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A review on electrospun membranes for potential air filtration application

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Abstract

Air pollution is one of the major environmental concerns in most highly populated cities, which is typically caused by particulate ($PM_{2.5}$ and $PM_{0.1}$) or gaseous pollutants. In this framework, membranes produced by the electrospinning technique are attracting more and more interest thanks to their peculiar properties such as interconnected pore structure, tunable porosity and fiber dimension, high surface area to volume ratio and controllable morphology. This review aims to provide an exhaustive overview on the electrospun membranes applied in air filtration introducing the key principles and fundamentals of the separation mechanisms and discussing the influence of membrane properties (e.g., morphology and charge) on their filtration efficiency. The materials generally employed for the fabrication of electrospun membranes (polymers, solvents) and their combination with additives with defined properties are reviewed also in light of the new environmentally friendly approaches which are increasingly adopted in membrane fabrication. Finally, the practical use of electrospun membranes in several application fields such as individual protection devices, environmental remediation, recovery of volatile organic compounds (VOCs), and ventilation and climate control aspects is widely discussed providing also an outlook on the upscaling potential of electrospun membranes and future directions.

Key Words: Electrospinning; electrospun nanofiber membranes; air filtration; aerosols; air pollution.

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1. Introduction

The World Health Organization (WHO) has estimated and declared that around seven million people die per year due to air pollution. Atmospheric pollution is a serious matter, which can be classified into indoor and outdoor pollution. The first one, also named household air pollution, is caused by burning, in inefficient stoves or open hearths, solid fuel sources, including firewood and crop wastes, for cooking and heating. Among these non-controlled human activities, a number of compounds are extensively produced such as methane, carbon monoxide, particulate matter (PM), and volatile organic compounds, resulting in a negative impact on human health. The exposure to these compounds becomes relevant for low- and middle-income countries that often do not have access to clean fuels. On the other hand, outdoor air pollution, or ambient air pollution, is primarily caused by elemental necessities and activities in combustion processes from industries, motor vehicles, power generation, agriculture/waste incineration, among others. This later type of pollution is responsible for 4.2 million deaths per year due to heart disease, lung cancer, stroke, and respiratory diseases [1]. Apart from the inherent pollution of human activities, other natural sources of pollution are also produced such as pollen, spores, fungi, bacteria, and virus carrying-aerosols that can be responsible for various health effects, including asthma, allergy reactions, and infectious illnesses, such as influenza and chronic pulmonary diseases [2].

The hazardousness and toxicity of inhaled particles strongly depends on their dimensions. For instance, if thoracic particles with a diameter lower than 10 μm (PM_{10}) are partially blocked by nasal cavities [3,4], fine (diameter lower than 2.5 μm ($PM_{2.5}$)) and ultrafine particles (diameter lower than 0.1 μm ($PM_{0.1}$) can be deeply inhaled into the lungs and be accumulated on the alveoli causing a series of harmful effects [5] by crossing into the

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pulmonary and systemic circulations and directly affecting the heart and blood vessels [6]. Therefore, there is a need of implementing devices with ability to sequestrate both natural and anthropogenic pollutants from the air. In this sense, various air filtration materials have been intentionally studied over the last years to protect human health against particle pollution [7]. Potentially, membrane filtration can act as a physical barrier and thus remove, depending on the membrane pore size, various types of particles, molecules, contaminants, and microorganisms. Ideally, a membrane aimed for air purification must display the ability to retain exclusively the pollutant particles while facilitating the transport of air [8]. In addition to this, membranes should also meet other requirements in terms of high lifetime, low-pressure drop, easy to handle and installation, and low-production cost [9,10]. Regarding the particle's separation efficiency, current conventional air filtration membranes are based on micro-sized fibers, which in fact are not efficient enough to remove smaller contaminants than the range of 0.1-2.5 microns (i.e., $PM_{0.1}$ and $PM_{2.5}$) due to their larger pore size [11]. At this point, electrospun membranes are becoming more and more attractive as a key tool to satisfy such efficient air filtration performance due to their interconnected pore structure, tuneable porosity, and fiber dimension (from 40 to 2000 nm in diameter), high surface area to volume ratio and controllable morphology [12,13]. Graphically, **Figure 1** describes a typical electrospun membrane that present a membrane support.

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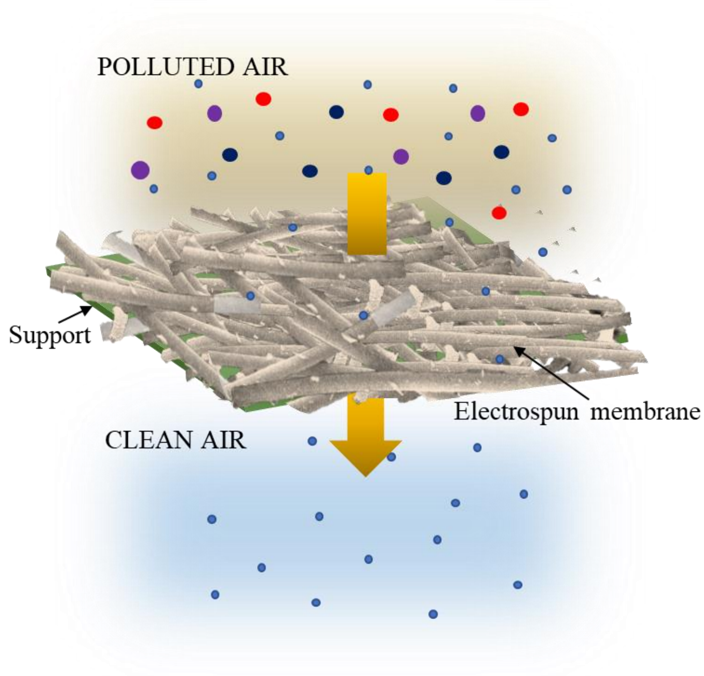

Figure 1. Graphical depiction of a typical electrospun membrane used for air filtration.

Electrospun nanofiber membranes are mostly fabricated by means of electrospinning technique, which is a very versatile technique allowing the tailoring of fibers with a very narrow diameter, a large specific surface area, a tuneable pore size, and more importantly, it gives the possibility to blend different types of nanoparticles (e.g. catalysts, antimicrobial agents) into the nanofibers and thus enhance their properties and purification efficiency [14,15]. Importantly, nanofibers can also be directly electrospun from a polymer dope solution as self-supporting membranes, but generally, the nanofibers are deposited onto a substrate made of polyethylene terephthalate (PET) or polypropylene (PP), which acts as a supporting layer conferring mechanical stability to the nanofiber.

