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Comparison of the performance and efficiency of PET/ZIF-8 polymer media synthesized by solution electrospinning with a HEPA filter (Type H13) in removing pollutant particles from the air stream

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ABSTRACT

Introduction: Production of high-performance media with low pressure drop in air pollution control is an important issue in air filtration. In this study, polyethylene terephthalate (PET) and different weight percentages of zeolite-8 imidazolate framework (ZIF-8) were used to investigate the performance of PET/ZIF-8 polymer media produced by solution electrospinning in removing particles from air flow compared to the HEPA filter.

Materials & Methods: To manufacture PET/ZIF-8 media, after synthesizing ZIF-8, different weight concentrations of it were dissolved in a PET20% solution. Then, the manufactured solutions were transferred to the ESDP30 two-pump electrospinning machine, and based on the defined parameters of the electrospinning machine, PET/ZIF-8 media were produced. The efficiency and pressure drop of the media were measured by the mask and media efficiency and pressure drop test machine at a speed of 10 cm/s (Q=30 L/min). XRD, FTIR, and FE-SEM analyses were used to evaluate the properties of the produced nanofibers.

Results: The XRD pattern results were consistent with previous findings, confirming the structure of ZIF-8. The FTIR spectrum of the obtained materials confirmed that the chemical bond structure was consistent with that reported for ZIF-8. The PET/ZIF-8 media (1 wt.%) had an efficiency, pressure drop, average nanofiber diameter, and quality factor of 100%, 320Pa, 171.18±37.91 nm, and 0.143 Pa-1, respectively, which performed better than other electrospun PET/ZIF-8 media and HEPA media (type H13).

Conclusion: According to the results, a concentration higher than 5 wt.% of ZIF-8 resulted in a decrease in the efficiency of the media due to an increase in the diameter of the nanofibers and a decrease in the efficiency of the electrospinning process due to an increase in the solution jet.

Keywords: Polyethylene Terephthalate (PET), Zeolite-8 Imidazolate Framework (ZIF-8), Electrospinning, Filtration, High-Efficiency Particulate air (HEPA) filter

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Introduction

Respiration is a basic and inevitable task in human life, and considering that air covers the entire earth and is one of the necessary conditions for survival and life, polluted air affects people more than other types of pollution because it is impossible and more difficult to avoid (1). Air pollution has become one of the main challenges of human life and a major problem for the environment and human health, which can lead to many diseases such as cardiovascular diseases, malignant tumors, infectious allergic diseases, dry eyes, etc. (2-5). Air pollution causes a lot of human and financial losses every year, and most of these losses and deaths occur in developing countries (6). Important sources of air pollution emission and production include human activities and interventions such as vehicles, factories and various industries, construction, power plants, mass fires, etc. (2). In 2013, the International Agency for Research on Cancer (IARC) classified air pollution and particulate matter as 100% carcinogenic to humans (7). All these statistics and studies indicate that the problem of air pollution must be eliminated or controlled in some way.

There are various methods for removing particles from the air flow and controlling air pollution (8). Among these methods, filtration is recognized as the simplest and most common approach for purifying air and minimizing the effects of air pollutants on health. This is largely due to its ease of use, accessibility, low cost, and high efficiency in collecting fine particles (8, 9).

HEPA filters stand out as highly effective tools for particle removal and air pollution control. They are frequently utilized in air purification systems to enhance air quality in both residential and commercial settings. However, despite their high efficiency, HEPA filters have some drawbacks (10). They can be costly, have a limited lifespan, contribute to environmental pollution during disposal, and may experience reduced performance based on installation, operational, and maintenance conditions—such as being used in dark, humid, or extreme temperature environments (11).

The performance of filters and their media is typically assessed by their filtration efficiency, pressure drop, and lifespan, all of which are closely related to the filter's structure (12). To meet the increasing demands for high-efficiency air filters with low pressure drops, advancements in science and technology have led to the consideration of nanoscale fibers in filter construction (9, 13). One of the most effective methods for producing these nanofiber media is electrospinning, which is widely accepted for generating nanometric fibers (14-17).

