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An Experimental Design Approach to Examine the Influencing Parameters of Poly (Butylene Succinate) (PBS) Nanofibrous Nonwoven by Solution Blow Spinning

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ABSTRACT

Green polymers have gained popularity in recent decades because of increasing pollution throughout the world. Poly (butylene succinate) (PBS) is an aliphatic polyester and a relatively new polymer. The application fields of its products when combined with the solution blow spinning (SBS), method may be expanded to textiles, food, packaging, filters, batteries, and biomedical products due to its outstanding biodegradability, processability, and thermal and chemical resistance. Therefore, this study focused on the SBS process as a PBS polymer solution to scale up the nanofibers manufacturing process to the commercial level. PBS nonwovens were produced using a SBS apparatus. The PBS solution-blown nonwovens were characterized using scanning electron microscopy. A full factorial design was used to test the data for statistical analysis to investigate how solution concentration, air pressure, and flow rate influenced average fiber diameter. The impact of the process control factors was examined using analysis of variance. The thickness, air permeability and contact angle values of the material obtained under optimum conditions were also measured. The results have shown that the solution concentration significantly influences the mean diameter. The optimum SBS production parameters factors were determined to be as follows: 9 % wt. PBS concentration, 4 bar air pressure and 80 mL/h feed rate. The smallest average fiber diameter was 156 nm and the greatest average fiber diameter was 315 nm on nonwovens obtained at different production parameters. The water contact angle of PBS nonwoven was 119°. The fast and economical SBS process, coupled with the environmentally friendly nature of the PBS polymer, may contribute significantly to the industrial-scale manufacture of nanofibrous nonwoven made from this polymer.

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Solution blow spinning, Poly (butylene succinate), Green polymers, Nanofibrous nonwoven, Design of experiments

1. INTRODUCTION

The global plastics sector has been growing steadily by 10–20 million tons with annual production levels above 350 million tons, despite continuing to be primarily an oil-based industry [1]. As a result, long-term waste management and sustainability issues are a matter of great concern. Over 50 % of the plastic waste produced is dumped in open spaces, causing long-term environmental harm and decreasing the amount of land that can be used for other purposes. To accomplish comprehensive plastic life cycle management, a shift to a bio-based and circular economy has begun [2, 3]. A novel class of sustainable polymers can be created using various bio-renewable resources like biomass, microbiological sources, and agricultural products because these polymers do not produce various hazardous elements during their decomposition, making them environmentally friendly materials [3]. Poly (butylene succinate) (PBS), a new class of polyesters, has been recognized as one of the most promising alternatives to traditional oil-based polymers and is also considered to be biodegradable.

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For structural and functional uses in biomedical engineering and equipment, agriculture, water treatment systems, and packaging, bio-based polymers have shown considerable promise. Despite the need for new societal norms and technological infrastructure, sustainable material applications have obvious advantages, and their markets have been expanding significantly. PBS has good thermal characteristics, ductility, and mechanical features. Its processing capabilities and characteristics are like those of the widely used polyolefins poly(ethylene) (PE) and poly(propylene) (PP). It can be produced from petroleum- based chemicals or biobased materials and is created by the polycondensation process using succinic acid and 1,4-butanediol [4, 5].

In recent years, there has been a dramatic rise in interest in nanofibers. Solution blowing, electrospinning, melt spinning, melt blowing, and other techniques can be used to produce nanofibers. Nanofibers can be used in a diverse range of possible applications due to their astonishingly high surface-to-weight ratio [6]. For insantance, nanofibers can be used in filtration [7, 8], wound dressing [9, 10], drug delivery [11, 12], tissue engineering [13,14], batteries [15, 16] and in the manufacture of functional fabrics [17, 18]. PBS nanofiber is produced using the cheap and simple electrospinning method [19-24]. However, it has been found that increasing the production rate using this method is quite challenging. It has also been observed that solvent mixtures [19, 24] and auxiliary additives [23] are needed to improve electrospinnability.

SBS is a relatively new technology to produce nanofiber. It was developed by combining classical melt blowing with electrospinning. SBS provides a greater yield than electrospinning technology, requires less time to prepare, and has a higher utility value. The polymer solution's application range is increased since conductivity is not required. Additionally, the solution spinning process does not require high-voltage electrostatic field support, making it safer and requiring fewer devices. SBS uses a wider variety of raw materials than melt-blowing technology and has a higher level of material compatibility. Additionally, because the technique employs compressed air at room temperature, it can successfully stop the polymer's thermal degradation. SBS has attracted a lot of interest due to its adaptability and economic competitiveness. In the SBS process, which has been proposed as a novel technique for the fabrication nanofibers, polymer solutions are directly blown and attenuated to fibers using high velocity pressurized airflow [6, 25, 26]. A variety of polymers, such as poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) [27],

poly(acrylonitrile) (PAN) [28, 29], polystyrene (PS) [30], poly(methyl mathacrylate) (PMMA) [31, 32], poly(lactide) (PLA) [33-39], poly(ethylene oxide) (PEO) [40, 41], poly(ε-caprolactone) (PCL) [42, 43], poly(vinyl alcohol) (PVA) [44, 45], poly(vinyl pyrrolidone) (PVP) [46], poly(vinylidene difluoride) (PVDF) [47, 48], poly(vinyl chloride) (PVC) [49], polyurethane (PU) [50], thermoplastic polyurethane (TPU) [51], polyamic acid (PAA) [52], poly(ether ether ketone) (PEEK) [53], poly(ether sulfone) (PESU) [54], nylon [55, 56], polyaniline/polyimide (PANI/PI) [57], cellulose [58], carboxymethyl cellulose (CMC) [59], soy protein [60], chitosan [61], lignin [62], zein [63], and silk fibroin [64] are fabricated using the SBS method. Additionally, SBS technology can be used to fabricate fibers with small diameters, including TiO2 [65], ZnO [66], and Al2O3 [67] fibers. SBS can industrialize nanofibers, as indicated by the available data. According to research, SBS can produce nanofibers at a rate up to thirty times faster than electrospinning [6, 26, 25]. Recently, Park et al. have developed PBS-based nanofiber as an oil/water separation via SBS [68]. However, the influence of the SBS process parameter on the morphology of PBS nanofibrous nonwoven has not yet been investigated and is thus a major focus of this work.

