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Feasibility of Production of PET/ZIF-8 Polymer Media to Remove Particles from the Air Stream Compared to HEPA Filter

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ABSTRACT

Polyethylene terephthalate (PET) and Zeolitic Imidazolate Framework-8 (ZIF-8) were used to investigate the feasibility of producing electrospun PET/ZIF-8 polymer media in removing particles from the air stream to compare with the HEPA filter. To make PET/ZIF-8 media, concentrations of 0.5, 1, 2.5, and 5 wt.% of ZIF-8 were dissolved in PET20% solutions, and dispersed for 10 min. Then, PET/ZIF-8 media was produced with an ESDP30 model electrospinning device. The efficiency and pressure drop of nanofiber media were measured with a respiratory mask and filter test device. The FTIR, XRD and SEM analysis were carried out to obtain the characteristics of nanofibers. The overall XRD pattern and its peaks were in reasonable agreement with previous findings that confirmed the structure of ZIF-8. The FTIR spectra of the obtained materials confirm that the chemical bond structure corresponds to that reported for ZIF-8. In total, The PET/ZIF-8(1%) media efficiency, pressure drop, the average diameter of nanofibers, and the quality factor were 100%, 320 Pa, 171.18±37.91 nm and 0.0143 Pa-1, respectively, which was better than other electrospun PET/ZIF-8 media and HEPA filters. According to the results, with an increase in the weight percentage of Zif-8 (>5 wt.%) in the structure of PET/Zif-8 media, due to the increase in the viscosity of the solution jet, the diameter of the produced nanofibers increased and the efficiency of the electrospinning medium decreased.

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INTRODUCTION

Breathing is an unavoidable primary task in human life and considering that air covers the whole earth and is one of the necessary conditions for survival and life, therefore polluted air affects people more than other types of pollution because avoiding it is impossible and more difficult (Zeng et al., 2019). Air pollution has become one of the main challenges of human life and a major problem for the environment and public health. This can lead to many diseases such as cardiovascular diseases, malignant tumors, infectious allergic diseases, and dry eyes, etc (Salatin et al., 2016). Annual air pollution causes many deaths and financial losses, most of these occur in developing countries (He et al., 2018). The most significant sources of air pollution are human activities and interventions, such as vehicles, factories, various industries, constructions, power plants, mass fires, etc (Salatin et al., 2016). In 2013, the International Agency for Research on Cancer (IARC) classified air pollution and its suspended particles as

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100% human carcinogenic compounds (Reyhaneh Shams et al., 2020). All these statistics and research indicate that the problem of air pollution must be eliminated or controlled in some way. Among the various air pollution control methods, filtration is the simplest and most common method for air purification and reducing the effect of air pollutants on the human body is known (Zhou et al., 2022).

High-Efficiency Particulate Air (HEPA) filters are among the filters that have high efficiency in removing particles and controlling air pollution. These filters are widely used in air cleaning systems to improve air quality in residential and business environments (Chotigawin et al., 2010). HEPA filters also have disadvantages, including high costs, limited lifetimes, and environmental pollution during disposal. In addition, the performance of these filters can be reduced under the influence of parameters related to installation and maintenance conditions such as relatively high temperature, darkness and humidity (Mousavi et al., 2017).

Generally, the performance of filters and media is determined by their filtration efficiency, pressure drop, and lifespan, which are all strongly related to their structure (Farhang Dehghan et al., 2016). To meet the needs of society and industries for high-efficiency air filters with low pressure drops, along with the advancement of science and technology, nano-scale fibers have been considered as a way to increase the performance and effectiveness of fiber filters (Zhou et al., 2022). One of the methods of making nanofibrous media is electrospinning. Electrospinning is the best and most accepted method for producing nanometric fibers (Farhang Dehghan et al., 2016; Chazelet et al., 2011). Electrospun nanofibers have high particle retention capacity, small-sized pore structures, high porosity, high permeability, high surface area, small-diameter fibers, and low basis weight (Farhang Dehghan et al., 2016). This attributes improves the filtration efficiency of nanofibrous filters and media compared to HEPA filters and other traditional filters (with micron-sized fibers), and it can remove the pollution of particles in the air more effectively by eliminating the shortcomings of existing filters (Farhang Dehghan et al., 2016; Zhou et al., 2022).

Metal-organic frameworks (MOFs) are widely used in filtration through the production of polymer nanocomposites by the electrospinning method (Lai et al., 2016). Their high surface area, porosity, low density, and flexibility in pore size, shape, and structure allow them to improve their capacity for removing particles from air streams (García-Palacín et al., 2020). The structure of MOFs is such that they can create good interaction with polymers and are usually used in the preparation of mixed matrix membranes (Jiang et al., 2018).

