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Performance Assessment of Meltblown TPU Nanofiber-Based Air Filtration Membranes

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Abstract

Air pollution has emerged as one of the most pressing environmental challenges, primarily driven by rapid industrialization and climate-related phenomena. Within this context, nanofiber-based filter materials offering high particle capture efficiency and low pressure drop (ΔP) play a crucial role in ensuring access to clean air. In this study, nanofibrous filter surfaces based on thermoplastic polyurethane (TPU) were fabricated via the melt-blowing (MB) technique a solvent-free and high-throughput production method. The experimental design was structured using a Taguchi L9 orthogonal array, considering three processing parameters at three levels each: feeding rate (1, 5, and 10 rpm), die (nozzle) temperature (220, 240, and 260 °C), and air pressure (1, 2, and 3 bar). The morphological characteristics of the produced nanofibers were examined through scanning electron microscopy (SEM). Their AFDs, filtration efficiencies, pressure drops (ΔP), air permeabilities, and quality factors (QFs) were systematically compared. The sample produced under the optimal conditions -1 rpm feeding rate, 260 °C die temperature, and 3 bar air pressure- demonstrated the best performance, achieving a filtration efficiency of 82.12% and a ΔP of 95 Pa, with an average fiber diameter (AFD) of 423 ± 47 nm. Moreover, this optimal sample was subjected to mechanical strain levels of 5%, 10%, and 20%, and successfully preserved its functional integrity, maintaining a filtration efficiency of 71.44% even at 20% elongation. These findings highlight the potential of the melt-blown process as an environmentally friendly, rapid, scalable, and solvent-free method to produce high-performance TPU based nanofibrous air filters.

Anahtar Kelimeler: Nanofiber, Air filter, TPU, Melt-blowing

Eriyikten Üfleme Yöntemiyle Üretilmiş TPU Nanolif Bazlı Hava Filtrasyon Membranlarının Performans Değerlendirmesi

Öz

Artan sanayileşme ve iklim kaynaklı olaylar hava kirliliğini, insan sağlığını tehdit eden önemli çevresel sorunlardan biri hâline getirmiştir. Bu kapsamda, yüksek partikül tutma kapasitesine sahip, düşük basınç kaybı sunan nanolifli filtre malzemeleri, temiz hava elde etmede kritik öneme sahiptir. Bu çalışmada, melt-blowing (MB) yöntemiyle yüksek üretim hızlarında termoplastik poliüretan (TPU) bazlı nanolifli yüzeyler çözücü kullanılmadan üretilmiş ve hava filtrasyonu uygulamaları açısından performansları değerlendirilmiştir. Deneysel çalışmalar, üç farklı seviyede belirlenen besleme hızı (1, 5, 10 rpm), kalıp (nozül) sıcaklığı (220, 240, 260 °C) ve hava basıncı (1, 2, 3 bar) parametreleri doğrultusunda, Taguchi L9 ortogonal deney tasarımı ile gerçekleştirilmiştir. Üretilen nanolifli yüzeylerin morfolojik analizleri taramalı elektron mikroskobu (SEM) ile yapılmıştır. Ortalama lif çapları, filtrasyon verimlilikleri, basınç düşüşleri, hava geçirgenlikleri ve kalite faktörleri karşılaştırılmıştır. 1 rpm besleme hızı, 260 °C nozül sıcaklığı ve 3 bar hava basıncı ile üretilen numune, 423 ± 47 nm ortalama lif çapı ile %82.12 filtrasyon verimliliği ve 95 Pa basınç düşüşü sunarak en iyi performansı göstermiştir. Ayrıca bu numune, uygulanan %5, %10 ve %20 gerinim altında da filtre performansı test edilmiş; en yüksek gerinim seviyesinde dahi %71.44 oranında filtrasyon verimliliği göstererek fonksiyonel dayanıklılığını korumuştur. Elde edilen bulgular, MB yönteminin çevre dostu, hızlı, ölçeklenebilir ve çözücü içermeyen bir üretim süreci olarak TPU esaslı nanolifli hava filtreleri üretiminde önemli bir alternatif sunduğunu ortaya koymaktadır.

Keywords: Nanolif, Hava filtresi, TPU, Eriyikten üfleme.

