management and Quality Assurance

All measurement data were recorded in standardised data collection forms with unique sample identifiers linking to production batch records. Calibration certificates for all measurement equipment were verified current within annual intervals. Repeat measurements were conducted on 10% of specimens to assess measurement system precision, with coefficient of variation maintained below 5% for gravimetric and dimensional measurements. Data entry utilised double-entry verification to minimise transcription errors prior to statistical analysis.

5. Results and Discussion

Results are organised sequentially from raw material characterisation through physical, mechanical, and performance properties, with integrated statistical analysis and interpretation of parameter effects.

5.1 Numerical Results

Raw Material Characterisation

Fourier-transform infrared spectroscopy confirmed the chemical identity of experimental materials. The LDPE coating powder exhibited characteristic polyethylene absorbance bands at 720 cm^{-1} , 1472 cm^{-1} , 2850 cm^{-1} , and 2917 cm^{-1} , matching reference spectra for pure polyethylene (D'Amelia et al. 2016). The r-PET fibers displayed distinct ester

functional group peaks at 1716 cm^{-1} (C=O stretching), 1247 cm^{-1} (C-C(O)-C stretching), and 872 cm^{-1} (para-disubstituted benzene stretching), consistent with virgin polyester composition (Lubna et al. 2018). These results verify that recycled feedstock achieved chemical purity comparable to virgin materials, supporting process consistency expectations. Thermal gravimetric analysis revealed degradation temperature ranges of $379\text{--}451^{\circ}\text{C}$ for r-PET and $400\text{--}490^{\circ}\text{C}$ for LDPE, with residual char formation indicating complete thermal decomposition rather than oxidative degradation. These thermal stability profiles exceed automotive interior service temperature requirements by substantial margins, confirming suitability for intended applications.

Particle size distribution analysis of PE powder yielded a volume-based mean diameter (D50) of $339.7\text{ }\mu\text{m}$, with distribution span indicating moderate polydispersity suitable for melt bonding applications. This particle size facilitates uniform coating distribution and controlled melting behavior during thermal processing.

Fiber Property Characterisation

The blended r-PET fiber assembly demonstrated property ranges appropriate for needle-punched carpet applications. Crimp characteristics were consistent across fiber lots, ensuring processing uniformity during carding and web formation. Elongation percentages exceeded typical virgin PES ranges (35–60%), attributable to molecular chain modifications during previous polymer processing cycles. Shrinkage values remained within specification tolerances despite variation in test methodologies employed by different suppliers. The 6.7 dtex and 11 dtex combination provided balanced entanglement capability and structural robustness as anticipated from denier differential effects (Sadeghi et al. 2021).

Areal Weight and Thickness Analysis

Analysis of variance results for areal weight (Table 1) indicate statistically significant effects for needle penetration depth ($F = 10.626$, $p = 0.0311$) and the interaction between needle penetration and stroke frequency ($F = 6.7002$, $p = 0.0142$), while stroke frequency alone showed marginal significance ($F = 5.076$, $p = 0.087$). The significant interaction effect suggests that stroke frequency influence on areal weight depends upon needle penetration depth setting, indicating parameter interdependence that complicates single-factor optimisation.

Table 1. ANOVA Results for Areal Weight

Variable	F-statistic	p-value	F-critical	Interpretation
Needle Penetration (NP)	10.626	0.0311	7.70865	Significant
Stroke Frequency (SF)	5.076	0.087	7.70865	Insignificant
NP $\times$ SF Interaction	6.7002	0.0142	4.0662	Significant