ZIF-8 is one of the most widely used MOFs in electrospinning, because of their high specific surface area, high porosity, diverse structures, wide surface area, high mechanical and thermal strength and adjustability (Li T. T et al., 2020). In various studies, ZIF-8 MOFs have been used in combination with other polymers to increase the absorption rate of these polymers (Liu et al., 2019). Based on the results of various studies (Yang et al., 2023; Abdelhamid et al., 2022; Chen et al., 2020; Guan et al., 2021), ZIF-8 contributes to the developments in the fields of ranging from sensing and electrical devices to drug delivery, therefore, it seems that use of Zif-8 in small amounts can even have positive and beneficial effects on the performance of the media in filtration.

PET is a linear polyester that is widely produced in the world which is used in synthetic fiber, coating, packaging, and plastic construction (Çavuş et al., 2016). PET non-woven media has a porous structure and low cost to manufacture and it can probably play an vital role in dust filtration in combination with its mechanical properties such as high mechanical resistance (Khorram et al., 2017). Choudhary et al. (2019) showed in their study that PET can be used in fibrous media for reasons such as high chemical and tensile resistance, favorable thermal stability, and cheapness (Choudhary et al., 2019).

In the present study, the feasibility of PET/ZIF-8 polymer media production using the solution electrospinning method was investigated in order to improve particle filtration performance compared to HEPA filters.

MATERIALS AND METHODS

Synthesis of ZIF-8 MOF nanoparticles

First, ZIF-8 was synthesized to make PET/ZIF-8 electrospinning solution. For this purpose, firstly, the amount of 2.582 gr of ZN (NO3)2. 4H2O (Mw= 261.44 g/mol; CAS Number 19154-63-3) was dissolved in 200 ml of methanol (Mw= 32.04 g/mol; CAS Number 67-56-1) which were purchased from Merck (Germany). Also, at the same time, 3.242 g of 2-methylimidazole (HmIM) (Mw= 82.11 g/mol; CAS Number 693-98-1) purchased from Merck (Germany) was dissolved in 200 ml of methanol. These two solutions were completely mixed and then dispersed to ensure the complete dissolution of these compounds. The obtained solution was kept at room temperature for 24 hours. In the next step, the resulting powders were collected using a centrifuge and washed completely with methanol. The obtained powder was vacuum dried at 100°C for 12 hours in an oven (Yong et al., 2020). X-ray powder diffraction (XRD, Philips CO. PW 1730, Netherlands) was used to determine the structure of the synthesized ZIF-8 MOF using Cu Kα radiation (40 kV and 30 mA) ranging from 10° to 80° with a scanning speed of 0.05° (2θ) s^{-1}.

Preparation and electrospinning of PET solution

Typically, 3.605gr of Polyethylene terephthalate (polyester granule grade MOD 6694) purchased from Shahid Tandgoyan Petrochemical Company (Iran), was dissolved in mixture of trifluoroacetic acid (TFA) (MW=114.02 g/mol; CAS Number 76-02-1) and dichloromethane (DCM) (MW=84.93 g/mol; CAS Number 75-09-2) purchased from Merck (Germany) with a mixing ratio of 70:30. Then this mixture was stirred at room temperature for 3 hours (Bonfim et al., 2021; Strain et al., 2015). Afterwards, two medical syringes (with G21 needles) were used to draw 4 mL of the solvent for electrospinning, and the electrospinning processes were carried out using a two-pump/bidirectional electrospinning machine model ESDP30 (Fanavaran Nano Scale CO, Tehran, Iran) at feeding rate of 0.7 $ml.h^{-1}$, a collecting distance of 10 cm, a voltage of 13 kV, a collector speed of 180 rpm and at room temperatures (23-25 °C) for 90 min. Electrospinning parameters were adjusted based on the results of the previous study by the authors of this article (Kazemi et al., 2023).

Preparation and electrospinning of PET/ZIF-8 solution

After preparing $PET_{20\%}$ solution, ZIF-8 crystals (0.5, 1, 2.5, and 5 wt. % of ZIF-8) were dispersed in $PET_{20\%}$ solutions by ultrasonic treatment for 30 min and stirred for 24 h at room temperatures to produce a homogeneous spinning solutions of PET/ZIF-8. The electrospinning process of PET/ZIF-8 solutions was carried out similarly to section 2.2.

A field emission scanning electron microscope (FE-SEM) (DSM-960A Model, ZEISS, Germany) were used to observe the morphology of nanofibers and the distribution $PET_{20\%}$ and PET/ZIF-8 media, and HEPA filter. Fourier Transform Infrared Spectroscopy (FTIR) analysis was used to determine the presence of ZIF-8 in the structure of PET/ZIF-8 media.