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1. Introduction

In today's world, air pollution has become a major global public health concern, driven by increasing industrialization, urbanization, fossil fuel consumption, and climate-related disasters (Feng et al., 2024). Air pollutants are broadly categorized as gaseous or particulate matter. (Becerra Casas et al., 2020). Among them, fine and coarse particles such as dust, pollen, bacteria, viruses, and metal fragments have significant adverse effects, particularly on the human respiratory system (Papa et al., 2021). Therefore, the development of high-efficiency air filtration systems capable of capturing harmful airborne particles is of vital importance for ensuring clean air and maintaining healthy living environments (Alhussain et al., 2024).

In recent years, nanofiber-based air filters have attracted considerable attention due to their high particle capture efficiency and low pressure drop (ΔP) compared to conventional filtration media (Calisir et al., 2022; ETICHA et al., 2023; Gungor et al., 2021; Toptas et al., 2023). Their exceptionally high surface area-to-volume ratio, controllable porosity, and submicron fiber diameters enable efficient filtration of ultrafine particles, including aerosols smaller than 0.3 µm (Toptas et al., 2024a). The morphological structure of the nanofibers—largely influenced by the production method plays a key role in determining the final filter performance (Barhoum et al., 2019).

Electrospinning, one of the most common nanofiber fabrication techniques, allows for the production of ultrafine fibers with relatively uniform morphology (Balogh et al., 2015; Demina et al., 2022). Despite its advantages, the method suffers from several drawbacks, particularly its low production rate and the necessity of using organic solvents, which limits its industrial scalability and environmental compatibility (Kilic et al., 2023; Stojanovska et al., 2016). To overcome these limitations, the melt-blowing (MB) technique has gained significant attention. In this method, thermoplastic polymers are extruded in a molten state and attenuated into micro- or nanofibers by high-velocity hot air (Nayak et al., 2015). MB stands out due to its solvent-free, environmentally friendly, high-throughput, and scalable nature, making it a strong candidate for industrial-scale nanofiber filter manufacturing.

The performance of nanofibrous structures produced via MB depends on several key factors, such as fiber diameter, pore structure, mat thickness, and fiber orientation (Soltani et al., 2018). These properties, in turn, are highly sensitive to processing parameters including feeding rate, die temperature, and air pressure. Thus, systematic optimization of these parameters is essential for producing filter materials with desired performance characteristics. In this regard, Design of Experiments (DOE) methodologies, particularly the Taguchi approach, offer a robust framework for investigating the effect of multiple parameters through a reduced number of experiments and identifying optimal production conditions (Toptas et al., 2024b).

In previous studies, thermoplastic polyurethane (TPU)-based nanofibers were produced via melt-blown techniques under various conditions. For example, Lee and Wadsworth reported fiber diameters ranging from 2 to 6 µm using a die temperature of 216 °C and air temperature of 240 °C at different die-to-collector distances (Lee et al., 2007). Similarly, Zapletalova et al. (2006) processed TPU materials, producing fibers with diameters between 1–20 µm using die-to-collector distances between 14 and 30.5 cm (Zapletalova et al., 2006). More recently, Pawar et al. (2024) utilized Elastollan® B85A-based TPU and a 3D MB setup at 235 °C polymer temperature and 260 °C air temperature, yielding fibers with diameters ranging from 12.1 to 17.6 µm (Pawar et al., 2024).

Hassan et al. demonstrated meltblown membranes with average fiber diameters of 300–500 nm achieving 88% filtration efficiency at reduced basis weights while maintaining high quality factors (Hassan et al., 2013). Eticha and colleagues also developed a flexible PP TPU meltblown filter for $PM_{0.3}$ aerosols, reporting efficiencies between 80–90%, highlighting the mechanical flexibility and filtration performance trade-off (Eticha et al., 2024). Additionally, core–sheath meltblown filters containing PP and TPU achieved over 94% efficiency after 30 days of storage, indicating strong durability (Lin et al., 2024). These findings demonstrate that meltblowing techniques, especially with TPU or electret treatments, frequently deliver >80% and up to 99% efficiency, closely matching many electrospun systems.

In the present study, nanofiber-based air filters were fabricated using TPU via a MB technique, and the effects of production parameters on fiber morphology and filtration performance were systematically investigated. A three-level Taguchi L9 orthogonal array was employed to optimize feeding rate, temperature, and air pressure. The resulting samples were characterized in terms of filtration efficiency, ΔP and air permeability. Findings of the study contribute to the development of high-performance, environmentally sustainable, and scalable nanofiber filter media through an efficient melt-blown production approach.

2. Experimental Methods

2.1. Materials

TPU (BASF C95) is selected for its mechanical flexibility (elongation at break > 500%), moderate tensile strength (~30–40 MPa), and thermal stability (up to 250–270 °C), which support its usability in filter media exposed to deformation and thermal cycling.