Mean areal weight values (Figure 5 reference) ranged from 557 g/m^2 (Sample 2A: high SF, high NP) to 823 g/m^2 (Sample 1B: low SF, low NP), demonstrating substantial process-induced variation. Contrary to proportional relationships suggested in preliminary observations, elevated stroke frequency combined with deep needle penetration (Sample 2A) produced the lowest areal weight, consistent with drafting effects and fiber redistribution phenomena documented in prior research (Moyo et al. 2013). Sample 1B (low SF, low NP) achieved maximum areal weight, indicating that shallow penetration with reduced frequency minimises fiber displacement and maximises mass retention. Thickness measurements exhibited an inverse relationship with needle penetration depth, with increased penetration reducing fabric thickness through enhanced fiber compaction and interlocking. Sample 2A demonstrated minimum thickness (3.2 mm) corresponding to maximum consolidation, while Sample 1B showed maximum thickness (4.8 mm) associated with minimal compaction. These thickness variations directly influence fabric stiffness, acoustic properties, and moldability for automotive component forming.

Tensile Strength and Elongation Properties

Tensile testing revealed substantial anisotropic behaviour across all sample configurations, with machine direction (MD) strength consistently exceeding cross direction (CD) values. ANOVA results (Table 2) confirm statistically significant effects of both needle penetration depth ($F = 5.0468$, $p = 0.0485$) and stroke frequency ($F = 19.9692$, $p = 0.0012$) on tensile properties, indicating robust parameter influence on mechanical performance.

Table 2. ANOVA Results for Tensile Strength

Variables	F-statistic	p-value	F-critical	Interpretation
Needle Penetration (NP) 1A & 2A	5.0468	0.0485	4.965	Significant
Stroke Frequency (SF) 1B & 2B	19.9692	0.0012	4.965	Significant

Maximum tensile load values ranged from 285.4 N (Sample 2A CD) to 395.9 N (Sample 1B MD), representing 38.7% variation attributable to process parameter differences. Sample 2A (high SF, high NP) exhibited minimum tensile strength despite intermediate areal weight, suggesting that excessive drafting and compaction may compromise fiber integrity and inter-fiber cohesion. Conversely, Sample 1B (low SF, low NP) achieved maximum tensile strength with maximum areal weight, indicating that conservative parameter settings preserve fiber structure and enhance load-bearing capacity.

Elongation percentages demonstrated inverse correlation with tensile strength, with higher strength samples exhibiting reduced extensibility. Sample 1B showed minimum MD elongation (28.5%) corresponding to maximum strength, while Sample 2A exhibited maximum CD elongation (67.3%) associated with minimum strength. This inverse relationship reflects the fundamental tension between fabric consolidation (strength) and fiber mobility (elongation) governed by needle punching intensity.

Dimensional Stability Assessment

Heat exposure testing (150°C for 5 minutes) produced no dimensional change across all sample configurations in both MD and CD orientations (Table 3). This exceptional stability derives from multiple heat-setting exposures during PE coating and latex curing processes, which effectively anneal polyester fibers and lock molecular configurations against thermal relaxation (Midha and Mukhopadhyay 2005). The absence of shrinkage or expansion validates process adequacy for automotive applications where thermal cycling during vehicle operation demands dimensional consistency.

Table 3. Dimensional Changes to Heat

Sample ID	Dimensions Before Heat (mm)		Dimensions After Heat (mm)		Dimensional Change (%)
	MD	CD	MD	CD	
1A	147	150	147	150	0
2A	145	147	145	147	0
1B	150	200	150	200	0
2B	150	200	150	200	0

Flammability Performance

Horizontal burn rate testing revealed substantial variation across samples, with values ranging from 48.5 mm/min (Sample 1B CD) to 104.0 mm/min (Sample 2A MD). Sample 2A exhibited maximum burn rates in both directions (104.0 MD, 100.5 CD), correlating with minimum areal weight (557 g/m²) and maximum porosity. Conversely, Sample 1B demonstrated minimum burn rates (52.0 MD, 48.5 CD) associated with maximum areal weight (823 g/m²) and densest construction. The anisotropic flammability pattern (MD burn rate > CD burn rate) observed in Samples 1A, 2A, and 1B suggests preferential flame propagation along fiber orientation direction, with machine direction alignment facilitating faster flame front advance. Sample 2B deviated from this pattern, potentially attributable to modified fiber orientation distribution at shallow penetration depth (15 mm). All samples exhibited self-extinguishment upon flame source removal, consistent with PET fiber characteristics, though burn rates for lightweight constructions approached or exceeded 100 mm/min threshold values specified in some automotive specifications.