Figure 2.a shows the publications during the last ten years. It is clear that the academic interest in this research area has continuously increased and by 2019 over 50 papers per year were published. **Figure 2.b** provides a general overview of the publications by type.

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About 80 % of the publications used are articles published in academic journals. The other 20 % is divided by reviews, conference papers, book chapters, conferences and review conference.

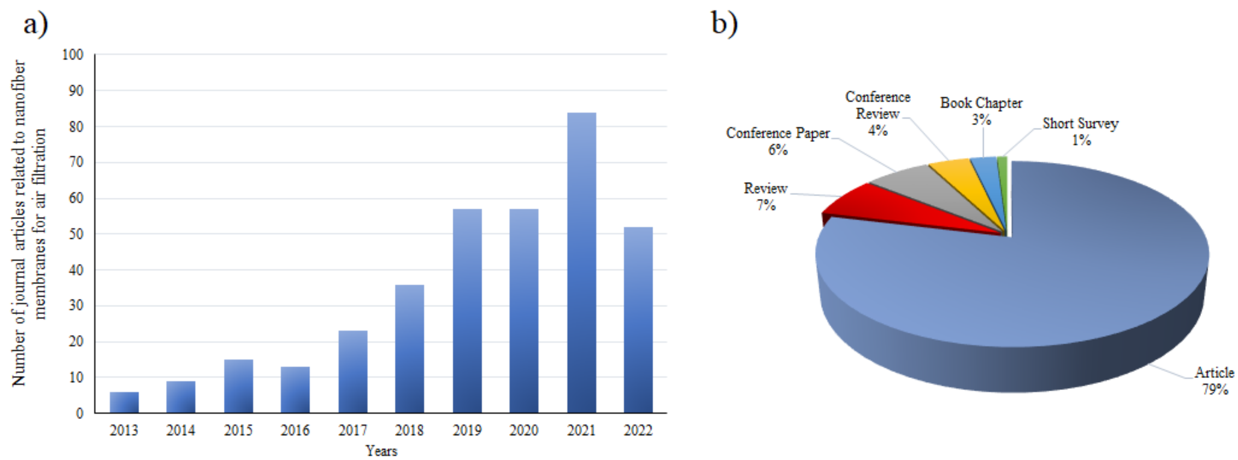

Figure 2. a) Journal articles and b) document types related to nanofibers for air filtration over the past 10 years (updated until July 2022). Search engine: Scopus using the keywords "nanofiber membranes" and "air filtration".

Reviews on various aspects of electrospun membranes for air filtration have been published in the last two years (2021-2022). Most of them focused on nanofiber materials for that specific application. The research of Zhou Y. et al. [16], for example, based their approach on the characteristics, advantages and disadvantages of single-polymer, composite or hybrid nanofibers. Deng Y. et al. [17] proposed to assess the performance of nanofibers prepared from bio-based polymers and novel bio-matrix such as cyclodestrin, lignin and konjac glucomannan (KGM). Another interesting work was also proposed by the group of Lu T. et al. [18]. They summarized the performance of electrospun air filtration membranes (EAFMs) with different structures such as nanoprotrusion, wrinkled, porous, branched, hollow, core–shell, ribbon, beaded, net structures. Ji et al. [19] introduced some basic concepts involved in particulate matter (PM) filtration, such as classification and source of

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PM, classic filtration mechanism, and the key evaluation parameters of PM filtration. Moreover, Schneider R. et al. [20] described recent advances on the post-modification strategies of spun micro/nanofibers surfaces using 0D, 1D, 2D, and 3D inorganic structures while the group of Valecia-Osorio L.M. et al. [21] studied the electrospinning process for air filtration nanofibers through three moments: solution preparation, fabrication parameters and post-treatment techniques. In this review, we have provided a comprehensive overview of the different aspects of electrospun membranes for air filtration. We initially introduced the key principles and fundamentals of the filtration mechanisms involved in electrospun nanofibers for air filtration, along with the influence of membrane properties (e.g., morphology and charge) on their separation filtration efficiency. Lately, we reviewed the preparation procedures employed for their fabrication overviewing the membrane materials, solvents, additives, electrospun configurations. ~~and finally~~ Finally, we presented the practical applications of nanofibers in air filtration such as individual protection devices, ventilation and climate control, recovery of volatile organic compounds (VOCs) and environmental remediation. We also focused the attention on the upscaling potential of nanofiber air filters, the current companies for electrospun membranes production and the future challenges.

2. Filtration mechanism in electrospun membranes

2.1. Theory

~~Even if~~ Air filtration has a long history ~~and~~ consolidated over time and is closely linked to industrial and technological developments. However, until the last century ~~that~~ it was not possible to find theoretical studies elucidating the various filtration mechanisms [22]. More

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importantly, the lack of steady-state during filtration, which is characterized by the variation of process efficiency over time together with airflow resistance because of particles deposition, makes it challenging and limits a comprehensive description of the phenomena [23].

Considering a moderate concentration of particles in the air, the particle accumulation on the filter is minimal and does not alter the effective diameter of the nanofibers. Thanks to this, the air filtration performance of an electrospun fibrous membrane is usually considered stable (i.e. steady-state) [2]. Then, according to the widely known theory, filtration occurs due to the following trapping mechanisms: interception, inertial impaction, Brownian diffusion, electrostatic effect, and gravity effect, as represented in **Figure 3~~2~~**.