2.2. Nanofibrous Mats Production

The nanofibers have been produced using an industrial-scale MB system developed by Areka Group LLC. The system (Figure 1) comprises a feeding unit, a heated extruder, hot air die and a movable collector unit. Prior to processing, TPU granules were thoroughly dried and fed directly into the extruder without the use of any solvents.

Unlike solvent-based techniques such as electrospinning, melt-blowing requires no toxic organic solvents, offering significant environmental and economic advantages. Solvent evaporation during electrospinning releases volatile organic compounds (VOCs), which contribute to air pollution, pose health risks, and require costly recovery or ventilation systems. Melt-blowing eliminates these concerns, reducing both environmental impact and operational complexity.

Moreover, avoiding solvent use lowers production costs by removing the need for drying and solvent handling infrastructure. This makes melt-blowing a safer, more energy-efficient, and scalable method for sustainable nanofiber fabrication.

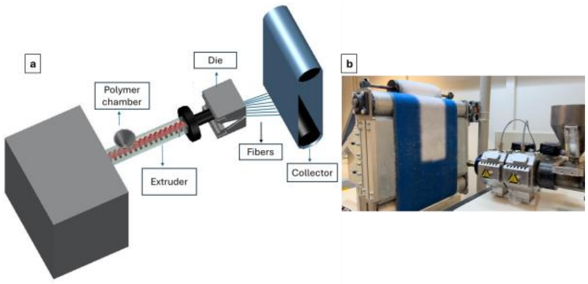

Figure 1. (a) Schematic presentation and (b) Photograph of the melt-blowing machine

During production, the nozzle-to-collector distance was set to 25 cm, while the compressed air temperature was maintained at 300 °C. In the experimental design (Table 1), three primary process parameters that influence fiber morphology in the MB process were selected: feeding rate (1, 5, and 10 rpm), nozzle temperature (220, 240, and 260 °C), and air pressure (1, 2, and 3 bar). Each parameter was evaluated at three levels, and a Taguchi L9 orthogonal array was employed to design the experimental matrix. Each produced sample was individually subjected to a comprehensive characterization process. The nanofibrous mats were collected on the collector surface with a target basis weight of approximately 20 gsm and subsequently prepared for testing under standardized conditions.

Table 1. Taguchi L9 design and average fiber diameters of the samples

Sample IDs	Feeding Rate (rpm)	Temperature (°C)	Air Pressure (bar)	AFD (nm)
1	1	220	1	543 ± 61
2	1	240	2	463 ± 51
3	1	260	3	423 ± 47
4	5	220	2	615 ± 67
5	5	240	3	553 ± 72
6	5	260	1	515 ± 55
7	10	220	3	678 ± 79
8	10	240	1	711 ± 83
9	10	260	2	643 ± 77

2.2. Characterization

The morphology of TPU nanofibers was examined using SEM at 5000× magnification with TESCAN VEGA3. The average fiber diameter (AFD) and diameter distribution were determined based on 100 individual measurements using ImageJ software for each sample.

To evaluate the influence of processing parameters on the AFD, Signal-to-Noise (S/N) ratios (Equation 1) and Analysis of Variance (ANOVA) were performed following the Taguchi method. All statistical analyses were carried out using Minitab 18 software. In the Taguchi approach, the S/N ratio can be categorized into three types: "Smaller-the-better", "Larger-the-better", and "Nominal-the-best". Since the objective of this study was to minimize fiber diameter, the "Smaller-the-better" criterion was adopted for the analysis. In this method, the term yi represents the AFD obtained from the i-th trial at a specific factor level, while n denotes the number of experimental repetitions at that level (Oktem et al., 2007).

In addition to fiber morphology, the air permeability of the nanofibrous mats was also investigated as a critical factor influencing overall filter performance. Air permeability is directly related to the porosity, fiber packing density, and thickness of the mat. Therefore, its relationship with ΔP and AFD was analyzed in detail to assess the efficiency–resistance trade-off of the filtration media.

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad \text{(Eq. 1)}$$

The air permeability of the samples was measured using an Airtest II device (Prowhite) in accordance with the ASTM D737 standard. During the tests, the sample area was fixed at 38 cm², the applied air pressure was 125 Pa, and the ambient temperature was maintained at 22 ± 2 °C and relative humidity at 50 ± 5%.