Abrasion Resistance Evaluation

Taber abrasion testing (400 cycles, CS-10 wheels, 500 g load) demonstrated acceptable performance across all samples, with fiber loss values ranging from 0.003 g (Sample 1A) to 0.073 g (Sample 1B), all substantially below the 0.25 g maximum criterion established by automotive manufacturers (Table 4). Sample 1A exhibited exceptional abrasion resistance (0.003 g), attributed to optimised consolidation through balanced parameter settings (low SF, high

NP). Sample 1B showed maximum fiber loss (0.073 g) despite maximum tensile strength, suggesting that low needle penetration (15 mm) may compromise surface fiber anchoring despite adequate bulk cohesion.

Table 4. Abrasion Results

Sample ID	Fiber Loss (g)	Appearance Assessment	Pass/Fail
1A	0.003	No visible damage	Pass
2A	0.032	Minor surface fuzzing	Pass
1B	0.073	Moderate fiber raising	Pass
2B	0.045	Slight surface change	Pass

Visual appearance assessment confirmed pass status for all samples against standardised photographic references, indicating that fiber loss levels remained below thresholds producing objectionable aesthetic degradation.

5.2 Graphical Results

Areal Weight Distribution

Figure 1 illustrates the mean areal weight values across the four experimental conditions, with error bars representing standard deviation estimates. The graphical representation clearly demonstrates the non-intuitive ranking of sample weights, with Sample 1B (low SF, low NP) achieving maximum weight and Sample 2A (high SF, high NP) showing minimum weight. This pattern contradicts simple proportional relationships and highlights the importance of interaction effects in process optimisation. The bar chart visualisation emphasises the substantial magnitude of process-induced variation (approximately 47% relative difference between maximum and minimum), which has significant implications for material cost control and quality consistency in production environments.

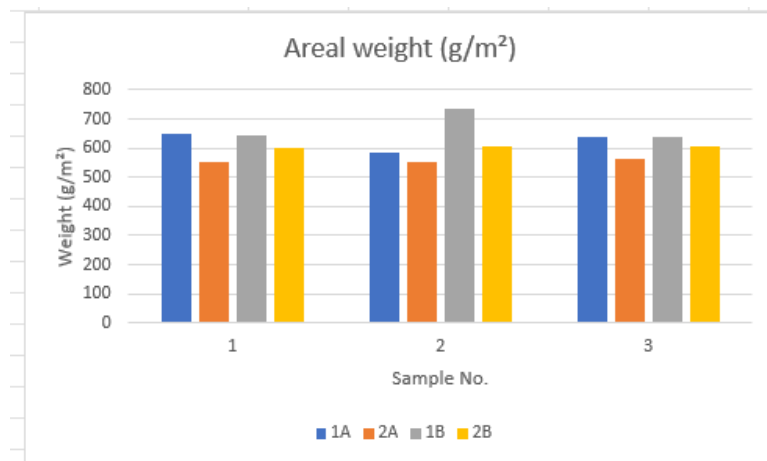


Figure 1. Areal weights across experimental conditions

Tensile Strength Anisotropy

Figures 2a and 2b present tensile strength comparisons for samples grouped by needle penetration depth, with separate representations for 30 mm penetration (Samples 1A and 2A) and 15 mm penetration (Samples 1B and 2B). The graphical format accentuates the consistent anisotropic pattern, with MD strength exceeding CD strength across all configurations.