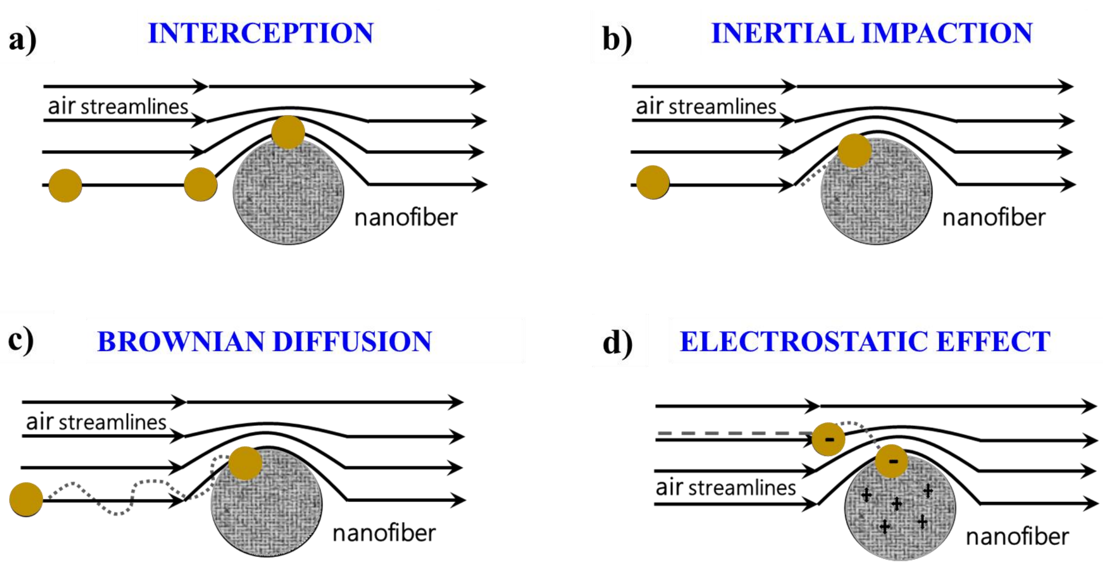

Figure 3~~2~~. Graphical depiction of the air filtration mechanisms through electrospun nanofibers: a) interception, b) inertial impaction, c) Brownian diffusion, d) electrostatic effect.

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Typically, the particles tend to flow together with the air streamlines and are intercepted while contacting nanofiber surface due to the van der Waals forces (see **Figure 3.~~2~~a**). This latter phenomenon, so-called interception, is recognized as the primary filtration mechanism. The interception is indeed independent of the flow velocity but still efficient for capturing particles with size ranged from 0.1 to 1 μm [24].

Since the electrospun membranes own randomly oriented nanofibers, the pathway of the streamlines is commonly tortuous through air filtration. Particles often deviate from the airflow line due to the effect of inertia force, impact subsequently against the nanofibers, provoking an effective filtration thanks to the inertial impaction [25]. Of course, smaller particles can succumb to the drag effect and be transported with the streamlines, while the inertial momentum increases with the particle size and may overcome the drag force in the case of larger nanoparticles, which causes a perceptible deviation from the streamlines and, as a consequence, the impact against the nanofibers [26], as illustrated in **Figure 3.~~2~~b**. Herein, the efficiency of inertial impaction increases as a function of the particle size and it is affected by the air velocity.

In addition to this, particles could slightly and arbitrarily deviate from their original flow line thanks to the Brownian motion (see **Figure 3.~~2~~c**), and pronounced divergences guarantying the diffusion of the particles towards nanofiber and then a consequent interception [27]. This latter phenomenon typically occurs for particles smaller than 1 μm.

Besides the previous mechanisms, Coulombic attraction between charged particles and unipolar or bipolar charged nanofibers substantially improves the filtering efficiency, as represented in **Figure 3.~~2~~d**. It is worth mentioning that neutral particles can be also polarized by unipolar or bipolar charged nanofibers or dielectrophoretic forces originated

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by an external field [28]. Ultimately, the contribution of the gravity effect tends to be negligible for particles smaller than 0.5 μm.

Definitively, the sum of the contributions of each mechanism of filtration- which are significantly affected by the particle size- determines the overall air filtration efficiency of electrospun membrane (**Figure 4**).

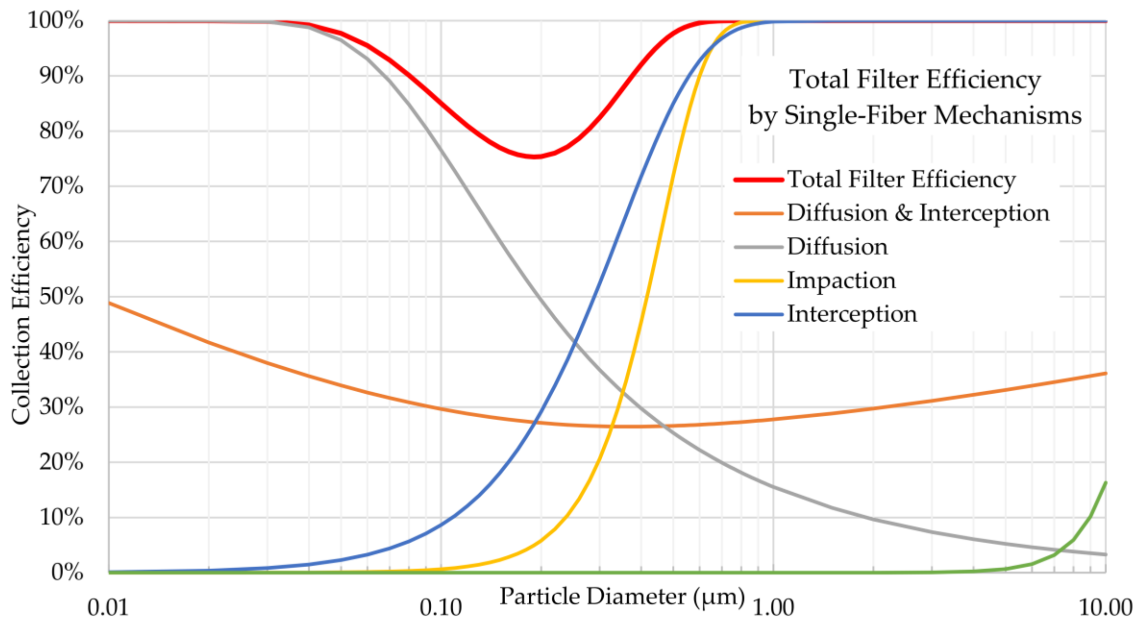

Figure 4. Filtration efficiency of a single nanofiber and contribution of the different mechanism of air filtration modelled with a Digital Twin [29]. This work is licensed under a Creative Commons Attribution 4.0 International License.