The pressure drop (ΔP) and filtration efficiency of the produced nanofibrous surfaces were evaluated using an 8130A automated filter tester (TSI Inc.). In these tests, aerosol particles with a mean diameter of 0.26 ± 0.07 µm were generated from a 2 wt.% sodium chloride (NaCl) solution. The filtration experiments were conducted by exposing the samples to these aerosols at a face velocity of 15.83 cm/s (equivalent to 95 L/min). The filtration efficiency of the samples was calculated according to Equation 2, where Cdown and Cup represent the particle concentrations downstream and upstream of the filter, respectively:

$$\eta = 1 - C_{down}/C_{up} \quad \text{(Eq. 2)}$$

To assess the overall performance of the filter samples by taking into account both efficiency and airflow resistance, the quality factor (QF) was calculated using Equation 3. This metric provides a comprehensive evaluation by penalizing filters with high pressure drop despite high efficiency:

$$QF = -\frac{ln(1-\eta)}{\Delta P} \quad \text{(Eq. 3)}$$

3. Results and Discussion

3.1. Fiber Morphology

The fiber morphology of the nanofibrous surfaces produced using the MB method with TPU polymer was evaluated based on the parameter sets defined by an orthogonal Taguchi L9 experimental design. The AFDs of the samples exhibited significant variations directly related to the processing parameters. Data obtained from SEM analyses revealed that feeding rate, temperature, and air pressure had notable effects on fiber fineness and morphological uniformity.

The smallest AFD, measured at 423 ± 47 nm, was observed in Sample 3, which was produced under the combination of the lowest feeding rate (1 rpm), highest nozzle temperature (260 °C), and highest air pressure (3 bar). Reduced viscosity facilitated melt flow and fiber elongation. As a result, finer and more uniformly distributed fibers were obtained, highlighting the synergistic effect of high temperature and air pressure on fiber refinement.

Similarly, Sample 2 (463 ± 51 nm) and Sample 6 (515 ± 55 nm), produced under intermediate temperature conditions (240 °C and 260 °C, respectively) with a moderate feeding rate (5 rpm), also exhibited relatively smaller fiber diameters, further supporting the influence of optimized thermal and flow conditions on fiber morphology.

On the other hand, the thickest fibers were observed in Sample 8 (711 ± 83 nm) and Sample 7 (678 ± 79 nm). These samples were produced under conditions that limited fiber attenuation, namely high feeding rate (10 rpm), low nozzle temperature (220–240 °C), and low air pressure (1 bar). A high feeding rate increases the amount of polymer extruded per unit time, thereby reducing the duration available for fiber elongation. As a result, the fibers tend to solidify before sufficient thinning can occur. Additionally, the combination of low processing temperature which maintains the polymer at high viscosity and inadequate drawing force due to low air pressure further contributes to the formation of thicker fibers.

SEM images of these samples revealed that the fibers were generally irregular, coarse, and in some areas, fused together, indicating morphological non-uniformity.

Samples with moderate fiber diameters, such as Sample 5 (553 ± 72 nm) and Sample 1 (543 ± 61 nm), were also identified. Although these samples were produced with low feeding rates, the relatively low temperature and air pressure limited the extent of fiber refinement. Similarly, Sample 4 (615 ± 67 nm), which was fabricated under a moderate feeding rate and low temperature, also exhibited a predominantly coarse fiber morphology.

Overall, it was concluded that a combination of low feeding rate, high processing temperature, and high air pressure is most effective in minimizing fiber diameter and achieving a uniform fiber structure. These findings underscore the sensitivity of the MB process to production parameters and highlight the critical importance of optimizing processing conditions for the successful fabrication of nanofibrous materials.