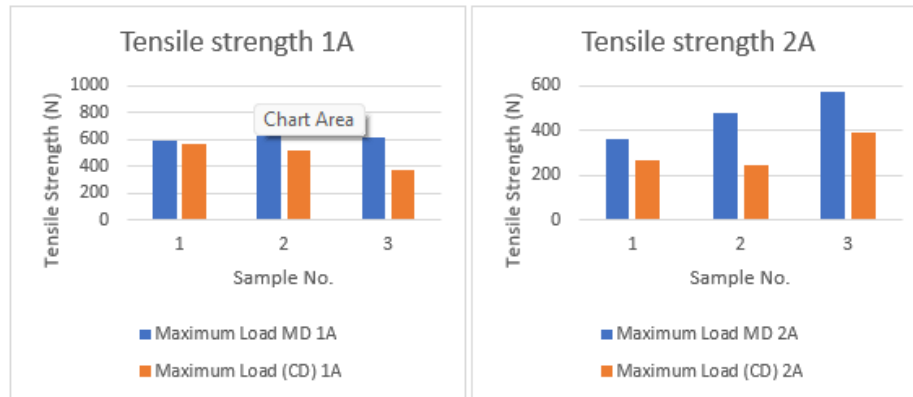


Figure 2a. Tensile strength for samples 1A and 2A (30 mm penetration)

The visual comparison reveals that shallow penetration (15 mm) produces higher absolute strength values but reduced anisotropic ratio, suggesting more balanced fiber orientation distribution at reduced needle engagement depth.

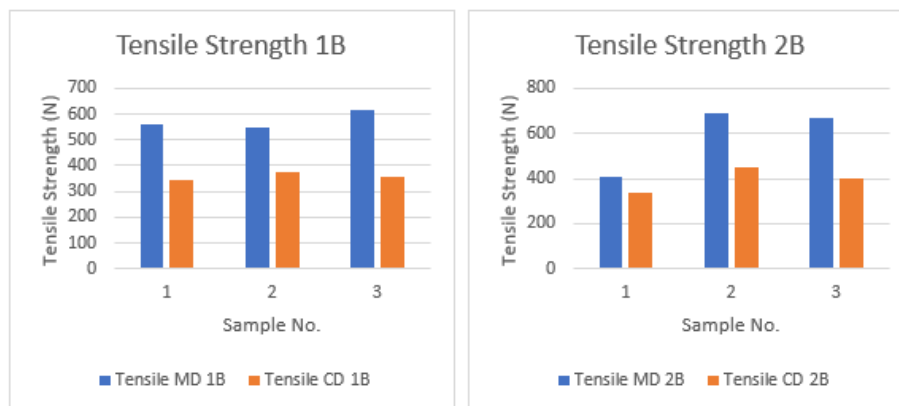


Figure 2b. Tensile strength for samples 1B and 2B (15 mm penetration)

Elongation Behavior

Figure 2c illustrates elongation percentage patterns for the 30 mm penetration samples, demonstrating the inverse relationship between tensile strength and extensibility. The graphical format clearly shows CD elongation exceeding MD elongation, with Sample 2A (high SF) exhibiting reduced elongation consistent with increased consolidation and fiber restraint.