2.2. Effect of membrane structure

As it is well known electrospinning is a versatile technique for the fabrication of efficient air filters possessing high level of control on membrane morphology. Handling the operative parameters of the electrospinning, as well as the chemical-physical properties of the polymeric dope solution, is feasible to tailor different features of the nanofibers such as their diameter, pore size, porosity and the packing density. These morphological and structural features of the air filters meaningfully affect their performance. In general, the

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filtration efficiency, represented as η, is usually described by the Kuwabara model, as follows (1):

$$\eta = 1 - exp\left[\frac{-4\eta_s \alpha L}{\pi d_f (1-\alpha)}\right] \quad (1)$$

where η_s represents the filtration efficiency of a single fiber, α corresponds the fiber volume fraction (i.e., packaging density), d_f represents the average fiber diameter, and L is the filter thickness [30]. For instance, Eq. 1 spells out the robust dependence of the filter efficacy on its structural and morphological properties, which is inversely proportional to the nanofiber' diameter. Such description has been proven by experimental results as with polyacrylonitrile (PAN) transparent electrospun nanofibers demonstrating a decrease of the filtration efficiency ($PM_{2.5}$) from 98.11±1.41% to 48.21 ± 4.19%, as a result of their diameter increase from ~0.2 to approximately 1 μm [31].

Surprisingly, nanofibers with a tiny diameter display minor pressure drop due to the slip effect induced by unique aerodynamic conditions [32] (**Figure 5a**). Actually, the diameters of electrospun nanofibers (d_f) and the mean free path of air molecules (λ) are comparable, while the Knudsen number (Kn), expressed as $Kn = 2\lambda/d_f$, achieves values ranged from 0.1 to 10, which correspond to transition flow regime (**Figure 5b**). Here, the drag force is substantially reduced and the air velocity on the nanofiber's surface is non-zero. This means that the slip flow reduces the friction effect, the air molecules bypass the nanofibers with the maximum probability of alleviating the pressure drop [31,33], as systematically proved by a study on 122 nanofibers [34].

Of course, the high porosity is fundamental in reducing the pressure drop in combination with "through" open pores, while "blind" closed pores remain as undesirable. Importantly,

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pore size becomes also crucial for meeting a good performance in terms of filtration efficiency and permeability: small pore sizes gives an effective filtration but limit the permeability by promoting the pressure drop [35].

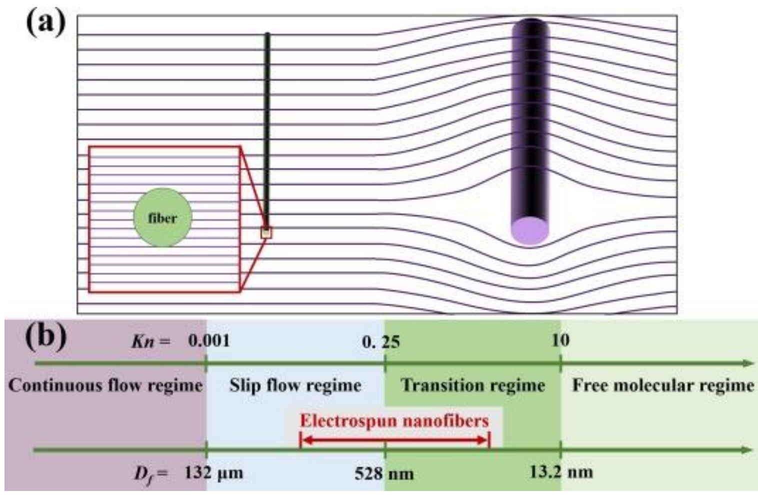

Figure 5. (a) The air flow field around two single fibers with different diameters according to the Kuwabara Model and (b) Knudsen numbers and fluid flow regimes of the electrospun fibers. Reprinted from [36] with the permission of Elsevier.

2.3. Effect of membrane and particle charge

As explained previously, Brownian motion is the random motion of particles suspended in the air, which is a result from their collision with the fast-moving of particles. However, this phenomenon is identified at a specific range of particle size. Particles with size smaller than ≈1 µm exhibit a significant Brownian motion [37], causing diffusion and deposition on the membrane surface, particularly in fibers [38]. Notably, Brownian motion becomes relevant with the decrement of particle size. Apart from described phenomena, if both particles/molecules or fibers are charged, the electrostatic effect is another parameter that interferes [39]. Theoretically, there are two ways to induce electrostatic forces in a

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membrane air filter; the first one is directly related by charging the airborne particles, while the second one can be a results of producing an electric field in the membrane [28]. In recent times, this latter scenario has been investigated by embedding inorganic nanofillers in membranes independently if the electrospun fibers already displayed any charge. It is worth mentioning that within the electrospinning process, the used high positive voltage may potentially confer a charge into the polymer solution, which certainly contributes to the formation of volume charges and surface charges [7].

A charged particle (i.e. airborne particle) polarizes the fiber releasing a force that is equal to the Coulombic force among the charge and the particle, but it is opposite to the charge located inside the fiber at a position related to the optical image of the particle. Usually, the image force is not highly crucial unless the particles own extremely high charges. The electrostatic interactions, along with Coulombic interactions and polarization forces [40], can indeed shift the pattern flow of particles in comparison with the initial air stream, this may promote particles to deposit onto the membrane surfaces. Potentially, the electrostatic effect will also promote the particle adhesion onto the fiber surfaces. This latter effect has been commonly utilized in various aerosol filtration devices during the separation of sub-micrometer particles [41], which in fact can enhance the particles' collection efficiency [28]. As an example, nanofibrous mats containing boehmite nanoparticles, proposed as electret filter, have shown exceptional separation performance by using the nanonomaterials, which played ~~as~~ an electrostatic charging agent [42]. In such research, PA6 nanofibers were fabricated via electrospinning, obtaining an average fiber diameter between 73-90 nm. Here, boehmite nanoparticles were smartly incorporated to induce higher electrostatic charging characteristics of the unfilled PA6 nanofiber. It was concluded

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that the filtration properties of PA6 nanofibers were mainly ascribed to the electrospinning and the corona charging device [42]. Alternatively, the electrically charged nanoparticles contained in polymer fibers may also provide another perspective when dealing with air disinfection, since electrostatic interactions between microorganisms and charged particles can lead to cell wall rupture, and thus the death of the possible bacteria, fungi, and viruses [43,44]. This has been evidenced by Selvam and Nallathambi [45], who observed a 99% bacterial filtration efficiency when using 10-12.4 wt.% of Ag nanoparticles into PAN composite membranes. Ag nanoparticles have ben also merged into electrospun fibers. In this case, Zhang et al. [46] have utilized -C(NH_2)=N-OH groups, coming from the reaction of hydroxylamine and acrylic on PAN substrate, to smartly coordinate Ag^+ ions [46]. As expected, the electrospun nanofibers displayed efficient antimicrobial properties, and no substantial morphological changes were observed in the resulting fibers while maintaining the filtration efficiency.