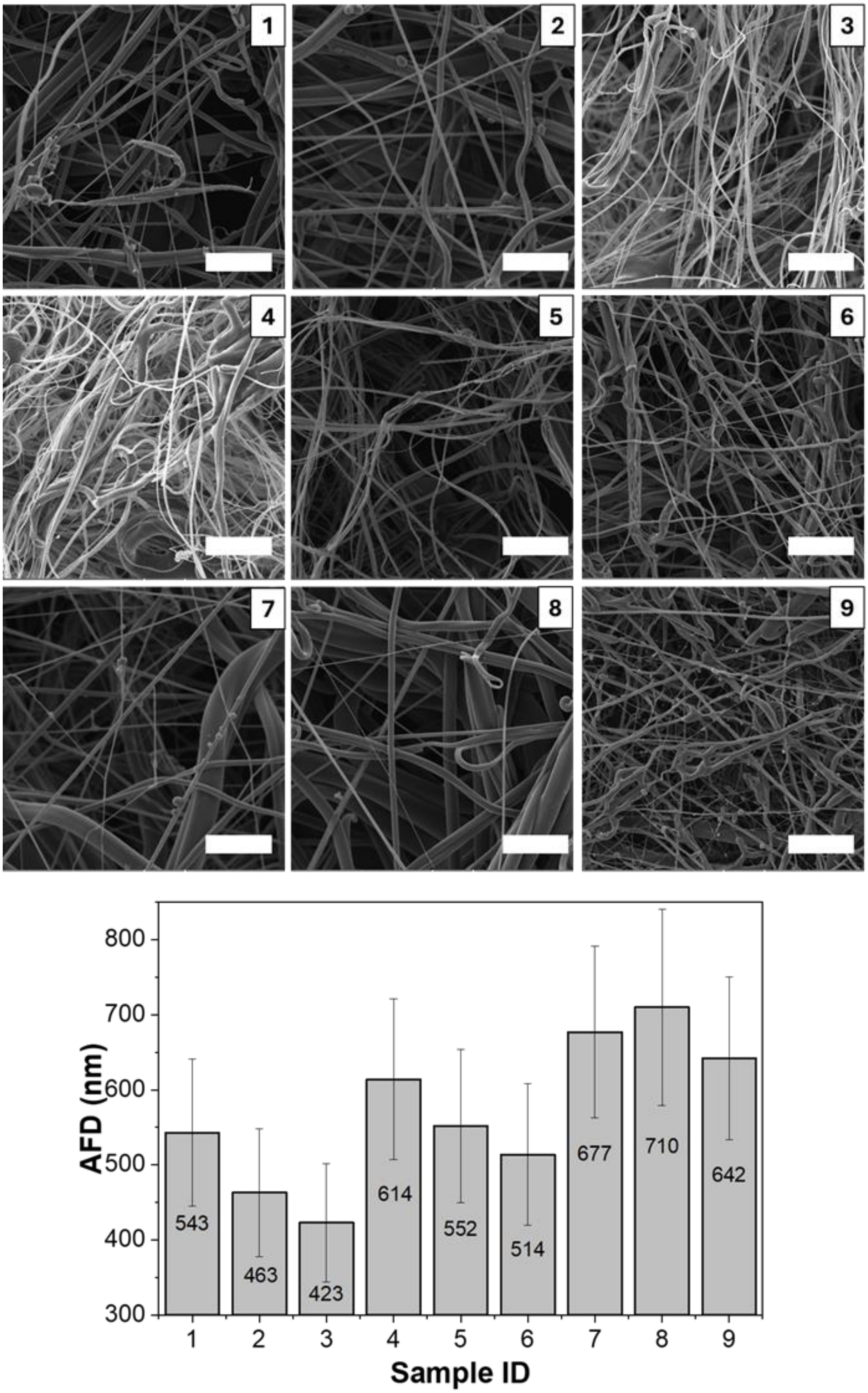

Figure 2. SEM images of the samples produced according to Taguchi Design (scale bars are 5 µm) and their AFDs.

3.2. Determination of optimum conditions

In this study, the Taguchi L9 orthogonal design approach was employed to identify the optimal processing parameters for minimizing the AFD of meltblown TPU nanofibers. Based on the "smaller-the-better" criterion, the AFD was selected as the target response variable. Three key processing parameters, feeding rate (rpm), temperature (°C), and air pressure (bar) were each evaluated at three levels. The influence of these parameters on fiber morphology was analyzed through both Signal-to-Noise (S/N) ratios and Analysis of Variance (ANOVA).

Table 2. S/N ratios of the design factors for "Smaller is better"

	Feeding Rate (rpm)	Temperature (°C)	Air Pressure (bar)
Level 1	-53.51	-55.70	-55.32
Level 2	-54.95	-55.07	-55.08
Level 3	-54.60	-54.31	-54.67
Delta	3.09	1.39	0.65
Rank	1	2	3

The S/N ratios presented in Table 2 illustrate both the stability of the experimental outcomes and the extent to which each parameter contributes to the targeted objective namely, the minimization of AFD. According to the S/N analysis, the feeding rate was identified as the most influential parameter, exhibiting the highest delta value of 3.09, indicating a much greater variation compared to the other parameters. The optimal result was obtained at a feeding rate of 1 rpm, which enables the system to process a lower amount of polymer, allowing the fibers more time to elongate and consequently form finer diameters. This can be attributed to the prolonged interaction between the polymer stream and the drawing forces in the MB system.