In the current study, the potential for producing PBS nanofiber utilizing SBS is investigated. Firstly, the viscosities and surface tensions of the prepared solutions were characterized. Different polymer concentrations (8, 9 and 10 wt.%), air pressures (3, 4 and 5 bar), and solution flow rates (60, 70, and 80 mL/h) of the production parameters were used to investigate the effect of the process parameters on the fiber morphology of the materials (Figure 1.). The influences of independent variables on fiber diameter were assessed. The study also investigated the effect of solution viscosity and the surface tension of the prepared solution, and how they affect the resulting fiber diameter and morphology. The novel aspects of this paper are (i) a demonstration of the solution-blown solution properties of PBS and (ii) a thorough solution-blown operating parameter optimization on the basis of significant experimental results. The controllable fabrication of SBS nanofibers from PBS can be better comprehended as a result of this work. The some physical properties of the PBS nonwovens were also investigated.

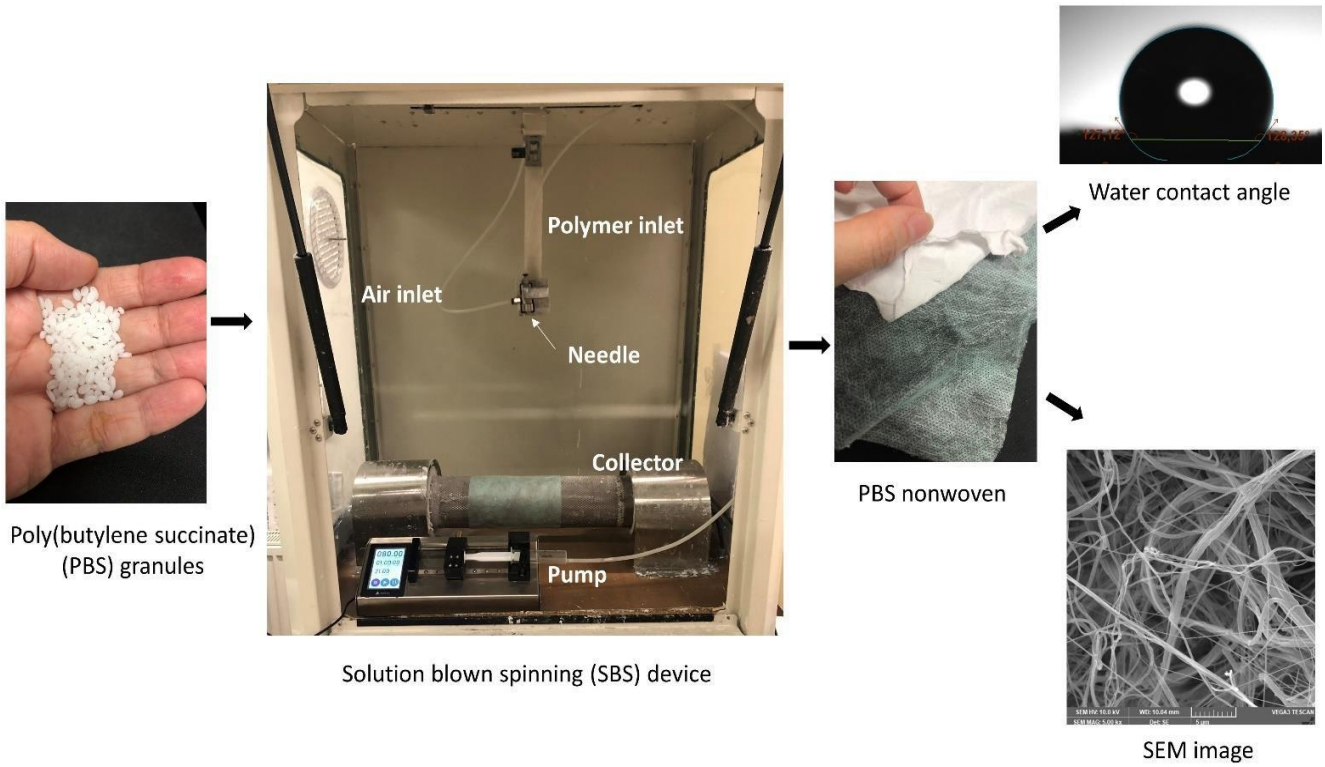

Figure 1. Scheme of the poly (butylene succinate) (PBS) nanofibrous nonwoven by solution blow spinning (SBS)

2. MATERIALS and METHOD

2.1 Production of PBS solution-blown nonwoven mats

Commercial PBS (a bio-based and biodegradable resin, FZ78TM®, melting point 115°C, density 1.26 g/cm3 and melt flow index MFI [190°C, 2.16 kg], 22 g/10 min [69]) was supplied by PTT MCC Biochem Company Ltd. (Thailand). The solvents used in this study were chloroform and ethanol from Merck & Co. which were used as received. PBS solutions with 8, 9, and 10 wt. % concentrations were prepared by dissolving in mixed solvents of chloroform and ethanol 3:1 (v/v) and continuously stirred at 400 rpm (ISOLAB GmbH, Germany) for 10 h. The bio-based and biodegradable nonwoven mats were fabricated in a lab-scale experimental design in Table 1. The PBS nonwoven was collected on the nonwovens with the help of a vacuum-assisted, rotating collector (circumference = 30 cm). All solution preparation and spinning operations were completed (temperature = 25±2 ˚C; relative humidity = 45±5%). All produced samples were stored in an oven (FN400P, Nuve, Turkey) at 50°C for 6 h to remove the residual solvent and obtain the dried samples.