Electrospun nanofibers possess several advantageous properties, including high particle retention capacity, small-sized pore structures, high porosity (up to 80% or more), excellent permeability, and a large surface area with a small fiber diameter and low basis weight (18, 19). These attributes enhance the filtration efficiency of nanofiber filters compared to HEPA filters and other traditional filter types, which generally have fibers in the micrometer range. Consequently, the use of nanofiber technology can significantly improve the removal of airborne particulate pollution, addressing the limitations found in existing filtration methods (13).

These attributes enhance the filtration efficiency of nanofiber filters compared to HEPA filters and other traditional filter types, which generally have fibers in the micrometer range. Consequently, the use of nanofiber technology can be significantly improved (13, 20). The challenges associated with electrospinning, particularly in selecting the right polymer and optimizing parameters for effective nanofibrous media that can efficiently filter particles of various sizes, remain significant (20). In this study, both Polyethylene Terephthalate (PET) and ZIF-8[1] were utilized to create nanofibrous media. PET

[1] Zeolitic Imidazolate Framework-8 (ZIF-8)

nonwoven media is advantageous due to its porous structure, low manufacturing cost, and strong mechanical properties, making it a promising candidate for dust filtration applications (21). Research by Choudhary et al. (2019) highlighted PET's suitable attributes, including its high chemical and tensile strength, thermal stability, and affordability (22).

ZIF-8, a Metal-Organic Framework[2] , stands out due to its diverse structures, expansive surface area, tunable pores, and impressive mechanical and thermal strength. Its high porosity makes it particularly attractive for creating polymer nanocomposites through electrospinning (23, 24), as seen in various studies that have explored its combination with other polymers to enhance adsorption rates (25, 26).

The current paper investigates the potential for producing PET/ZIF-8 polymer media using electrospinning, aiming to enhance particle filtration performance relative to HEPA filters.

Materials and methods

The present research was an experimental study conducted under laboratory conditions, focusing on data collection through various laboratory and device processes and tests.

Synthesis of ZIF-8 MOF Nanoparticles

To prepare the PET/ZIF-8 electrospinning solution, the synthesis of ZIF-8 was the first step. Initially, 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), sourced from Merck, Germany. Concurrently, 3.242 gr of 2-methylimidazole (HmIM) (Mw= 82.11 g/mol; CAS Number 693-98-1) from Merck, Germany, was also dissolved in 200 ml of methanol. The two solutions were thoroughly mixed using a magnetic stirrer to ensure uniform blending. To enable complete dissolution of the compounds, the mixture was subjected to ultrasonic treatment for 10 minutes. After this, the solution was left undisturbed at room temperature for 24 hours. Following this period, the powders obtained were collected via centrifugation and washed thoroughly with methanol. Finally, the resulting powder was dried in a vacuum oven at 100 °C for 12 hours (27).

Preparation of PET/ZIF-8 electrospinning solution

To prepare a PET electrospinning solution at a 20% weight concentration, 3.605 g of polyethylene terephthalate (polyester granule grade MOD 6694), sourced from Shahid Tondgoyan Petrochemical Company in Iran, was mixed with a solvent blend 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) from Merck, Germany, in a 70:30 ratio. This mixture was stirred at room temperature for 3 hours to ensure uniformity (28, 29). Specific weight percentages of ZIF-8 (0.5%, 1%, 2.5%, and 5%) were subsequently added to the PET solution, and the mixture was stirred again using a magnetic stirrer to achieve a consistent PET/ZIF-8 solution. Lastly, the solution was subjected to ultrasonic dispersion for 10 minutes to guarantee the complete dissolution of all components.

PET/ZIF-8 electrospinning process

The electrospinning of the Nanofiber media was executed using a two-pump/two-way electrospinning machine, model ESDP30, produced by Nanoscale Technologies Company, Iran. After transferring the polymer solutions into a plastic syringe fitted with a 21-gauge needle, various parameters crucial for the electrospinning process were examined. The optimal conditions were established based on pilot study results, as summarized in Table 1. All tests were performed under the optimal conditions listed in Table 1.