Temperature also proved to be a significant factor affecting fiber morphology, with a delta value of 1.39, ranking second in influence. The highest S/N ratio was observed at 260 °C, suggesting that increased temperature decreases the viscosity of the polymer, enhances melt flow, and facilitates fiber attenuation. This behavior is particularly important for elastomeric polymers like TPU, where elevated temperatures increase polymer chain mobility, leading to the formation of finer and more uniform fibers.

Table 3. Analysis of Variance for means

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Concentration	2	60851	30425.7	35.1	0.028
Air Pressure	2	10885	5442.4	6.28	0.137
Electric Voltage	2	2218	1109.1	1.28	0.439
Error	2	1734	866.8		
Total	8	75688			

Air pressure, on the other hand, was found to have the least effect on fiber diameter, with a delta value of only 0.65. While higher air pressure (3 bar) did result in finer fibers in certain samples, its overall influence was limited when compared to the other parameters suggesting limited influence of airflow on fiber diameter control.

ANOVA results in Table 3 support these findings, which quantify the statistical significance of each parameter. The feeding rate exhibited a highly significant effect on fiber diameter, with an F-value of 35.10 and p-value of 0.028 ($p < 0.05$), confirming it as the dominant factor contributing to total variance. The temperature parameter showed a moderate effect, with an F-value of 6.28 and a p-value of 0.137. Although this does not meet the conventional threshold for statistical significance, the physical impact of temperature on fiber formation is particularly evident in SEM images where higher temperatures resulted in finer and more homogeneous morphologies should not be overlooked.

In contrast, air pressure had the lowest influence, with a p-value of 0.439 and an F-value of 1.28, indicating no statistically significant effect on fiber diameter. This suggests that in MB systems, air pressure may influence secondary properties such as fiber orientation, mat thickness, or porosity, but has a limited direct impact on fiber diameter.

Based on all findings, the optimum combination of process parameters for producing TPU nanofibers with the smallest AFD was determined, as shown in Figure 3: 1 rpm feeding rate, 260 °C nozzle temperature, and 3 bar air pressure. The sample produced under these conditions exhibited the finest and most homogeneous fiber morphology, as confirmed by SEM analysis. This outcome aligns with the primary objective of the study to fabricate nanofibrous surfaces with high surface area and uniform fiber structure via an environmentally friendly and efficient MB process.

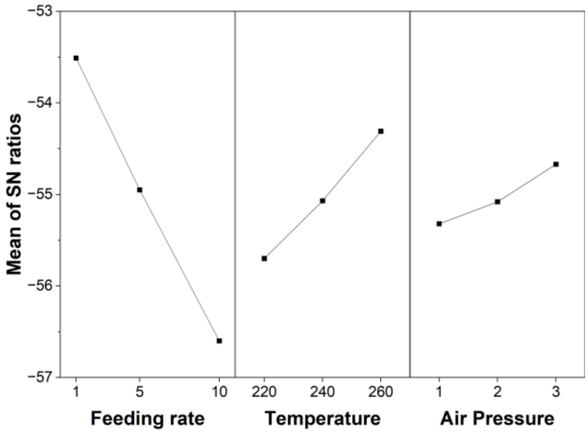

Figure 3. Main effects plot for SN ratios.