2.2 Characterizations and Measurements

A rotational viscometer (Fungilab S.A., Spain) (R2 spindle) was used to measure the viscosity of the polymer solutions used in SBS at rotational speeds of 20 to 100 rpm. Measurements of viscosity were made in room conditions (temperature = 25±2 ˚C). The standard pendant drop technique was used to determine surface tension. A droplet made with a needle was photographed using a contact angle analyzer (Biolin Scientific, Finland) for five seconds after it was produced, and the picture was then analyzed using the Young-Laplace equation. The mean values and the standard deviation were calculated after each measurement was repeated three times for each sample.

Analysis of pictures from a scanning electron microscope (SEM) was used to determine the morphology of PBS nonwovens (Tescan Vega 3, Czech). For SEM analysis, 10 mm x 10 mm square samples were prepared by cutting and coated with gold/palladium. The average fiber diameters and distributions for each sample were calculated using Image software, and by randomly measuring 100 fibers for the SEM image.

The thickness of the PBS-based nonwoven textiles was measured at five points using a digital thickness gauge (Loyka 5318, Loyka Instruments, Turkey). The average and standard deviation of the findings were the reported values.

The PBS-based nonwoven fabrics were weighed using a digital balance (ABT 220-4NM, KERN Sohn GmbH, Germany) in three different samples (10×10 cm^2). The average and standard deviation of the findings were the reported values.

The air permeability test was performed using an air permeability tester (Prowhite Air permeability II, PRO-SER LTD, Turkey). The samples were settled on the test

head of the testing machine. The air permeability test was applied at 100 Pa on an area of 20 cm^2 according to ISO 9237 standard test method. The average and standard deviation of the findings were the reported values.

The wettability of the PBS samples was studied through contact angle analyzer (Biolin Scientific, Finland). The contact angle was tested by dropping distilled water on 3 different points of the sample, and the mean and standard deviation of the angle measurements on both sides of each drop were calculated.

2.3 Statistical Analysis

Design of Experiments (DoE) can be used to optimize processes to achieve targeted responses. This method is also used to determine the impact of different experimental parameters on a specific response, either cooperatively or independently. A full factorial design can identify how the factors interact while also providing exact data for response surface methodology. SBS parameters may be optimized using factorial experimental methods. Other optimization methods, however, including the Taguchi method, central composite design, and fractional factorial design have also been documented, each having unique advantages and disadvantages. The Taguchi and fractional factorial methods solution-blown machine (Aerospinner L1.0, AREKA Group Ltd., Turkey) with the prepared solutions. The PBS solutions were placed in a plastic syringe tube and fed through a metal nozzle with a 22-gauge blunt-tip needle. The nozzle-tip-to-collector distance was fixed at 30 cm, and the drum speed was considered at 100 rpm. The PBS solutions were sprayed out at a pressure of 3-5 bar, a flow rate of 60-80 mL/h, and were based on the display limited knowledge of some aspect and thereby obtain few runs. The full factorial designs offer more precise measurements for the curvature of the model in response to surface methodology.

In this study, 3^3 full factorial experimental designs with three levels and three factors were applied, a total of 27 experimental design points were tested and measurements were made for each parameter. Solution concentration, air pressure, and flow rate were selected as the independent variables and the average fiber diameter was the response value. The factor and levels are shown in Table 2. ANOVA and data analysis were performed by Minitab 16. Degrees of freedom, the sum of squares, and mean squares are indicated in the ANOVA tables by the symbols df, SS, and MS, respectively. By dividing the MS of the variable by the MS of the mistake, the F value is obtained. The ρ-value is represented by the region under the suitable null sampling distribution of F that is greater than the observed F-statistic. The parameters with ρ values less than 0.05 have a statistically significant impact on the experimental setup's response, according to the 95% confidence interval.

Table 1. Full-factorial experimental design layout

Run	Concentration (%)	Air pressure (bar)	Flow rate (mL/h)	Average fiber diameter (nm)	Standard deviation (±)	Coefficient of mass variation (%)
R1	8	3	60	224	133	59
R2	8	3	70	212	150	71
R3	8	3	80	207	146	72
R4	8	4	60	237	146	62
R5	8	4	70	209	140	67
R6	8	4	80	177	114	64
R7	8	5	60	207	102	49
R8	8	5	70	202	115	57
R9	8	5	80	193	141	73
R10	9	3	60	199	115	58
R11	9	3	70	188	141	75
R12	9	3	80	156	95	61
R13	9	4	60	218	109	50
R14	9	4	70	185	151	82
R15	9	4	80	188	148	79
R16	9	5	60	218	151	69
R17	9	5	70	202	129	64
R18	9	5	80	212	136	64
R19	10	3	60	315	177	56
R20	10	3	70	213	135	63
R21	10	3	80	198	162	82
R22	10	4	60	250	210	84
R23	10	4	70	222	148	67
R24	10	4	80	205	125	61
R25	10	5	60	237	183	77

R26	10	5	70	238	191	80
R27	10	5	80	237	148	62

Table 2. Factors and levels of the experimental design

Variable levels and range			
Factors	-1	0	1
Concentration (%)	8	9	10
Air pressure (bar)	3	4	5
Flow rate (mL/h)	60	70	80

3. RESULTS AND DISCUSSION

3.1 Properties of PBS solutions

SBS is only achievable with convenient control of a few process variables, such as the solvent evaporation rate, viscosity, and surface tension of the polymer solution. A suitable solvent evaporation rate is essential to achieve stable fiber production. The jet formation caused by the scattered droplets present on the collector will be obstructed and clogged by solvents with high evaporation rates. Instead of a fibrous web, however, solvents with low evaporation rates will cause the creation of "wet" nanofibres on the collecting fabric, leading to the production of a film of merged fibers [6, 25, 26]. PBS is soluble in various solvents such as o-chlorobenzene, 1,1,1,3,3,3-hexafluoro-2-propanol dichloromethane, and chloroform. It has been noted that the electrospun fibers obtained from the solutions prepared with chloroform are more uniform and continuous [20, 21, 24]. Chloroform has a low boiling point and high volatility, making it ideal for use in solution-blowing spinning. However, it may have negative effects on human health and the environment. Therefore, in this study, we aimed to reduce the amount of chloroform used. After examining previous studies [19, 20, 24] and conducting preliminary trials, a solution mixture of chloroform/ethanol (3:1) (*v:v*) was found to be suitable as a solution-blown solvent-blend for this study.