It is important to point out that electrically charged fibers tend to create in its vicinity an electric field, which displays a force provoking the movement of a charged particle. Apparently, the field produced by a charged fiber could polarize a particle as well, unfortunately, such force on a polarized particle is considered negligible for small particles [47]. In particular fibers, such as electret fibers, ~~they can display~~ a permanent line dipole charge can be observed which results in a non-uniform field. Notably, the field may also provoke a dipole charge in a particle but it does not represent a relevant issue ~~fact~~ for small particles.

It is worth mentioning that the implementation of aerosol filtration via electrostatic forces is likely to be challenging, but it has been already investigated. As an example, the Hansen

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filter represents the first pioneering development and application of electrostatic forces in aerosol filtration. Hansen discovered that the collection efficiency can be notably improved when a wool filter was charged with colophony resin particles. Such an improvement induces a better action of electrostatic forces [28]. Resin particles of approximately 1 mm in diameter can be ~~be~~ negatively charged by contact (triboelectric charging). The charge was maintained on the resin particle for a long time due to the fact that the resin owns good electrical isolate agent. Electret filters have been initially based on dielectric fibers with a quasi-permanent electrical charge. Unfortunately, membrane filter devices charged electrostatically were fabricated using polymeric fibers including PP, PET, and nylon-6 (PA6). All fibers show relatively high electrical resistivity allowing them to be electrified via corona charging, triboelectrification and induction. The applications of such electrostatically charged filters can be extended to other relevant approaches, such as face masks, building air conditioning systems [48], automobiles, air purifiers, to mention just a few [42,49,50].

In current times, researchers are endeavouring on the design and development of innovative electrically charged membrane materials to fabricate more efficient filtration systems. Al-Attabi et al. [51], for instance, developed silica doped electrospun nanofiber membranes with tuned surface roughness for potential aerosol air filtration, which revealed filtration efficiencies as high as 95%. The research also pointed out that both surface charge and electrostatic attraction of aerosol particles could also foster the air filtration performance improvement of tetraethyl orthosilicate (TEOS)/PAN electrospun nanofibers. Simultaneously, the filtration efficiency of polyvinylidene fluoride (PVDF) electret nanofiber filters was also evidenced by Sun et al. [52], who studied the dielectrophoretic

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effect toward neutrally charged nano- and sub-micron aerosols. Their size was ranged from 50 to 500 nm. Theoretically, the dielectrophoretic effect involves the induction of dipole charges on neutrally charged aerosols as long as they are close to the charged nanofibers; afterward, the polarized aerosols can be electrostatically caught by the charged fibers [53]. Apart from the stability for 24 h operation, the PVDF fiber filters displayed high filtration efficiency and low-pressure drops. Punctually, the long-time operating effectiveness of the electret multi-layer membrane filter was credited to the superhydrophobic properties and exceptional electrical resistant properties of PVDF, leading to suitable electrostatic charge stability and thus stable filtration performance [54,55].

3. Electrospun nanofiber materials for air filtration

Most of the research has been focused ~~emphasized~~ on the exploration of different classes of polymers ~~with the view of~~ for tailoring nanofibers properties to be used in different ~~for various~~ applications, but particularly for air filtration at room and high temperatures. The choice of utilizing several ~~relative~~ materials either polymeric or biopolymeric, organic or inorganic additives, and appropriate solvents, for the fabrication of fibers ~~aimed for air filters~~ becomes relevant from the fluid dynamics point of view, since the properties of a polymeric solution in terms of viscosity, surface tension, and conductivity may have ~~display~~ a great impact on electrospinning process parameters [35]. Initially, polymers, as organic materials, have been primarily explored for the fabrication of electrospun nanofibers with ~~an~~ application in the air filtration. Polyimide (PA) [56,57],

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~~polyacrylonitrile (~~PAN~~)~~ [58], polyurethane (PU) [11], polysulfone (PS) [59], polyamide-56 [60] and polyamide-66 (PA 6,6) [61] are, for example, among the most utilized polymers in nanofibers preparation as enlisted in **Table 1.** ~~enlists some of these polymers successfully used in nanofibers prepared by electrospinning aimed for air filtration applications.~~ However, according to the current necessities in finding better materials, the merging of inorganic materials into polymer phases has conducted to the fabrication of mixed matrix nanofibers or composites. Today, the preparation of this latter type of membranes stands out as compelling strategy at enhancing the filtration efficiency of nanofibers while improving their chemical, mechanical and thermal stability together with enhanced antimicrobial properties [55,62]. Various nanomaterials, such as TiO_2 [63], SiO_2 [64], ZnO [65], and Ag nanoparticles [63], have been successfully imbedded into polymer nanofibers.

Table 1. Polymer electrospun nanofibers fabricated via electrospinning. Adapted from [35].

Polymers	**Polymer conc.**	**Solvent**	**Electrospinning parameters**			**Ref.~~erence~~**
			Voltage	Flow rate	Distance	
	(wt%)		(kV)	(ml/min)	(cm)	
PVA	10	Boric acid (BA)	15	0.5	15	[66]
	35.5	N,N-dimethylformamide (DMF)/acetic acid (AA)	24	0.5	16	[15]
PVA/ TiO_2	-	Water	14	-	15	[67]
PA 6/6	9-14	Formic acid (FA)	20-50	0.25	11-16	[15]
PA 6	12	2,2,2-tri-fluoro ethanol (TFE)	8-20	0.3	15	[68]
PAN	15	DMF	19	0.8	20	[15]
	-	DMF	12.5-22.5	2	10-16	[69]
PAN/ SiO_2	-	DMF	30	1.5	15	[62]
PU	-	DMF	10-30	0.6-1.2	20	[70]

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The following subsections give an overview of the different materials applied in electrospun nanofiber fabrication via electrospinning technique.