[2] Metal-Organic Frameworks (MOFs)

Table 1. Parameters used for the electrospinning process of PET/ZIF-8 polymer solution (29, 30)

Electrospinning process parameters						
Optimal concentration (%)	Electrospinning temperature (℃)	Voltage (kV)	Injection rate (ml/h)	Needle tip to collector distance (cm)	Collector speed (rpm)	Duration of electrospinning (min)
20	23-25	13	0.7	10	180	90

Investigation of the properties of the synthesized PET/ZIF-8 media

XRD[3] was used to determine the structure of the synthesized PET/ZIF-8 MOF. Field-Emission Scanning Electron Microscopy (DSM-960A Model, ZEISS, Germany) was used to study the morphology and determine the diameter of the nanofibers in the electrospun PET/ZIF-8 media, as well as the fibers in the HEPA filter. Fourier-transform infrared spectroscopy (FTIR) analysis was additionally performed to confirm the presence of MOF (ZIF-8) in the structure of the PET/ZIF-8 media.

Evaluation of the performance of the synthesized PET/ZIF-8 media

The performance of filters and media is typically assessed through parameters such as filtration efficiency for removing various particle sizes, quality factor, and pressure drop (31, 32). In this study, the pressure drop and the efficiency of the nanofibrous media in capturing different particle sizes were measured using a respirator and filter testing device (manufactured by Nanoscale Technologies Company, Iran) at a velocity of 10 cm/s (Q=30 L/min) (30).

Filters and media that exhibit high efficiency and low pressure drop yield a higher Quality Factor (Qf). Thus, it is crucial to find the optimal point that establishes a proper balance between pressure drop and efficiency of the filters and media to achieve an acceptable quality factor (33). To determine the quality factor of the nanofibrous substrates manufactured at different superficial velocities under investigation, the following formula is used (34):

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

In this formula, Qf is the quality factor (Pa^{-1}), ΔP the pressure (Pa), and ŋ0F also includes the filtration efficiency value for particles of size dp (nm).

A uniaxial tensile strength tester (Instron 5566, USA) was utilized to assess and compare the tensile strength and resistance of the produced media against each other and a HEPA filter. Tensile testing, a destructive method in materials science, involves subjecting a sample to uniaxial tension until it fails, allowing for real-time behavior recording on a computer. The tensile properties of the electrospun nanofibers were evaluated in accordance with the ASTM D882-10 standard. Samples measuring 30 × 5 mm^2 were prepared, and the testing was conducted at a constant tensile deformation rate of 10 mm/min in dry conditions. At least three samples were tested, and the average results were determined to represent the tensile characteristics of the samples (35).

Results & Discussion

FE-SEM facilitated the analysis of the morphological features and the creation of a size distribution histogram for the synthesized ZIF-8 nanoparticles. Additionally, X-ray diffraction confirmed the synthesis of ZIF-8 MOF and provided insights into its structure (Figure 1).

[3] X-ray powder diffraction

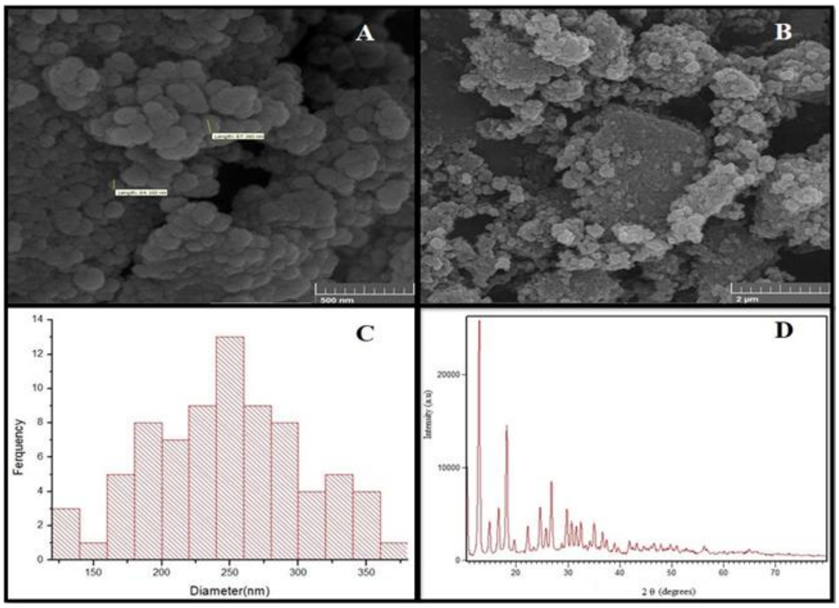

Figure 2. SEM images (A&B) and fiber diameter size difference diagram (C) and X-ray test results for synthesized ZIF-8 powder

The SEM images indicate that the synthesized ZIF-8 nanoparticles possess a nearly uniform shape, with an average size of 246.95±48.54 nm. The crystalline nature of ZIF-8 was confirmed through X-ray testing (Figure 1), aligning well with findings from previous research on ZIF-8 structures (36-38).