The attraction between the liquid molecules below the surface and the gas molecules was stronger, resulting in a net downward force that produced surface tension. The pendant drop method is one of the most popular methods used to measure the surface tension of polymer [70]. Figure 2. illustrates the surface tension quantitative findings that result from the pendant drop method in the prepared solutions. The obtained values for the PBS solutions of 8, 9, and 10 % wt. were 33.8±1.4, 30.4±2.5, and 25.9±0.2 mN/m, respectively. It was observed that the surface tension decreased as the polymer concentration increased. Lower surface tension makes it easier for fibers to reach their destination in the solid state and prevents the creation of intertwined fibers, which can lessen the formation of beads. It has already been demonstrated that the viscosity of polymer solutions affects the fiber diameter, initial droplet form, and jet trajectory during the SBS process. A limited range of suitable viscosities could encourage the growth of fibers; any decrease in viscosity below or an increase beyond that range would prevent the capacity to spin [25, 26].

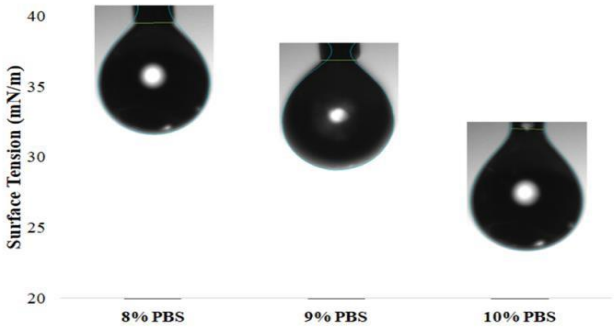

Figure 2. Surface tension measurements of PBS solutions at three concentrations (8%, 9% and 10% wt.) (The droplets that were seen are shown in the figure's inset frames)

Figure 3. demonstrates how the viscosity of PBS changed slightly when the ratio moved up from 8% to 10%. The entanglement of the polymer chains will expand as the dissolved polymer's viscosity increases because of the system's spinnability, and it will eventually reach a polymer concentration window that supports the elongation of the jet and prevents its breakdown. The prepared polymer solutions that were examined exhibited shear thinning behavior; this means that the solution viscosity decreases with higher shear rates. This indicates that these are all non-Newtonian fluids [71].

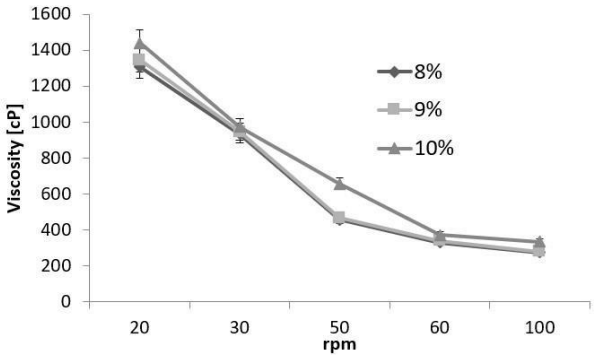

Figure 3. Viscosity measurements of PBS solutions at three concentrations (8%, 9% and 10% wt.)

3.2 Morphology of PBS nanofibrous nonwovens

3.2.1 The influence of polymer concentration on the morphology of the fibers

The literature has demostrated the dependence of the SBS process on variables such as solution concentration [33, 38, 72]. The various solutions that have been prepared, as mentioned in the experimental section are utilized in the creation of PBS nanofiber to investigate the impact of the solution concentration on the structure of the nanofiber

and the SBS process. SEM photographs of the PBS nonwovens are shown in Figures 4-6. The SEM pictures revealed that the production parameters did not have a noteworthy visual influence on the fiber morphology. Similarly, other researchers have also experienced the same situation in their work with nanofiber fabrication using the SBS method [38, 46]. However, when the diameter measurements, fiber distributions and standard deviation are carefully examined, some differences can be discerned.

The SEM images demonstrated that the PBS nanofiber exhibited randomly oriented fibers. At a concentration of 8 wt.% (Figure 4.), the fibers were successfully formed with a small quantity of droplets (Figure 4. R3: Concentration: 8%-Air pressure: 3 bar- Flow rate: 80 mL/h and R9: Concentration: 8%-Air pressure: 5 bar-Flow rate: 80 mL/h). Droplet formation is caused by inadequate solvent evaporation; hence a larger solvent content and lower viscosity values in the solution with low concentration can be used to explain why there are more droplets in the sample.