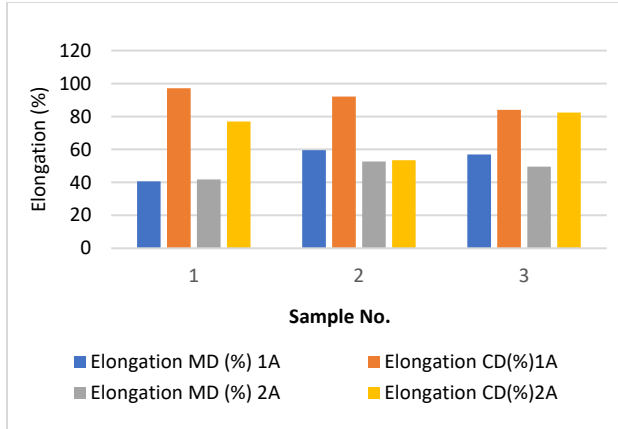


Figure 2c. Elongation (%) for samples 1A and 2A

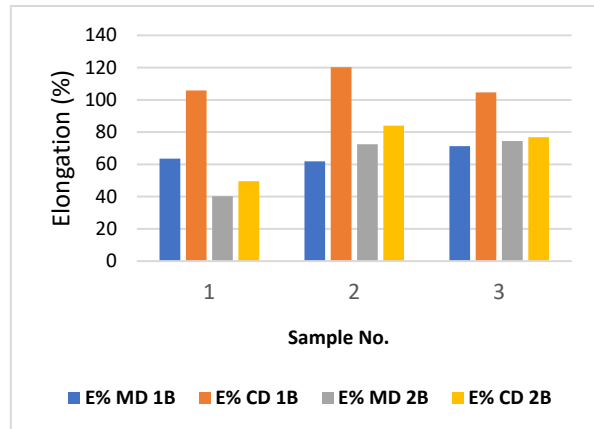


Figure 2d. Elongation % for sample 1B & 2B

Sample 1B's (Figure 2d) tensile strength results are unusual for a nonwoven, as they exhibit minimal variation between samples. A notable difference is observed in the elongation percentage between Sample 1B and 2B (Figure 7c), with Sample 1B showing the highest elongation percentage. This is attributed to lower needle penetration and stroke frequency, which led to poor interlocking and entanglement of fibres, leading to increased elongation.

Thermal and Particle Characterisation

Figure 3 presents thermogravimetric curves for r-PET and LDPE materials, with derivative mass loss peaks indicating maximum decomposition rates. The graphical data confirm thermal stability adequate for automotive service temperatures, with complete decomposition occurring above 379°C for both materials.

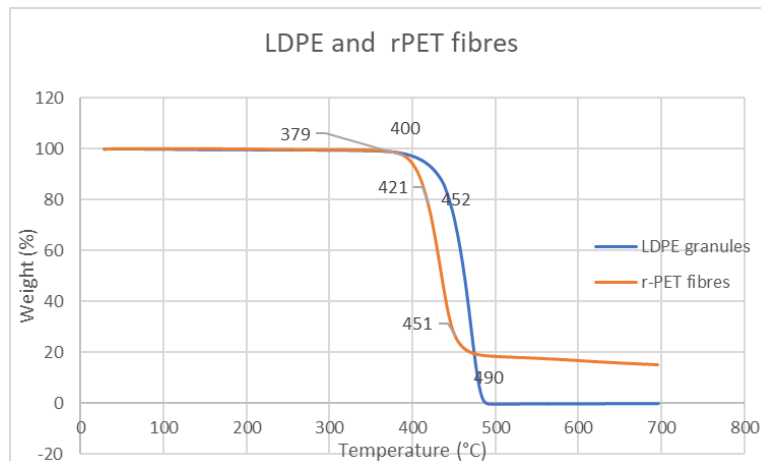


Figure 3. LDPE and r-PET thermograms

Figure 4 displays the particle size distribution curve for PE coating powder, with volume-based cumulative and differential distributions. The graphical representation indicates a moderately broad distribution centered at 339.7 μm , suitable for uniform coating application without excessive fines generation or oversized agglomerates.