Following the synthesis of ZIF-8 MOF, various weight percentages of ZIF-8 (0.5, 1, 2.5 and 5 wt.%) were utilized to create PET/ZIF-8 media. FTIR analysis was subsequently performed to verify the incorporation of ZIF-8 MOF nanoparticles in the PET/ZIF-8 media structure (Figure 2).

In this study, FTIR analysis was performed to validate the incorporation of ZIF-8 within the synthesized PET/ZIF-8 composite. The observed spectral features were compared with previously identified peaks associated with ZIF-8 in existing literature. The FTIR spectrum demonstrated that the characteristic bands attributed to ZIF-8 were consistent with findings from comparable studies (39-41).

Specific peaks in the FTIR spectrum were identified at 3434.25, 2964.02, 1578.35, 1454.07, 1372.08, 973.27, and 434.66, corresponding to the unique structural characteristics of ZIF-8. Additionally, several other peaks displayed in Figure 2 were at 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, which are associated with the characteristic bands for PET (41–43).

Then, the synthesized PET/ZIF-8 media were compared with a HEPA filter (Type H13) in terms of functionality and structure.

The results of the performance evaluation (Filtration efficiency, pressure drop and quality factor), SEM images and histograms of the size distribution of nanofibers in the structure of each of the synthesized PET/ZIF-8 media and the HEPA filter (Type H13) are given in Table 2 for evaluation and comparison with each other.

According to the results of Table 2, increasing the weight percentage of ZIF-8 (from 0.5 to 5 wt.%) in the PET/ZIF-8 media led to the production of nanofibers with a larger diameter. In such a way that the electrospun PET/ZIF-8 media with a concentration of 0.5 % and 5 wt.% of ZIF-8, with an average diameter of 28.92±9.51nm and 708.44±242.60 nm, respectively, accounted for the lowest and highest diameters of nanofibers. In this study, a concentration higher than 5% ZIF-8, due to an increase in the viscosity of the solution, led to instability of the solution jet and a decrease in the efficiency of the electrospinning process. Bahmani et al. reported in their study that increasing the loading of ZIF-8 to 3 wt.% led to a gradual increase in the diameter of the produced fibers due to an increase in the viscosity of the solution (44).