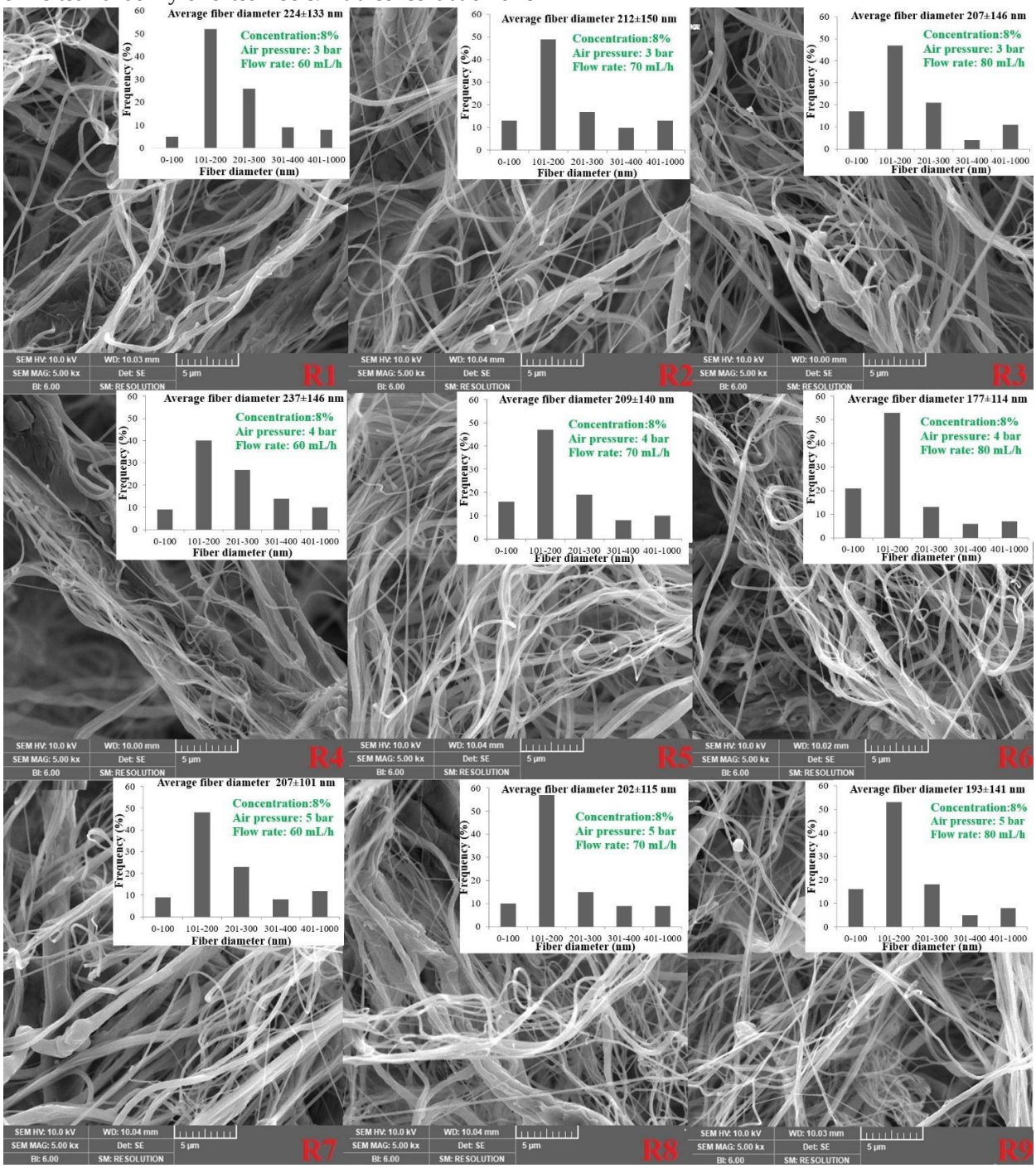

Figure 4. SEM images and fiber diameter distributions of PBS fibers (R1-R9)

There is a greater propensity for solvent molecules to separate polymer molecules from entanglement during spinning when the solvent concentration is high [41, 46]. From a solution concentration of 9 wt. %, the thinner fiber structure was seen (Figure 7). This was ascribed to the solutions' increased viscosity, which led to a drop in surface tension and ultimately led to a reduction in the production of defected structure. Further, a high solution concentration increased the fiber diameter (Figure 7), the fibers were thicker as seen in Figure 6 (R19 Concentration: 10%- Air pressure: 3 bar-Flow rate: 60 mL/h, R22: Concentration: 10%- Air pressure: 4 bar-Flow rate: 60 mL/h and R25: Concentration: 10%-Air pressure: 5 bar-Flow rate: 60 mL/h). As the solution concentration increased, the fiber diameter increased. Solution- blown PBS nanofibers typically have a satisfactory shape and fiber fineness for use in many application fields such as tissue engineering and filtration. Huang et al. [14] and Gavande et al. [73] demonstrated that PBS electospun nanofibers are excellent candidates for tissue engineering. These characteristics allow nanofibers to resemble the extracellular matrix of healthy skin or tissue and aid in the promotion of cell development and dissemination. Scaffolds, which have a structure like that of collagen, are made up of fibers with a diameter in the range of 50– 500 nm.