Performance evaluation of synthesized PET/ZIF-8 media

The pressure drop resistance and the filtration efficiency of $PET_{20\%}$, PET/ZIF-8 media and HEPA filter were measured by the Fanavaran Nano-Meghyas (FNM's) filter tester (FNM CO, Iran) at a speed of 10 cm/s (Q=30 L/min) (Li et al., 2013; Farhang Dehghan et al., 2016; Kazemi et al., 2023). Filter testers are equipped with a high precision particle counter (particle sizes: 0.3, 0.5, 1.0, 3.0) for counting the particles generated by a salt particle generator or atmospheric dust in order to calculate filtration efficiency. Filters and media with high efficiency have a low-pressure drop and a high-quality factor (QF). To calculate the QF of nanofibrous media synthesized, the following formula is used (Huang et al., 2013; Farhang Dehghan et al., 2016):

$$Q_f = \frac{\ln\left(\frac{1}{1-(\eta_{0F})}\right)}{\Delta p} \tag{1}$$

Where QF is the quality factor (Pa^{-1}), Δp is the pressure drop (Pa) and η0F is the filtration efficiency value for the particle size dp (nm).

Tensile testing

A uniaxial tensile strength test device (Instron 5566, USA) was used to measure and compare the resistance and tensile strength of each of the produced media and HEPA filter. Tensile tests were conducted on at least four samples of each electrospun media according to a previously reported Template Transfer Method (Andersson et al., 2014; Strain et al., 2015).

RESULTS AND DISCUSSION

Characterization of synthesized PET/ZIF-8 media

The FE-SEM images and X-Ray diffractogram of ZIF-8 powder are presented in Fig. 1. The

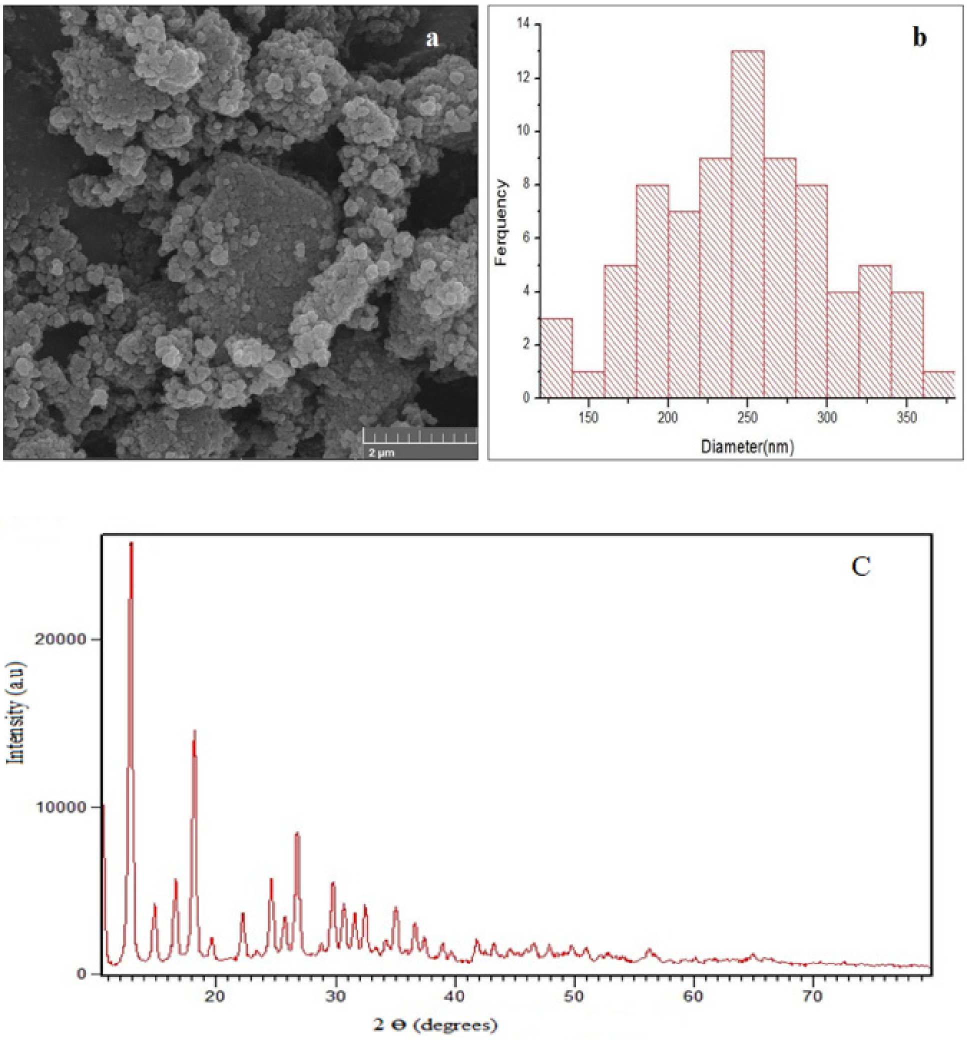

Fig. 1. FE-SEM images (a) and fiber diameter distribution (b) for the Zeolitic Imidazolate Framework-8 (ZIF-8) powder. X-Ray Diffractogram (c) for ZIF 8 powder.