3.1. Polymers

~~Polyamide (~~PA~~)~~, PAN, and fluoropolymers such as PVDF and polytetrafluoroethylene (PTFE), are among the most used ~~preferred~~ polymers by the research community due to their inherent high chemical and thermal stability [71,72]. They also offer the advantage of excellent processability for spinning and versatility to be adapted in various membrane preparation protocols. For instance, PA is a widely investigated polymer for tailoring filters thanks to its ability to be dissolved by different solvents, such as formic or acetic acid, or dimethylformamide (DMF), to mention just a few. It also displays resistance to water and thus humidity. It is biocompatible and presents a good mechanical resistance. Promisingly, several researches documented the preparation of fibers from two types of PA, named PA 6 (Nylon 6) and PA 6,6 (Nylon 6,6) [73,74]. These membranes were able to perform ~~for~~ air filtration due to interesting features including their small diameter, narrow diameter distribution, large surface area, and electrostatic charge [75]. A comparative analysis among PA 6 and PA 6,6 fibers has been done by Matulevicius et al. [76], who concluded that PA 6,6 fibers were likely to be the most performing ones. In particular, electrospun fibers formulated with 8 wt.% of polymer concentration exhibited a filtration efficiency ranging from 84% to 90% with a quality factor (QF) from 0.0486 to 0.0749 1/Pa.

PAN is yet another synthetic polymer with exceptional thermal resistance (degradation above 300°C). The polymer is inert to plenty of organic solvents and acids and certainly

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displays good processability. PAN fibers also represent a valid choice in producing carbon membranes, e.g., they can be used as precursors for high-quality carbon fibers [77]. It has been reported that PAN nanofibers have demonstrated high mechanical and thermal stability, together with good efficiency for gaseous pollutants filtration in respect to other polymer fibers [15]. Additionally, they can be operated in a wide and extreme hazardous air-quality conditions ($PM_{2.5}$ index >300, exhibiting an efficiency of 95-100% ascribed to the surface capture ability and higher dipole moments [31].

Fluorine polymers on their own present also advantages due to~~,~~ ~~such as~~ presence of the C-F bond, which is stronger with respect to the C-H bond. The use of F instead of H in the C-H bond fosters the bond strength that passes from 99.5 kcal/mol for the C-H bond to 116 kcal/mol for the C-F bond, resulting in a higher thermal and chemical stability of PTFE, ~~this is because more~~ because of the high energy ~~is~~ needed to break the C-F bond [78] considering that the fluorine atom is larger than hydrogen and it has unshared electron pairs with higher electron density. Polymers presenting more fluorine atoms (such as PTFE) own a high melting point, low coefficient of friction (e.g., PVDF: 0.3 Dynamic and PTFE: 0.04 Dynamic), and low surface tension (e.g., PVDF: 25 dyne/cm and PTFE: 18 dyne/cm). Interestingly, the C-F bond is mainly responsible for the insolubility of the polymer in common solvents; PTFE, for instance, is fully overlaid with fluorine atoms and frequently demands high temperatures to be solubilized; while, PVDF, presenting the C-F bond and the C-H bond in the structure, shows greater flexibility to be solubilized in different solvents. Fiber filters based on fluoropolymers tend to show high filtration efficiency with low-pressure drops and good filtration stability over time. On the other hand, PVDF filters present high hydrophobic nature and a suitable electrical conductivity, allowing them to

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display good charge stability and stable filtration performance [54,79]. PVDF filters were combined with the typical air conditioning filters meshes based on polyester, PA, and nylon for the air filtration of $PM_{2.5}$~~2.5~~ (PM with aerodynamic diameter ≤ 2.5 μm) [80]. Also, polyvinylpyrrolidone (PVP) and silver nitrate crystals were incorporated into the dope solution to reduce defects or beads ~~while~~ benefiting also of the ~~for~~ antibacterial properties. The scope of this study was devoted to outline the importance of the materials, such as polymers, meshes, and the operating preparation parameters (such as voltage: 40, 45, 50, 55, 60 kV) on the final nanofiber's features and thus performance. By using polyester 80 mesh material, the QF turned to be the largest at 40 kV (QF: 23 10^{-3}), the smallest at 45 Kv (QF: 21 10^{-3}), with a filtration efficiency of 90%. Thanks to the properties of PVDF, the recent development works rely on the production of novel electret fiber filters with high strength, low air resistance, and outperforming for long-term aerosol filtration [52,81].

Similar to PVDF, PTFE fibers stand out as alternative candidates for air filtration thanks to their high-temperature resistance, low-pressure drops, and high efficiency. The filtration operation presenting PTFE filters take places at the surface of the fibers, which make them suitable for a number of applications in high-efficiency particulate arresting (HEPA) and ultralow penetration air (ULPA) in class cleanrooms. Very recently, Xu et al. [66] fabricated and then tested PTFE nanofiber membranes for fine particulate filtration. In this study, the filtration performance against aerosol particles was as high as 98% with a relatively low-pressure drop (ca. 90 Pa). At this point, the area of the filter acted as the contact surface, and due to its microporous structure, expressed as millions of pores per square centimetre, the submicron particles were successfully separated. It is important to mention that the layer below played merely as a support and its contribution to the filtration

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process was considered as negligible. Strictly, the evaluation performance of these fibers must be suitable for the filtration of particle sizes comparable with dust particles, which are much larger than the pore size of the fibers, permitting only gas molecules to go through. Its main disadvantage deals with the fouling phenomenon that can occur at the surface. In other words, the particles can potentially form a cake layer on the surface of the material, which will definitely compromise its separation performance [82]. Aiming to address this latter point, several cleaning strategies have been investigated to restore the functionality of the membranes including the passive cleaning with carbon particles [66] or synergic effects based on adsorption photochemical catalysis, non-thermal plasma photocatalysis, among others [22].

3.2. Biopolymers

In recent times, there is a strong necessity to produce and apply biopolymers [83,84], produced from raw materials, for manufacturing nanofibers aimed for different membrane separation techniques, but specially for air filtration. As an example, polyurethane (PU) is a polyester that can be found in soft and rigid forms. It has a hydrophilic nature and it is ~~of course~~ derived from renewable sources [85,86]. PU fibers have shown fast absorption of volatile organic compounds (VOCs) at both surface and the polymeric matrix, revealing a competitive uptake capacity compared with traditional adsorbents such as activated carbon [70].

PVA is yet another biopolymer that owns a semi-crystalline structure presenting hydroxyl groups and hydrogen bonds. Interestingly, it is a water-soluble polymer with exceptional hydrophilicity and good adhesive and barrier properties [87]. It is worth mentioning that

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has been investigated in producing membranes for selective gas and solvent separations [71,88,89]. When dealing with air filtration applications, Lv et al. [90] blended PVA with a high molecular weight polysaccharide, like konjac glucomannan (KGM), ~~to obtain~~ displaying an efficiency of 99.9% in air filtration testing. A mixture of DEHS and neutral monodispersed NaCl were employed as model aerosol particles with diameter ranging from 300 nm to 10 μm.