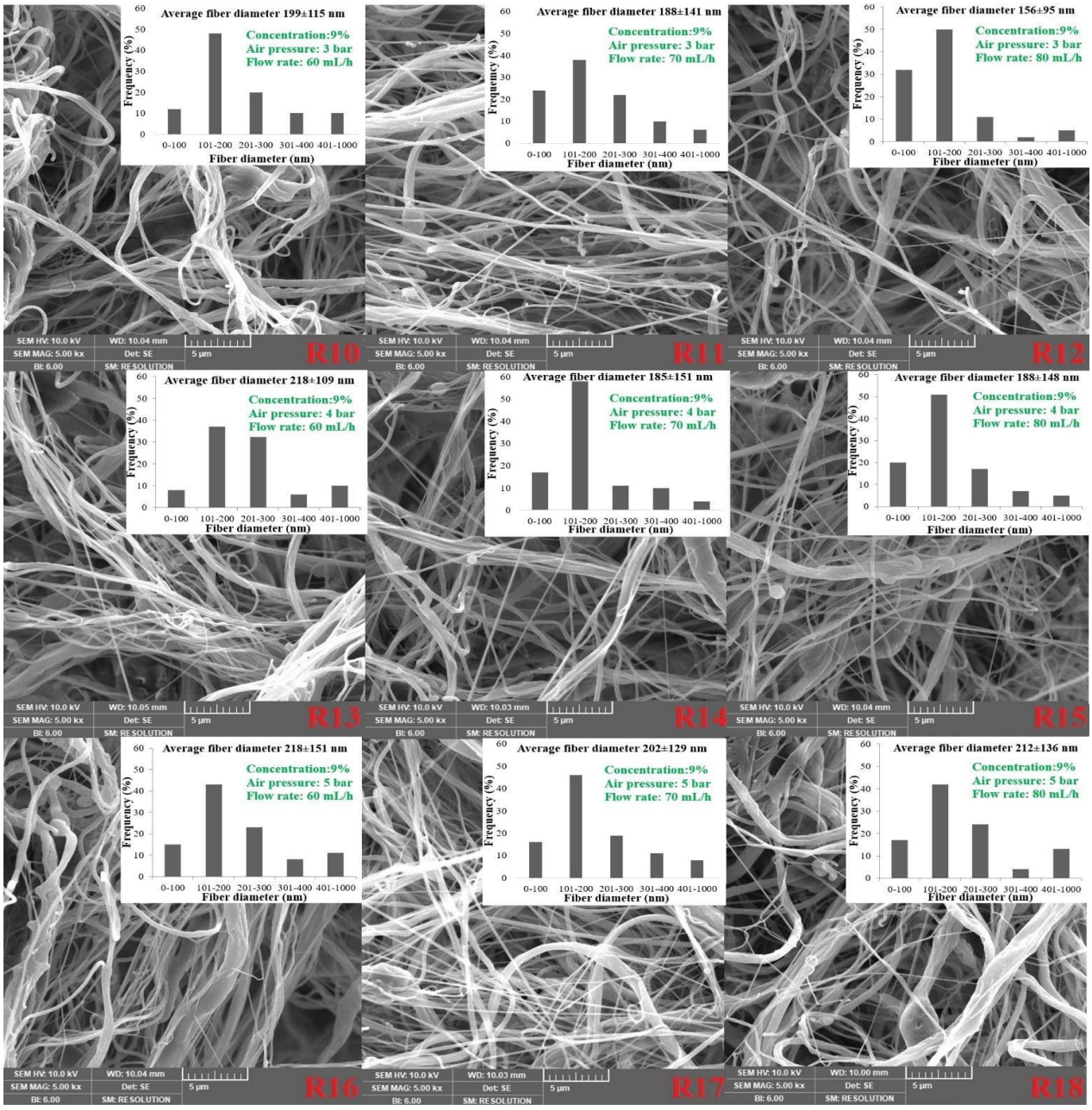

Figure 5. SEM images and fiber diameter distributions of PBS fibers (R10-R18)

3.2.2 The influence of air pressure on the morphology of the fibers

The air pressure in the SBS process has an impact on fiber morphology. The shearing action of the polymer solution is impacted by air pressure, which also has an impact on the fiber morphology, particularly the fiber diameter [33, 41]. The air pressure was changed to see how it affected the structure and diameter of the fibers. As shown in Figures 4-6, the SEM images of PBS were obtained using three different pressures: 3, 4, and 5 bars, respectively. The average fiber diameter decreased at first as the air pressure increased from 3 to 4 bars (Figure 7) and then the fiber diameter increased as the air pressure from 4 to 5 bars. The

PBS solution jets were prolonged and attenuated at the higher air pressure (4 bar), which caused the solvent to evaporate during the flight of the fibers from the nozzle to the collector and cause them to form into thinner fibers [51]. Oliveira et al. [33] also found the production of SBS fibers, to have a similar parabolic-like relationship between fiber diameter and air pressure. The nanofiber diameter was not greatly influenced by air pressure (ρ=0.817). This has also been experienced in previous studies and it has been suggested that it may be due to the solvent type [38].