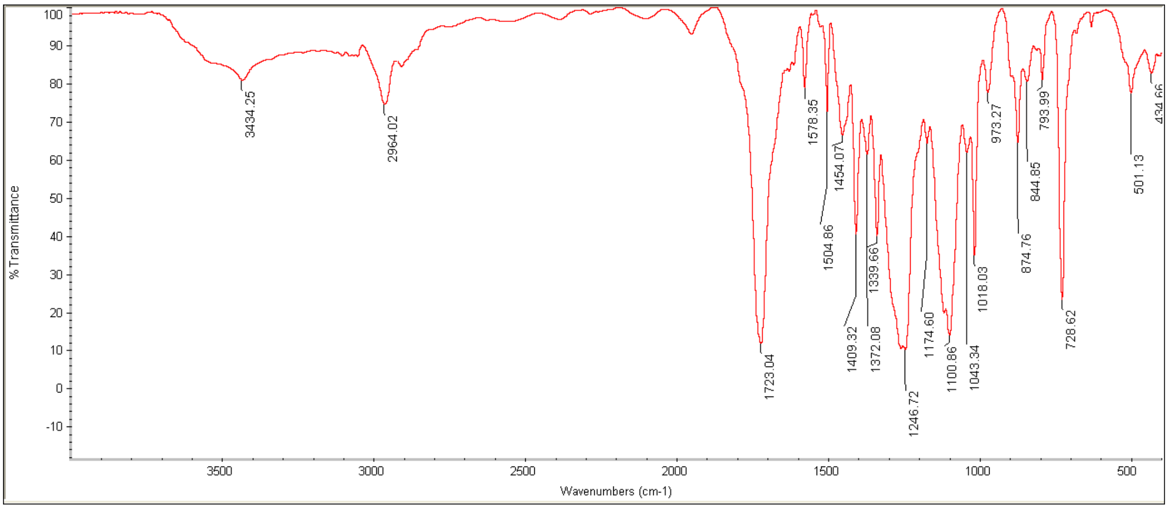

Fig. 2. FTIR spectra of PET/ZIF-8.

FE-SEM images (Fig. 1a) showed that the synthesized ZIF-8 nanoparticles have a relatively uniform shape. The average size of these nanoparticles was equal to 246.95 ± 48.54 nm (Fig. 1b).

The XRD diffractogram was obtained from ZIF-8 powder sample and analyzed (Fig. 1c). The formation of ZIF-8 was confirmed by XRD analysis which indicates the formation of highly crystalline ZIF-8. The diffraction peaks at $2\theta=10.4°$, 12.7°, 12.8°, 12.9°, 13.1°, 14.8°, 18°, 18.1°, 18.2°, 24.6°, 26.7°, 26.8°, and 29.8° indicated the crystalline structure of ZIF-8 MOFs. The overall XRD pattern with its peaks was in good agreement with previous findings that confirmed the structure of ZIF-8 (Bahmani et al., 2019; Zhang et al., 2018). In this paper, $\text{PET}_{20\%}$ media was used as the base substrate for the production of PET/ZIF-8 media with different weight percentages of ZIF-8 MOF, and FTIR test was used to investigate the structure of the constituent spectra of PET/ZIF-8 media, the results of which are shown in Fig. 2.

In the FTIR spectrum of PET/ZIF-8, all of the characteristic vibrations of ZIF-8 and PET were detected. Obtained data of FTIR were compared to the literature finding to identify characteristic bands (Kohsari et al., 2016; Morillo Martín et al., 2017; Zhang et al., 2018).

In the FTIR spectrum, the characteristic bands identified at 3434.25, 2964.02, 1578.35, 1454.07, 1372.08, 973.27, and 434.66 cm^{-1} are related to the structural peaks of ZIF-8 MOF (Zhang et al., 2018). Other peaks identified (Fig. 2) include 1723.04, 1504.07, 1409.32, 1339.66, 1246.72, 1174.6, 1100.86, 1043.34, 1018.03, 874.76, 844.85, 793.99 and 728.62 cm^{-1} for PET bands (Morillo Martín et al., 2017; Zhang et al., 2018). The FTIR spectra of the obtained materials (Fig. 2) confirm that the chemical bond structure corresponds to that reported for ZIF-8.