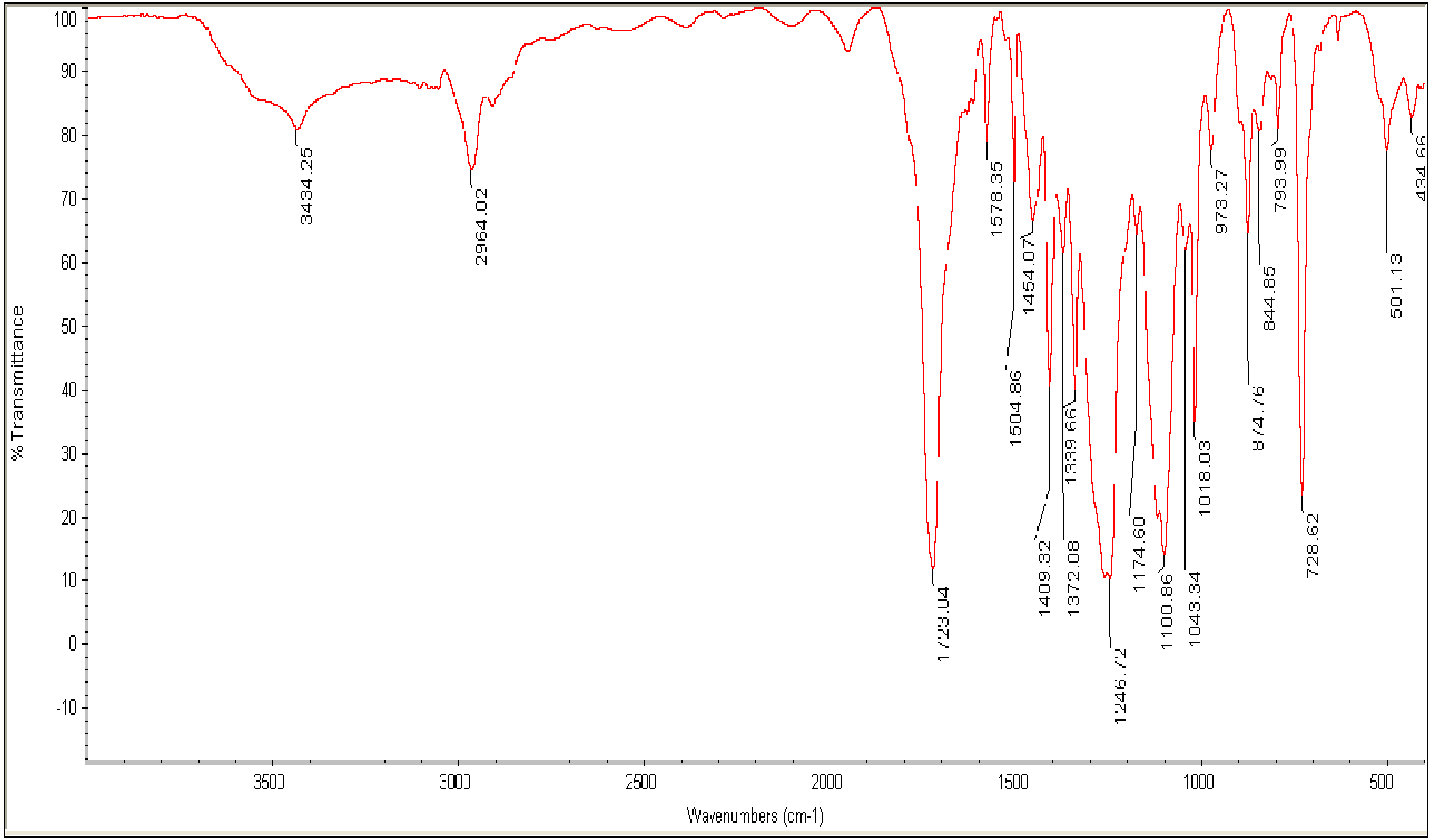

Figure 2. FTIR spectrum for PET/ZIF-8.

According to the results of Table 2, PET/ZIF-8 media (1%) with an average nanofiber diameter of 37.91±171.18 nm and QF values of 0.0143 for submicron and micron particles, had the best performance compared to other electrospun media, and it can be stated that it has a more suitable and acceptable performance compared to the HEPA filter used in this study (Type H13) with a quality factor of 0.0124 and a nanofiber diameter of about 533.52±26.10 nm). In the study of Bahmani et al., the highest increase in adsorption capacity for chitosan-g-PNVCL/ZIF-8 nanofibers was obtained when ZIF-8 was loaded to 3 wt.%, and at amounts greater than 3 wt.% of ZIF-8, the adsorption capacity decreased (44).

Table 2. Comparison of functional and structural evaluation results of electrospun media with HEPA filter

Media/filter	**Particle size** (μ)	**Filtration efficiency *** (Mean±SD)	**Pressure drop*** (Pa)	**QF** (Pa^{-1})	**Diameter** (nm)
$PET_{20\%}$	0.3	96.23±0.98	26.33±5.5	0.1536	600.37±73.55
	0.5	98.60±0.02		0.1544	
	1	99.70±0.15		0.1548	
	3	100		0.1549	
PET/ZIF-8 (0.5 %)	0.3	99.99±0.0057	366	0.0125	28.92±9.51
	0.5	100		0.0125	
	1	100		0.0125	
	3	100		0.0125	
PET/ZIF-8 (1 %)	0.3	100	320	0.0143	171.1±37.91
	0.5	100		0.0143	
	1	100		0.0143	
	3	100		0.0143	
PET/ZIF-8 (2.5 %)	0.3	97.66±0.66	128	0.0357	372.96±63.95
	0.5	98.72±0.20		0.0357	
	1	99.77±0.17		0.0359	
	3	100		0.0359	
PET/ZIF-8 (5 %)	0.3	93.16±0.70	189	0.0239	708.44±242.60
	0.5	95.69±0.41		0.0241	
	1	99.16±0.22		0.0243	
	3	100		0.0243	
HEPA (H13)	0.3	99.97	371	0.0124	533.52±26.10
	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 the speed of 10 cm/s (Q= 30 L/min) for PET/ZIF-8 media and HEPA media.