Poly(lactic acid) (PLA), made up of elements similar to lactic acid, is characterized by excellent processability and high melting point temperature between 170-180 °C, and T_g values in the range of 50 - 65°C [83,91]. An important environmental aspect behind PLA regards its ~~a~~ low carbon footprint , making it as a good candidate for the production of fibers for air filtration [35,86,92]. Finally, poly(acrylic acid) (PAA) [93] polyethylene oxide (PEO), polyvinyl acetate (PVAc) [15], keratin, chitosan [94], and aliphatic polyhydroxy-butyrate (PHB) [95–97] are among other biopolymers to be potentially used for nanofibers production and implemented in air filtration.

3.3. Nanomaterials and other additives

The application of additives, such as inorganic materials or salts, within the fabrication of nanofibers for air filtration applications, are frequently needed to improve not only the filtration efficiency but also the pressure drop and QF. Presently, it is a common practice the blending of additives in the electrospinning technique in order to favour the formation of nanofibers. For instance, the incorporation of additives results in a viscosity increase of the solution and, in some particular cases, in the reduction of the fibers diameter ~~of the~~

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~~fibers~~. Common salts are generally LiCl [79,98], tetraethylammonium bromide (TEAB) [99], $NaNO_3$, NaCl, $CaCl_2$ [100]. ~~In the case of~~ LiCl has an electrical conductivity estimated about 394 µS cm^{-1} and it can be employed for changing the conductivity of the solution and thus improving the charge density on the surface of the charged jet. This latter fact becomes relevant in producing nanofibers with a more uniform morphology. TEAB, for example, exhibits similar conductivity than LiCl in water. In general, salts dissolve in the aprotic solvents in which the solvation can depend on the dielectric constant of the solvent (known as general solvation), or the chemical structure of both solute and solvent (known as specific solvation) [99,101]. Metal oxides, including Al_2O_3, TiO_2, SiO_2, β-cyclodextrins (β-CDs) [55,67,102,103], and ZnO [90], are other additive agents that can increase the surface roughness of the membranes, and particularly TiO_2 exhibits antimicrobial and photocatalytic activities [104]. TiO_2 particles have been involved in nanofiber production reducing the diameter of PS [59] and PVA nanofibers [105]. Another important material is graphene oxide (GO), which has received considerable attention lately [106–108]. GO has improved the filtration efficiency of $PM_{2.5}$ (~ 99%) - thanks to its ability to effectively absorb $PM_{2.5}$ particles (**Figure 6.a**) - demonstrating an excellent air filtration system in combination with PAN nanofibers [107].

Silver nanoparticles (Ag NPs), which are also known by their inhibitory activity towards various bacteria [109], are typical dispersing inorganic phases in biocomposite nanofiber fabrication. Zinc oxide nanoparticles (ZnO NPs) can improve the surface roughness resulting into ~~translated to~~ a uniform narrow pore size distribution with an almost complete air filtration efficiency (approximately 99.99%). β-CDs, which are cyclic oligosaccharide presenting seven glucose units, are commercially available, low-cost, non-toxic,

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biodegradable items derived from starch digestion. Such compounds have been recently investigated in air filtration applications according to their particular cone-shaped cavity structure. β-CDs have been involved for composite nanofibers preparation based on classic polymers, such as PAN, where it has improved the adsorption capacity against VOCs. Additionally, the combination of β-CDs with biopolymers, such as gelatin, allows the production of bio-nanofibers ~~as a green solution and~~ as a green alternative solution to ~~the use of~~ fossil-based materials. As an example, composite gelatin/β–cyclodextrin nanofibers displayed the ability to separate aerosol particles (0.3–5 μm) with <95% filtration efficiency at 0.029/Pa [110]. Such biodegradable nanofibers owned a uniform morphology with a second "web" structure, characterized by superimposed and interconnected fibers which presented a much smaller dimension than the main nanofibers, as showed in **Figure 6.b**.

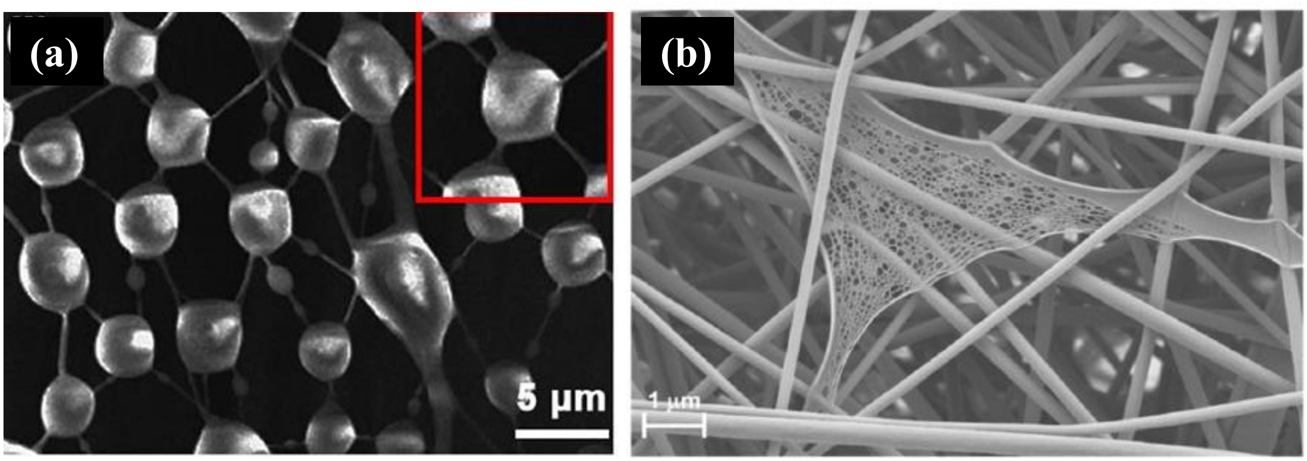

Figure 6. (a) Absorbed PM2.5 particles on the PAN/GO. Reprinted (adapted) with permission from [107]. Copyright 2019 American Chemical Society. (b) SEM images of composite gelatin/β–cyclodextrin nanofibers with "web" structure. Reprinted from [110] with the permission of Elsevier.