Comparison of structural and functional characteristics of electrospun media with HEPA filter

The results of measuring parameters such as pressure drop, filtration, nanofiber size distribution, and QF are shown in Table 1.

Increasing the amount of ZIF-8 (from 0.5 to 5 wt.%) in PET/ZIF-8 media led to the production of nanofibers with a larger diameter (Table 1 and Fig. 3). In such a way that PET/ZIF-8 electrospun media with 0.5% and 5 wt.% of ZIF-8, with an average diameter of 28.92±9.51 nm and 708.44±242.60 nm, had the smallest and largest diameter of nanofibers, respectively. As a result of the increase in viscosity of the solution jet at concentrations greater than 5 wt.% Zif-8, the diameter of the nanofibers increased and the efficiency of the electrospun media decreased.

Table 1. Comparison of functional and structural evaluation results of electrospun media with HEPA filter.

Media/filter	Fiber diameter (nm)	Particle size (μ)	Filtration efficiency * (Mean±SD)	Pressure drop* (Pa)	QF (Pa^{-1})
PET$_{20\%}$	600.37±73.55	0.3	96.23±0.98	26.33±5.5	0.1730
		0.5	98.60±0.02		0.1740
		1	99.70±0.15		0.1744
		3	100		0.1745
PET/ZIF-8 (0.5 %)	28.92±9.51	0.3	99.99±0.0057	366	0.0125
		0.5	100		0.0125
		1	100		0.0125
		3	100		0.0125
PET/ZIF-8 (1 %)	**171.18±37.91**	**0.3**	**100**	**320**	**0.0143**
		0.5	**100**		**0.0143**
		1	**100**		**0.0143**
		3	**100**		**0.0143**
PET/ZIF-8 (2.5 %)	372.96±63.95	0.3	97.66±0.66	189	0.0242
		0.5	98.72±0.20		0.0242
		1	99.77±0.17		0.0243
		3	100		0.0243
PET/ZIF-8 (5 %)	708.4±242.604	0.3	93.16±0.70	127	0.0356
		0.5	95.69±0.41		0.0358
		1	99.16±0.22		0.0361
		3	100		0.0362
HEPA (Type H13)	**533.52±26.10**	**0.3**	**99.97**	**371**	**0.0124**
		0.5	**99.96**		**0.0124**
		1	**99.96**		**0.0124**
		3	**100**		**0.0124**

* Values were measured using a respiratory face mask test machine at a speed of 10 cm/s (Q= 30 L/min) for PET/ZIF-8 media and HEPA media.

Bahmani et al. (2019), reported in their study that increasing ZIF-8 loading up to 3% by weight led to a gradual increase in the diameter of the produced fibers due to an increase in solution viscosity. In the study of Bahmani et al., the average diameter of nanofibers containing 1, 2, and 3 wt. % ZIF-8 was 290, 340, and 390 nm, respectively (Bahmani et al., 2019).

In this study, increasing ZIF-8 (up to 3 wt.%) had a positive effect on increasing the filtration efficiency, but increasing ZIF-8 to more than this amount led to a decrease in the filtration efficiency. So that PET/ZIF-8 (5%) electrospun media had the lowest efficiency compared to other PET/ZIF-8 media. While in 1 and 0.5 wt.% of ZIF-8, nanofibrous media had an efficiency almost as high as 100%. These results were consistent with those previously reported by Zhang et al., and Saghir et al., who have stated that the use of Zif-8 can be effective in improving the absorption or removal of pollutants (Zhang et al., 2018; Saghir and Xiao, 2021).

Based on the results of various studies, it can also be useful to apply the QF to check and compare the performance of media and filters (Rebai et al., 2010; Chazelet et al., 2011). The results (Table 1) showed that PET/ZIF-8(1wt.%) media with an average nanofiber diameter equal to 171.18±37.91 nm, a pressure drop of 320 Pa, 100% efficiency in removal of particles micron and submicron, and a QF = 0.0143 Pa^{-1}, have a more suitable and acceptable performance compared to other electrospun media and the HEPA filter (type H13 with a QF = 0.0124 Pa-1 and fiber diameter of about 533.52 ± 26.10 nm) used in this study. In the study of Bahmani et al. (2019), the greatest increase in adsorption capacity for chitosan-g-PNVCL/ZIF-8 nanofibers was obtained when ZIF-8 was loaded up to 3 wt.% and in amounts greater than 3 wt.% ZIF-8, the adsorption capacity decreased (Bahmani et al., 2019). According to Zhang et al. (2018) study, the additions of ZIF-8 doubled the filtration efficiency, and in addition, the prepared