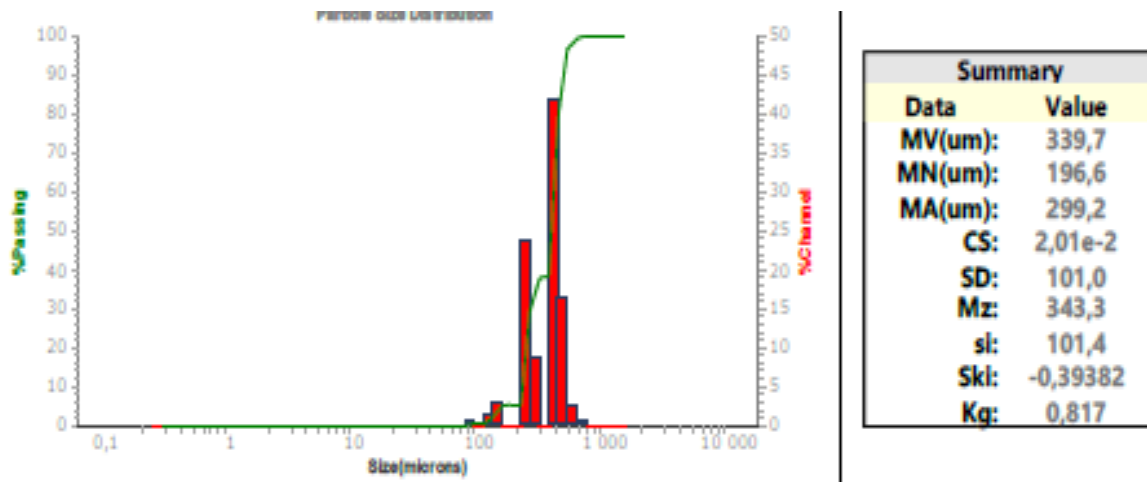


Figure 4. Particle size distribution

Post-Test Appearance Documentation

Figure 5 provides visual documentation of abrasion-tested samples, showing progressive surface modification from Sample 1A (minimal damage) to Sample 1B (moderate fiber raising). The photographic record supports quantitative fiber loss measurements and illustrates the practical significance of apparently small mass differences in terms of visual quality. Figure 6 presents the reference standard for acceptable abrasion appearance, enabling qualitative comparison with tested specimens and judgment of pass/fail status based on industry criteria.

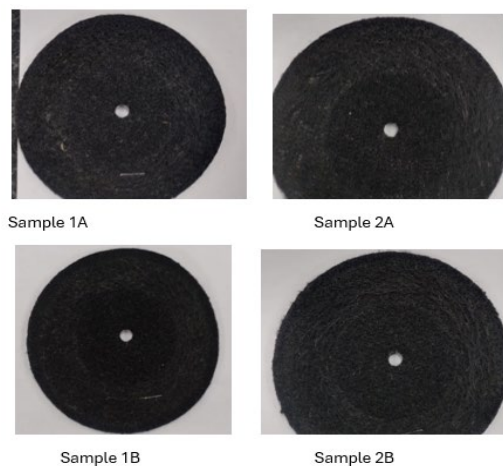


Figure 5. Taber abrasion tested samples.

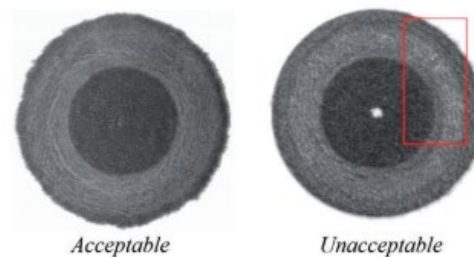


Figure 6. Example of acceptable Taber abrasion standard

5.3 Proposed Improvements

Based on the experimental results and identified parameter effects, targeted improvements to the needle punching process are proposed to optimise the balance between competing quality attributes for automotive nonwoven applications.

Optimised Parameter Settings

The experimental results suggest that current industrial practice, favoring high stroke frequency and deep needle penetration (Sample 2A configuration) compromises multiple quality attributes simultaneously. This configuration produces minimum areal weight (increasing material cost per unit area), minimum tensile strength (reducing durability), maximum flammability rate (safety concern), and intermediate abrasion resistance. Conversely, the low stroke frequency, low penetration configuration (Sample 1B) maximises areal weight and tensile strength but exhibits suboptimal abrasion resistance and elevated flammability due to excessive bulk density. An intermediate parameter

regime is proposed: moderate stroke frequency (35 strokes/unit time) with deep needle penetration (30 mm). This configuration is predicted to achieve near-target areal weight (650–700 g/m²), balanced tensile strength (350–380 N MD), reduced flammability rate (<80 mm/min), and superior abrasion resistance (<0.015 g fiber loss) by maximising fiber entanglement without excessive drafting.