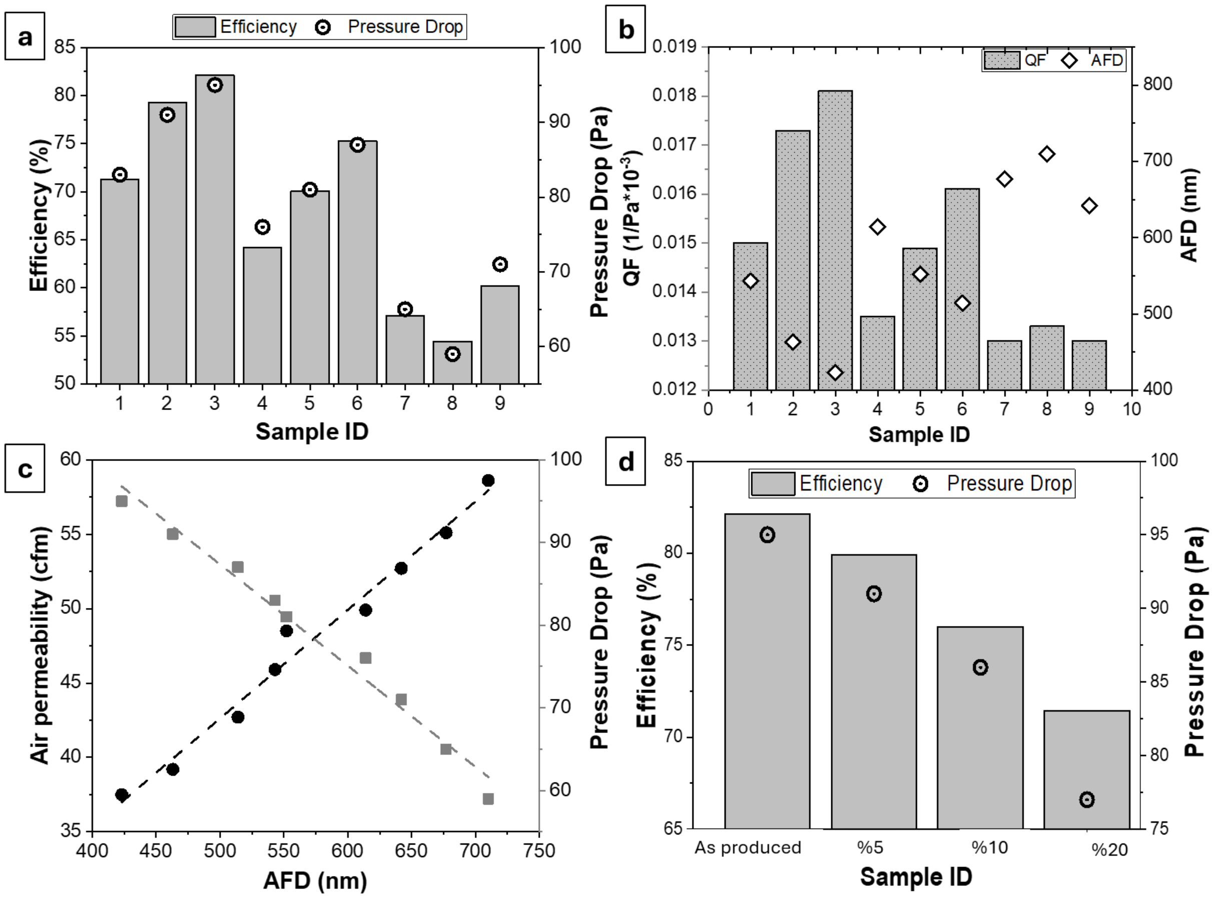

Figure 4: (a) Filtration efficiency and □P of the samples, (b) QF values, (c) air permeability and □P of the samples against AFDs and (d) filtration efficiencies at different tensions of the sample 3.

3.3. Filtration performances of the samples

The air filtration performance of the nanofibrous surfaces produced from TPU via the MB method was evaluated based on key parameters including filtration efficiency, ΔP, quality factor (QF), and air permeability. The results obtained within this scope were correlated with the morphological differences among the samples and are discussed in detail in Figure 4.

Figure 4a presents the filtration efficiency and ΔP values of all experimental groups. The highest filtration efficiency, recorded at 82.12%, was observed in Sample 3. This sample also had the smallest AFD (423 ± 47 nm), indicating that finer fibers provide greater surface area, thereby enhancing particle capture capacity. Notably, this sample was produced with the combination of the lowest feeding rate, highest nozzle temperature, and highest air pressure, which collectively promoted the formation of thinner and denser fiber structures. In contrast, Sample 8 exhibited the lowest filtration efficiency at 54.43%. This sample was fabricated at a high feeding rate, low temperature, and low air pressure conditions that limited fiber stretching. As confirmed by SEM images, it also possessed one of the largest fiber diameters (711 ± 83 nm). Thick fibers lead to larger pore sizes, reducing the available surface area for particle capture and ultimately lowering efficiency.

The ΔP data followed a similar trend. Finer fibers produced denser mats and increased ΔP. For instance, Sample 3, despite its high efficiency, exhibited a relatively elevated ΔP of 95 Pa. Conversely, Sample 8, with its thicker and more irregular fiber network, had a lower ΔP of 59 Pa, reflecting its more open and porous structure yet at the expense of filtration performance.