Table 2. Comparison the findings of this research with other studies

First author (publication date)	Membranes/Media	Additive (ZIF-8, wt.%)	Fabrication method	Optimal concentration (ZIF-8)	Diameter (nm)	Adsorpted particle size	Filtration efficiency * (%)
Kazemi et al., 2023	PET20%	0	Electrospining	-	600.37±73.55	$PM_{0.3}$	96.23±0.98
This study	PET/ZIF-8	0.5, 1, 2.5, 5	Electrospining	1 wt.%	171.18±37.91	$PM_{0.3}$	100
Bahmani et al., 2019	Chitosan-g-PNVCL[1]/ZIF-8	1, 2, 3, 5, 10	Electrospining	3 wt.%	390	Cr(VI) As(V) Phenol	98.98 96.85 87.9
Zhang et al., 2018	ZIF-8/PET	-	in-situ growth method	-	1000-2000	$PM_{2.5}$	77.15
Li et al., 2021	ZIF-8/PI[2]	0, 1, 2, 3	Electrospining	3 wt.%	300	$PM_{0.3}$	99.93
Guo et al., 2020	PAA[3]@ZIF-8	3.6, 5.4, 7.2, 9, 10.8	Electrospining	9 wt.%	720	$PM_{2.5}$	99.6

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[1] chitosan-grafted-poly(*N*vinylcaprolactam)

[2] Polyimide

[3] Polyacrylic acid

composites showed low pressure drop and good recycling performance (Zhang et al., 2018). Li et al. (2021) reported that by loading ZIF-8 up to 3 wt.%, the adsorption capacities of ZIF-8/PI nanofibers were increased and the highest increase in adsorption capacity for ZIF-8/PI nanofibers was obtained in 3 wt.% of ZIF-8 (Li et al., 2021).

In Table 2, the results of this study are compared with the results of other similar studies.

Tensile testing

Tensile testing was conducted on all the prepared media (Fig. 4 and Table 3). The values obtained for the parameters of strain (31.45 Cn/Tex), modulus (92.65 Cn/Tex), tensile load tolerance (345.5 cN), and maximum tensile load tolerance time (13.86 s) by fiber media before tearing/failure were higher for PET/ZIF-8(1%) media than other PET/ZIF-8 media and HEPA filters (Table 2). Therefore, in terms of tensile strength, it was identified as a media with better performance than other synthesized media and HEPA filters.

On the basis of the results obtained (Table 3), PET/ZIF-8(1%) media exhibited the best performance in terms of Stress, Extension, Maximum Tensile Load Endurance Time, and Tensile Load Amount. On the other hand, PET/ZIF-8 media that contained a lower weight percentage (<5 wt. %) of ZIF-8 had a smaller average diameter of nanofibers (Table 1). Therefore, the small diameter of the nanofibers in the electrospun media is probably the reason for the high values obtained for the mentioned parameters (Stress, Extension, maximum tensile load endurance time, and tensile load). The study of Strain et al. showed that the tensile strength of the produced fibers increased with the reduction of the diameter of the fibers, and in this sense, the results of the present study are consistent with the results of the Strain study (Strain et al., 2015).

To better compare the results of the tensile strength of the electrospun media with each other and the HEPA filter, the results of measuring the tensile strength of the media are shown in Fig. 4.

According to Fig. 4, it can be seen that $PET_{20\%}$ media (as the base substrate) has the highest