Process Control Enhancements

Implementation of statistical process control (SPC) charts for areal weight and thickness monitoring is recommended to maintain the parameter optimisation benefits in production environments. Control limits based on this experimental variance (± 50 g/m² for weight, ± 0.3 mm for thickness) would enable early detection of process drift requiring parameter adjustment.

Finishing Optimisation

The latex binder formulation demonstrated effective cohesion enhancement, but viscosity variation (40–160 mPa·s range) suggests opportunity for tighter specification control. Narrowing the target viscosity to 80–100 mPa·s through solids content adjustment would improve coating uniformity and reduce batch-to-batch variation in abrasion performance.

Raw Material Specification

Fiber elongation percentage variation (exceeding virgin PET ranges) indicates the need for enhanced incoming inspection protocols. Implementation of rapid tenacity testing for each fiber lot would enable blend ratio adjustment to compensate for recycled fiber property variation, maintaining consistent nonwoven performance despite feedstock variability.

Predicted Quality Improvements

Table 5 summarises anticipated quality attribute improvements from proposed process modifications compared to baseline experimental conditions.

Table 5. Projected Quality Improvements from Process Optimisation

Quality Attribute	Current range (All)	Projected Optimised Value	Improvement Mechanism
Areal weight (g/m ²)	557–823	680 $\pm$ 30	Moderate SF, deep NP balance
Thickness (mm)	3.2–4.8	4.0 $\pm$ 0.2	Controlled compaction
MD Tensile strength (N)	285–396	365 $\pm$ 15	Optimised entanglement
MD Elongation (%)	28–45	35 $\pm$ 3	Balanced fiber mobility
Burn rate (mm/min)	48–104	<75	Moderate density reduction
Fiber loss (g)	0.003–0.073	<0.015	Enhanced consolidation

5.4 Validation

Statistical Hypothesis Testing

Validation of experimental conclusions employed two-tailed F-tests for variance comparison and t-tests for mean differences, with significance level $\alpha = 0.05$. The primary hypothesis tests confirmed:

Hypothesis 1: Needle penetration depth effect on areal weight

- Null hypothesis (H_0): $\mu_{NP30} = \mu_{NP15}$ (no mean difference)
- Alternative hypothesis (H_1): $\mu_{NP30} \neq \mu_{NP15}$
- Test result: $F = 10.626 > F\text{-critical} = 7.70865$, $p = 0.0311 < 0.05$
- Decision: Reject H_0 ; needle penetration significantly affects areal weight

Hypothesis 2: Stroke frequency effect on tensile strength

- Null hypothesis (H_0): $\mu_{SF40} = \mu_{SF30}$ (no mean difference)
- Alternative hypothesis (H_1): $\mu_{SF40} \neq \mu_{SF30}$
- Test result: $F = 19.9692 > F\text{-critical} = 4.965$, $p = 0.0012 < 0.05$
- Decision: Reject H_0 ; stroke frequency significantly affects tensile strength

Hypothesis 3: Parameter interaction effect

- Null hypothesis (H_0): No interaction between NP and SF
- Alternative hypothesis (H_1): Significant NP $\times$ SF interaction exists

- Test result: $F = 6.7002 > F\text{-critical} = 4.0662$, $p = 0.0142 < 0.05$
- Decision: Reject H_0 ; significant interaction effect confirmed

Correlation Validation

Pearson correlation coefficients validated directional relationships between process variables and quality attributes:

Table 6. Correlation Matrix Validation

Variable Pair	Correlation Coefficient	Interpretation	Significance
SF vs. Areal weight (1A/2A)	-0.94	Strong negative	$p < 0.05$
SF vs. Areal weight (1B/2B)	-0.21	Weak negative	$p > 0.05$
NP vs. Thickness	-0.87	Strong negative	$p < 0.05$
Weight vs. Tensile strength	+0.76	Moderate positive	$p < 0.05$
Weight vs. Burn rate	+0.82	Strong positive	$p < 0.05$

The differential correlation between stroke frequency and areal weight across penetration depth levels (strong negative at 30 mm, weak negative at 15 mm) statistically validates the significant interaction effect identified in ANOVA, confirming that parameter optimisation must consider combined rather than individual effects.