Tensile strength tests were performed on all prepared media. The strength and tensile strength of electrospun media were measured in comparison to the HEPA filter (Type H13) using a uniaxial tensile strength testing machine, the results of which are given in Table 3.

Table 3. Tensile strength test results for synthesized media in comparison to HEPA filter.

Media/ filter	Test Time (s)	Max Load (cN)	Max Extension (%)	Final Load (cN)	Extension at max Load (%)
PET 20%	23.15	1073	226.5	562.1	155.8
PET/ZIF-8 (0.5 %)	8	506.1	77.92	263.6	65.77
PET/ZIF-8 (1 %)	13.86	669.5	135.2	345.5	116.4
PET/ZIF-8 (2.5%)	3.48	271.2	33.4	141.5	26.37
PET/ZIF-8 (5 %)	2.68	149.2	25.44	78.1	17.67
HEPA (H13)	1.85	104.3	17.39	69.96	7.92

PET20% media was used in this study as a base substrate to more accurately investigate and better compare the performance of PET/ZIF-8 media with different weight percentages of ZIF-8 compared to the HEPA filter. As shown in Table 3, the values obtained for the parameters of strain, tensile load capacity, and maximum tensile load capacity by the media fibers before tearing/breaking were higher for PET/ZIF-8 media (1%) than for other electrospun PET/ZIF-8 media and HEPA filter, and hence it was identified as media with better performance in terms of tensile strength than other synthesized media and HEPA filter. Based on the results obtained, PET/ZIF-8 media that contained a lower weight percentage of ZIF-8 achieved the best performance in terms of strain, tensile, maximum tensile load capacity, and tensile load capacity.

On the other hand, PET/ZIF-8 media that contained a lower weight percentage of ZIF-8 also had a smaller average nanofiber diameter. Therefore, the small diameter of the nanofibers in the structure of the electrospun media is probably the reason for the high values obtained for the aforementioned parameters. Strain et al. showed in their study that by reducing the fiber diameter, the tensile strength of the produced fibers increased, which indicates that the results of the present study are consistent with the study of Strain (29).

Conclusion

The findings indicated that PET/ZIF-8 polymer media effectively removed particles of various sizes. When the weight percentage of ZIF-8 was increased to 5%, the resulting nanofibers demonstrated larger diameters. Specifically, the electrospun PET/ZIF-8 (0.5 wt.%) media had the smallest nanofiber diameter, while the PET/ZIF-8 (5 wt.%) media exhibited the largest average diameter. Increasing the ZIF-8 concentration beyond 5 wt.% led to increased solution viscosity, which destabilized the solution jet and reduced the electrospinning process efficiency.

To facilitate a thorough performance comparison of the electrospun media and the HEPA filter, a quality factor (QF) was defined. This factor represents the relationship between filtration efficiency and pressure drop across the media, providing a more accurate assessment of their performance. The results indicated that the electrospun PET/ZIF-8 (1%) media outperformed both other electrospun media and the HEPA filter in terms of quality factor, pressure drop, trapping efficiency, and average nanofiber diameter.

Based on the results obtained in this study, it was determined that the HEPA filter exhibited the weakest performance in terms of tensile strength parameters when compared to the electrospun media.

The use of PET, a cost-effective, readily available, and easily processed material that can be recycled multiple times, contributes to lowered production costs—an important factor in the context of air filtration and economic considerations. Additionally, ZIF-8 metal-organic frameworks (MOFs) enhance the absorption capacity of the resultant media, thereby improving the filtration efficiency in capturing and trapping particles of varying sizes.

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Ethics approval

Ethical approval for this study was obtained from Tehran University of Medical Sciences (TUMS), with an ethical identification number IR.TUMS.SPH.REC.1400.206.

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Conflict of interest

All authors have no conflict of interest, financial or otherwise.

Authors' contributions

FG, MK, and SK designed experiments. MK performed the experiments. AA reviewed the literature. FG cooperated as a consultant regarding the construction of MOF. MK wrote the manuscript in consultation with FG.

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