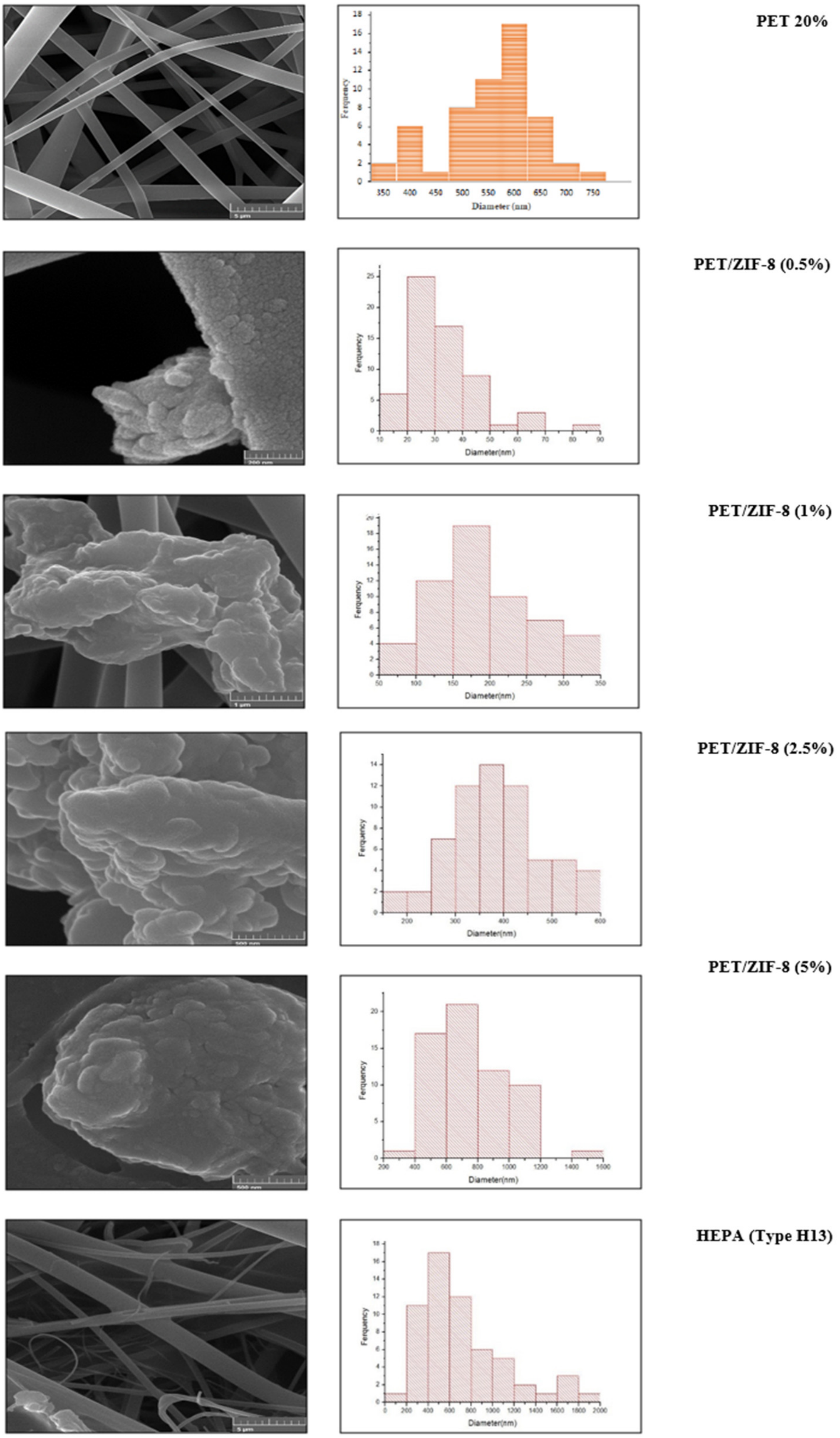

Fig. 3. SEM images and particle size distributions of the PET, PET/ZIF-8 media, and HEPA filter.