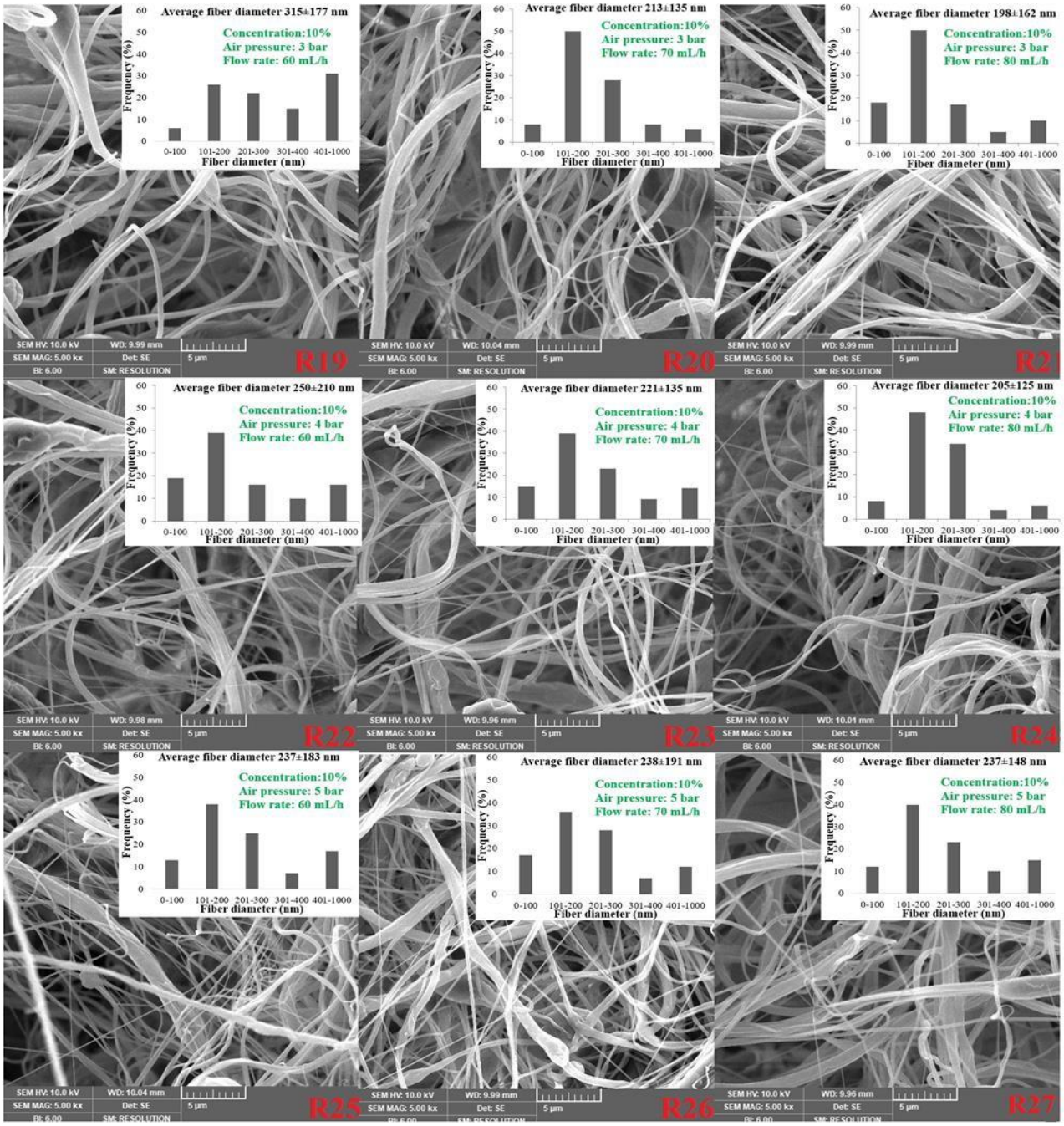

Figure 6. SEM images and fiber diameter distributions of PBS fibers (R19-

3.2.3 The influence of flow rate on the morphology of the fibers

It was necessary to have a specific volume of solution suspended at the nozzle's tip to maintain the dynamic equilibrium of the Taylor cone and produce a continuous stream. Additionally, the solution injection rate had a significant impact on the amount of solution needed for fiber formation [51, 52]. Solution flow has a significant impact on system productivity. Therefore, this study investigated the influence of solution flow on fiber structure by selecting and adjusting extremely high flow rates, which, although unusual in the literature, is also an essential indicator for industrial-scale production. The flow of the solution was adjusted from 60 to 80 mL/h. In contrast to other investigations, this one found that when feed volume increased, the fiber diameter decreased. This could be a result of the fibers' defective structure, which was ignored when the fiber diameter was measured. Figure

6 (R19: Concentration: 10%-Air pressure: 3 bar-Flow rate: 60 mL/h, R20: Concentration: 10%-Air pressure: 3 bar-Flow rate: 70 mL/h and R21: Concentration: 10%-Air pressure: 3 bar-Flow rate: 80 mL/h) demonstrates that when the flow rate is increased, the fine fibers are obtained. Due to the lack of time for polymer solvent evaporation at high feed rates, both more nonuniform structures and finer fibers were obtained. As previously observed, increasing the feed flow rate resulted in finer fibers but also in more deformed structures on the surfaces [74].

PBS is a semi-crystalline thermoplastic polyester from renewable resources, possessing biodegradability and biocompatibility, which provides greater benefits than non-biodegradable petroleum-based polymers in ecologically beneficial applications. It is a very promising biopolymer because its mechanical properties are comparable with those of widely used PE and PP [1, 4, 5]. A great deal of effort has gone into producing PBS-based nanofibers, and significant progress has been made [19, 20, 24, 73]. However, it has been observed that the rate of production of these studies is quite limited (0.3-1.5 mL/h). This could limit the transfer of scientific studies to industry and, as a result, their implementation. This study demonstrated that nanofiber PBS structures with very small diameters can be produced successfully at high production rates. Furthermore, the requirement for mixed solvent systems [19, 24] utilized to minimize clogging problems encountered during electrospinning and some additives (salts) used to diminish bead-like formations [23] both jeopardize the production process and increase manufacturing costs. Nevertheless, this study also revealed that much more work needs to be done in this area. This study focused on the following processing variables for the SBS system: polymer concentration, air pressure, and flow rate. It would be beneficial for future studies to focus on the many other parameters that affect fiber diameter and morphology in the SBS method, such as distance, needle diameter, and the like. Since a single-needle production mechanism was used in the current study, the multi-needle production method should be investigated further. This study is expected to pave the way for future research on the subject.

3.3 Statistical results

The average fiber diameter for the samples' ANOVA response is shown in Table 3. The SS value represents the influence of a parameter on the outcome, hence ,a parameter with a high SS value will have a significant impact on the outcome. According to the samples' SS and ρ values, both concentrations (ρ=0.010) and flow rate (ρ=0.013) seriously affect the samples' average fiber diameter (Table 3). The diameter of the fibers increases with the polymer concentration in the solution-blown solution as the amount of material that can be spun increases, a result that corroborates the findings of several other studies [33, 51, 52]. The fiber diameter generally increases as the feed amount increases; however, the overall trend tends to decrease somewhat in this study. This unexpected situation can be explained by the fact that more fiber agglomeration was observed at the high feed rate, which was not considered during the measurement. There was no discernible independent relationship between the air pressure parameter and fiber diameter. The R^2 obtained implies that only 85% of the response was explained by the model.

Table 3. ANOVA response tables of average fiber diameter of samples.