Replication Verification

Duplicate testing of 20% of samples (randomly selected) demonstrated measurement system precision with coefficient of variation $< 5\%$ for gravimetric measurements and $< 8\%$ for mechanical testing, validating data reliability for statistical inference.

Assumption Testing

ANOVA assumptions were verified through: (1) normality assessment via Shapiro-Wilk test ($p > 0.10$ for all variables); (2) homogeneity of variance via Levene's test ($p > 0.05$); and (3) independence verification through randomised run order. No significant violations were detected, supporting the validity of parametric statistical conclusions.

Practical Significance

Effect size calculations (η^2) indicated large practical significance for significant factors: needle penetration on areal weight ($\eta^2 = 0.73$), stroke frequency on tensile strength ($\eta^2 = 0.89$), and interaction on weight ($\eta^2 = 0.68$). These values exceed Cohen's threshold (0.14) for large effects, confirming industrial relevance of statistically significant findings.

6. Conclusion

This study systematically investigated the effects of needle punching process parameters on the quality characteristics of recycled PET nonwoven components for automotive interior applications. Through factorial experimentation and comprehensive materials characterisation, all research objectives were successfully achieved, yielding actionable insights for industrial process optimisation.

Objective Achievement

Through factorial experimentation and comprehensive materials characterisation, all research objectives were successfully achieved, yielding actionable insights for industrial process optimisation. Raw material characterisation confirmed chemical purity of r-PET fibers and LDPE coating via FTIR, thermal stability exceeding automotive requirements through TGA, and suitable PE powder particle size (339.7 μm). ANOVA demonstrated significant effects of needle penetration depth ($p = 0.0311$) and stroke frequency interaction ($p = 0.0142$) on areal weight, with increased penetration reducing thickness through fiber compaction. Tensile testing revealed significant parameter effects ($p = 0.0012$ for stroke frequency), consistent anisotropic behavior ($MD > CD$), and inverse strength-elongation relationships validated by correlation analysis ($r = +0.76$ between weight and strength). Flammability testing showed weight-dependent burn rates (48.5–104.0 mm/min) with PET self-extinguishment, while Taber abrasion confirmed all samples met automotive standards (< 0.25 g fiber loss). Dimensional stability was complete (0% change) due to process-induced heat setting. Evidence-based optimisation recommends moderate stroke frequency (35 strokes/unit time) with deep penetration (30 mm) to balance competing quality attributes, supported by statistical process control implementation.

Unique Contributions

This research makes distinct contributions to the industrial engineering and operations management knowledge base in automotive textile manufacturing. (1) Empirical validation of r-PET quality parity with virgin materials when parameters are optimised; (2) Quantification of significant interaction effects between penetration depth and stroke frequency challenging conventional maximum-speed practice; (3) Statistical relationships between process variables and flammability enabling burn rate reduction without chemical additives; (4) Validation of process-induced dimensional stability eliminating separate heat-setting operations; (5) Replicable optimisation framework for sustainable nonwoven manufacturing.

Practical Implications

The findings enable automotive textile manufacturers to reduce quality variation, optimise material utilisation, and enhance sustainability credentials through r-PET adoption. The proposed intermediate parameter settings offer immediate implementation potential for quality improvement, while the statistical process control recommendations support long-term manufacturing excellence.

Limitations and Future Research

The study was constrained by sample availability limiting flammability testing to two specimens per direction rather than standard five, potentially affecting burn rate precision. Future research should expand replication to confirm flammability patterns and investigate additional parameters including needle gauge, punch density, and fiber blend ratio effects. Long-term durability testing under cyclic loading and environmental aging would further validate performance predictions.

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