Figure 4b illustrates the QF values for each sample and their correlation with AFD. QF, which integrates filtration efficiency and ΔP into a single performance metric, reaches its highest values when high efficiency coincides with low resistance. As expected, Sample 3 demonstrated the highest QF, validating that optimal fiber fineness and packing density can be achieved simultaneously for improved performance. In contrast, samples with coarser fibers such as Samples 8 and 9 exhibited both lower efficiency and reduced QF values. A clear inverse relationship between fiber diameter and QF is also visible in the figure larger fibers result in a significant drop in QF, confirming fiber diameter as a critical determinant of filtration performance.

Figure 4c reveals the relationship between air permeability and ΔP. The data showed a generally linear correlation, where increasing air permeability corresponded to a decrease in ΔP. This is attributed to the influence of fiber morphology on the mat's pore structure. Samples with thicker fibers tend to have larger pore spaces, reducing air flow resistance and thus lowering ΔP. For example, Sample 8 showed high permeability and low ΔP, consistent with its thick, loosely packed fiber structure. Conversely, Sample 3, characterized by fine and tightly packed fibers, exhibited lower air permeability but significantly higher filtration efficiency, owing to its denser structure.

Figure 4d evaluates the filtration performance of Sample 3 under mechanical strain. Initially, the sample achieved the highest efficiency with a controlled ΔP. Upon application of 5%, 10%, and 20% strain, a gradual decrease in performance was observed. This indicates that TPU-based nanofibrous mats not only offer high filtration efficiency but also maintain their functional integrity under moderate mechanical deformation.

As strain increased, fiber spacing and porosity also increased, leading to reduced filtration efficiency and lower ΔP. Nevertheless, the ability of the mat to retain performance even at high deformation levels highlights its potential for flexible, durable, and long-lasting filter applications. The inherent elasticity of TPU contributes to this behavior. This indicates melt-blown TPU filters remain effective under repeated mechanical stress.

This study has shown that TPU-based nanofibrous filter surfaces can be successfully produced by the solvent-free meltblowing method and that these structures have the potential for high particle retention efficiency and mechanical durability. However, there are some research areas that need to be carried out in the future in order to transfer this production approach to wider application areas and ensure its sustainability at the industrial scale.

First, the production parameters optimized at the laboratory scale should be systematically evaluated for their equivalents at the industrial scale. Testing the meltblowing technology, which allows high production speeds, in terms of fiber homogeneity, quality control and process stability in large-scale production will reveal the applicability of the method.

Secondly, the performance durability of the nanofibrous structures obtained in this study under long-term environmental conditions (high relative humidity, UV radiation, temperature changes, mechanical stresses, etc.) was not evaluated. Such aging tests will provide an idea about the service life of the filter material in real-life conditions and increase its reliability.

Finally, improving the functional properties of filter structures is also an important focus for future studies. By incorporating functional components such as electret loading, antibacterial agents, volatile organic compound (VOC) scavengers or photocatalytic additives into the system, it will be possible to make filters multifunctional.

In this context, while the current study suggests an environmentally friendly, economical and scalable production method; topics such as performance verification, scale-up and functional extension should be addressed as priorities for future research.

4. Conclusions

In this study, nanofibrous surfaces were successfully fabricated using TPU via MB process, and their performance was evaluated for air filtration applications. Based on the optimization conducted through a Taguchi L9 experimental design, the parameter combination of 1 rpm feeding rate, 260 °C nozzle temperature, and 3 bar air pressure yielded the smallest AFD (423 ± 47 nm) and resulted in the most favorable morphology and filtration characteristics. The sample produced under these optimum conditions achieved a filtration efficiency of 82.17% and a ΔP of 95 Pa, indicating a high particle capture capability. In addition, the structure demonstrated significant functional durability, maintaining 71.44% filtration efficiency even under 20% elongation, thereby preserving its functional integrity under strain. These findings confirm that TPU-based nanofibrous mats provide a flexible and robust filtering medium suitable for demanding conditions. The MB method offers considerable advantages over conventional nanofiber production techniques, including high production speed, absence of solvents, industrial scalability, and environmental compatibility. The results obtained highlight MB as a strong alternative for large-scale production of high-efficiency nanofiber filters, particularly by enabling fiber diameters below 500 nm without the need for solution-based processes.

Author contribution

Ali Toptas confirms sole responsibility for the following: study conception and design, data collection, analysis, theoretical calculations and interpretation of results, and manuscript preparation and writing.

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Conflict of Interest Statement

Ali Toptas declares that there is no conflict of interest.

Ethical Standards:

Ethics Committee approval is not required for this study.

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