Source	DF	Seq SS	Adj SS	Adj MS	F	ρ
Concentration	2	7156.1	7156.1	3578.0	8.65	0.010
Air pressure	2	171.2	171.2	85.6	0.21	0.817
Flow rate	2	6466.1	6466.1	3233.0	7.81	0.013
Concentration*Air pressure	4	1856.6	1856.6	464.1	1.12	0.411
Concentration*Flow rate	4	933.7	933.7	233.4	0.56	0.696
Air pressure*Flow rate	4	2280.6	2280.6	570.1	1.38	0.323
Error	8	3309.6	3309.6	413.7		
Total	26	22173.9	22173.9			

Figure 7 shows the main effects plots of the concentration, air pressure, and flow rate concerning the mean. It shows that the optimal conditions for the fabrication of polymer nanofibers by SBS are a polymer solution concentration of 9 wt. %, an air pressure of 4 bar, and a feed rate of 80 mL/h. It can also be seen that the concentration of the polymer and the flow rate are the most significant parameter affecting the diameters of nanofibers. The main effects plots suggest that air pressure has very little effect on fiber diameter.

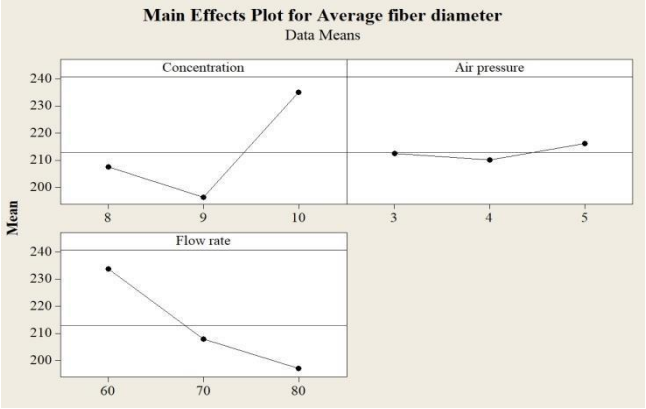

Figure 7. Main effect plot for average fiber diameter of PBS fibers

3.4 Some physical properties of the PBS nonwovens

Table 4 summarizes the comparison of the thickness, weight, air permeability and fiber diameter for PBS nonwoven (R15: Concentration: 9%-Air pressure: 4 bar-Flow rate: 80 mL/h) and other fabric that is obtained from different fabric production methods and polymers. The thickness, weight and air permeability values of the PBS sample are 155±10 μm, 27±3 g/m^2, and 126±11 mm/s, respectively. For textile materials, air permeability is a crucial performance factor. The diameter, thickness, and porosity of the fibers are factors that might impact a material's air permeability [75]. The air permeability values indicate that the breathability of PBS nonwoven is better than electospun r-PET nonwoven fabric and lower than meltblown PP nonwoven fabric [76]. The pore size determines how much air can pass through the material, the smaller the pore, the higher the barrier to air flow through the pores and the lower the material's air permeability. The most important factor in determining the pore size of a nanofiber web is the nanofiber size; as the nanofiber diameter increases, fewer larger-diameter holes appear in the web. Consequently, the difference in air permeability between electospun r-PET (95 nm) and solution blown spun PBS (188 nm) is mostly caused by the two polymers' differing nanofiber diameters and pore sizes. This implies that r-PET fibers obtained by electrospinning have finer and smaller pores than PBS obtained by solution-blown spinning. The value of air permeability is significant for nanofiber textile applications, such as providing oxygen permeability in wound dressings and breathability in masks.

The surface energy balance at the interface of air, liquid, and solid materials determines a nonwoven fabric's wettability, or its capacity to absorb liquid (fiber or fabric). The nonwoven fabric's initial response to contact with liquid is known as wetting, which entails replacing the solid-air (steam) interface with the solid- liquid interface. As a result, the nonwoven fabric's wettability is influenced by its structure, fiber geometry, and the surface roughness of the fibers [77]. The contact angle represents a quantitative measure of the wetting process. Figure 1 demonstrates the image of water drop coming into contact with PBS nonwoven fabric. The sample is s high water contact angle of 119±8° which was slightly higher than meltblown PP nonwoven (114°) [78]. Generally, a surface is hydrophobic when its water contact angle is >90° and is hydrophilic when is <90°. Hydrophobicity is a generally desirable characteristic for water/oil separation materials [68], so PBS nonwovens are a good candidate for this.

The influences of production parameters on the morphology of individual solution blow-spun PBS nanofibers were studied. The major influences of parameters such as PBS solution concentration, air pressure, and flow rate on average fiber diameter were evaluated. In general, solution-blown spun PBS nanofibers with an average fiber diameter of 100-350 nm were obtained. Although there were a few imperfections, PBS nonwovens were primarily found on the nanoscale. The diameter of the fibers was found to be predominantly influenced by the concentration and flow rate; however, the air pressure had no noticeable influence on the fiber diameter. Fibers with lower diameter can be obtained at intermediate concentration, moderate air pressure and high flow rate. That is, process parameters may be selected following the model in this work to produce PBS nanofibrous structures that are uniquely tailored. The produced solution-blown spun PBS nonwoven with good hydrophobicity and favorable breathability can be used in separation, filter media and biomedical materials.

Table 4. Some physical properties of the PBS nonwovens

Sample	Thickness (μm)	Weight (g/m^2)	Air permeability (mm/s)	Fiber diameter	*Reference*
Solution- blown SBS nonwoven fabric	155±10	27±3	126±11*	188 nm	*This study*
Meltblown PP nonwoven fabric	-	28	207*	-	*[76]*
Electrospun r- PET nonwoven fabric	*25*	*14*	*39**	*95 nm*	*[76]*

*According to ISO 9237

4. CONCLUSIONS

These results are particularly attractive for industrial-scale nanofiber production because PBS polymer is more expensive than conventional polymers (PE and PP). The production cost of the end-use nanofiber materials increases with the electrospinning method, which also has a low production rate, as frequently demonstrated in previous studies. This may limit the application areas of the products obtained from the polymer. The results of this study demonstrate that a sustainable strategy may be used in this process, which offers hope for the decades long global study on the use of nanofibrous PBS. In addition, this work expands the use of SBS technology to the quick fabrication of nanofibers in the textile industry.

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