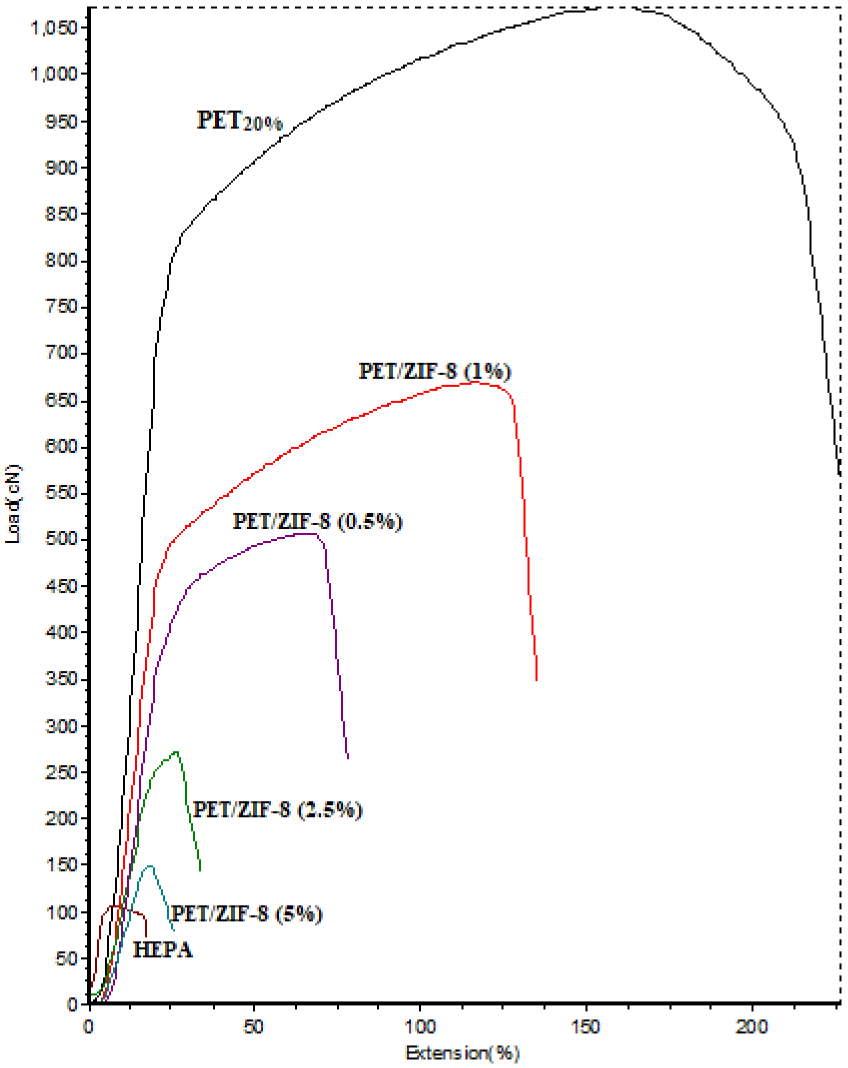

Fig. 4. Comparison diagram of the tensile strength of electrospun media.

Table 3. The results of tensile tests of electrospun PET, PET/ZIF-8 media and HEPA filter.

Media/Filter	Test Time (s)	Max Load (cN)	Max Extension (%)	Final Load (cN)	Modulus (cN/Tex)	Max Stress (cN/Tex)	Extension at max Load (%)
PET 20%	23.15	1073	226.5	562.1	141.6	50.42	**155.8**
PET/ZIF-8 (0.5 %)	8	506.1	77.92	263.6	48.53	23.77	**65.77**
PET/ZIF-8 (1 %)	***13.86***	***669.5***	***135.2***	***345.5***	***92.65***	***31.45***	***116.4***
PET/ZIF-8 (2.5%)	3.48	271.2	33.4	141.5	63.25	12.74	**26.37**
PET/ZIF-8 (5 %)	2.68	149.2	25.44	78.1	53.67	7.01	**17.67**
HEPA (Type H13)	1.85	104.3	17.39	69.96	3.31	4.901	**7.92**

tensile strength. But the tensile strength test results for electrospun PET/ZIF-8 media showed that PET/ZIF-8 (1%) media has better performance in terms of tensile strength parameters than other PET/ZIF-8 media and HEPA filter. The lowest tensile strength was obtained for the HEPA filter used in this study.

CONCLUSION

The results showed that PET/ZIF-8 polymer media can effectively remove particles with different sizes. Increasing of ZIF-8 (>5 wt.%) in the electrospun media led to the production of nanofibers with a larger diameter. Increasing the concentration of ZIF-8 above 5 wt. %, due to the increase in viscosity of the solution, led to the instability of the solution jet and reduced the efficiency of the electrospinning process.

Based on the results of this paper, it can be said that PET/ZIF-8 (1%) media had better performance than other electrospun media and HEPA filters. Considering that the PET used in this study is a cheap material, available and easy to work with, and that it can be recycled and reused many times. Therefore, it is possible to save production costs with this work. In addition to addressing economic problems and preventing environmental problems, this work will be a significant step forward in the discussion of air filtration. Additionally, ZIF-8 MOFs are able to enhance the absorption capacity of production media, thus improving the filtration efficiency of electrospun media in the absorption and suspension of particles of different sizes.

In general, comparing and evaluating results of the present study with HEPA filter (Type H13), electrospun PET/ZIF-8 (1%) media in terms of filtration efficiency, pressure drop, quality factor, average fiber diameter and parameters tensile strength had better performance than HEPA filter. Among the reasons for the better performance of the electrospun PET/ZIF-8 media in present study in comparison with the HEPA filter, we can mention the unique characteristics and properties of PET and ZIF-8. The porous structure and unique mechanical properties of PET polymer and ZIF-8 MOFs, such as high mechanical strength and excellent tensile strength, have created better performance of PET/ZIF-8 media. The main reason for the low tensile and mechanical strength of the HEPA filter comparison to the electrospun PET/ZIF-8 media is related to structure and components of the HEPA filter. The main part of the HEPA filter structure is made of glass wool or fiberglass fibers, which have low resistance to stretching and tear quickly.

Due to the excellent filtration performance of PET/ZIF-8(1%) media compared to HEPA filter, PET/ZIF-8(1%) media can be used in all industries where HEPA filter is used, such as hospitals, pharmaceutical industries, clean rooms, food industries, industries that produce sensitive electronic parts, vacuum cleaners, etc.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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