~~*3.4.*~~ 4. Solvents for electrospun membranes

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~~The~~ Solvent is an important component ~~dealing with the crucial items needed~~ necessary for the fabrication of most polymeric membranes ~~in membrane fabrication~~. ~~This becomes relevant since it~~ In electrospinnig processes, the solvent favours the formation of various interactions between materials ~~in the electrospinning process~~. Also, the physicochemical properties of the solvent can influence the morphology and more importantly the pore size diameters of the resulting fibers. The solvent influences drastically the dope solution properties such as viscosity and conductivity. To date, chloroform, DMF, and dimethylacetamide (DMA) were found to be the best solvents for fabricating nanofibers. Herein, solubility parameters are ~~essentially~~ pivotal to estimate solvent-polymer ~~the~~ affinity [111]. In theory, very close solvent-polymer parameters reveal a good solubility and also the possibility to electrospin the solution at room or mild temperatures. With the aim of tailoring defect-free nanofiber membranes, a second volatile solvent, such as acetone or alcohols, are usually utilized in combination with the main solvent. The usage of this co-solvent increases the time of solvent evaporation during the fibers formation thanks to the high vapour pressure, ~~this promotes~~ promoting the production of uniform 3D nanofiber networks ~~in nanofibers~~ [112]. National and international regulations limit the use of dangerous chemicals and encourage ~~promote~~ the transition to more sustainable and less toxic alternatives [113]. A series of other green solvents derived from biomass have been recently proposed for the fabrication of polymeric membranes (in flat-sheet and hollow fiber configuration) including dimethyl isosorbide (DMI) [114], γ-valerolactone (GVL) [115], dihydrolevoglucosenone (Cyrene™) [116] ionic liquids [117] and/or deep eutectic solvents (DESs) [118,119]. Recently, Russo et al. [79] produced PVDF electrospun membranes using dimethyl sulfoxide (DMSO) as a low toxicity solvent in a mixture with

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acetone. The results obtained have opened new perspectives for more sustainable production of electrospun membranes. The research in this direction remains open and attractive for the next future.

~~4.~~ 5. Characterizations and performance evaluation

It is widely known that the design and development of a new membrane concepts implies the characterization and performance when implemented in a specific membrane process. For instance, **Table 2** lists main ~~characterization~~ techniques used for the characterization of electrospun nanofiber membranes.

Table 2. Typical characterization methods and techniques used for electrospun nanofiber membranes. Adapted from [120].

Characterization	Method
Pore size	Bubble point method
Pore size distribution	Permporometry
Pore size distribution	Gas and liquid displacement methods (GLDP-LLDP)
Pore size distribution	Mercury porosimetry (MP)
Morphology, thickness	Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM)
Surface porosity, roughness	Atomic force microscopy (AFM)

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Studies of chemical group	Infrared Spectroscopy (FT-IR, ATR, Photoacoustic)
Surface studies, chemical analysis	Energy Dispersive X-rays Spectroscopy (EDX or EDS), wavelength dispersive X-ray spectroscopy (WDS)
Thermal analysis	Differential Scanning Calorimetry (DSC)
Wettability	Contact angle measurement
Mechanical properties	Mechanical resistance, Stress-Strain measurements
Chemical stability	Swelling and contact angle

In general, the characterizations methods reveal important information about the morphology, structural, physical, chemical and thermal properties. ~~While~~ When dealing with air filtration, a dust filtration set-up is usually employed to evaluate the typical filtration parameters including filtration efficiency and pressure drop. In this experimental testing, particles, with size ranged from 0.6 to 180 µm, are commonly used and fed at a given air velocity [121]. The filtration efficiency of each fiber membrane ~~for air filtration~~, which results in overall filter efficiency, is expressed ~~denoted~~ as follows (2) (3) [39]:

$$\eta_s = \frac{\text{particles collected by fiber}}{\text{particles in a volume of air geometrically swept out by fiber}} \quad (2)$$

$$\eta = 1 - \exp\ (-\eta_s\, S) \quad (3)$$

where η_s refers to the filtration efficiency of a single fiber, S refers to the filter area factor, which is the projected area of fiber per unit of filter area, and η denotes the overall filter efficiency.

In addition to the high filtration efficiencies, electrospun membranes also display antibacterial properties during the filtration of air, which not only presents submicron

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aerosol particles but also specific microorganisms (e.g., bacteria). Recently, Vanangamudi et al. [55] engineered new composite nanofibrous based on PVDF and Ag–Al_2O_3, with excellent antibacterial efficiency as high as 99.5%. Additionally, detoxifying properties higher than 35% against paraoxon were observed. In aerosol filtration containing particles (diameter of 0.36 μm), the filtration efficiency rate increased proportionally to the Al_2O_3 content, ranging from 2 to 8 wt.%. The filtration efficiency depended on the nanoparticle loading, achieving ca. 99% filtration efficiency (at 8 wt.% Al_2O_3 loading). Furthermore, the composite nanofibrous membranes revealed apparently stable antibacterial properties over 99% towards *E. coli* [55]. In a different investigation, Ding et al. also evidenced competitive filtration efficiency ranging from 80 to 90% of electrospun PVDF/SiO_2 nanofibrous membranes [122]. This latter development confirms the effect of nanoparticles into pristine polymer nanofiber ~~with an~~ in enhancing the filtration rate. Concurrently, Cannalli et al. [63], for instance, evaluated various inorganic particles into PAN nanofibers, including TiO_2, ZnO, and Ag. Basically, all membranes performed with an average filtration efficiency, but interestingly TiO_2-containing membranes owned the smallest fiber diameter along with a complete filtration efficiency (ca.100%).

Shao et al. [123] have intentionally designed self-powered electrospun nanofiber membranes for highly efficient air filtration. In this approach, the proposed electrospun membranes were fabricated based on polyvinyl chloride (PVC) nanofibers and polyamide-6 (PA6) nanofibers. By inducing air vibration, the triboelectric effect between both adjacent nanofibers resulted in electrostatic charges, which contributed to observe electrostatic adsorption capacity. Experimentally, the removal efficiency of the designed nanofibers was as high as 98%, while the pressure drop was estimated as 67.5 Pa, this

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proved a higher quality factor compared with the membrane lacking of electrostatic charges. This development works proposed by Shao et al. [123] opens a new window in the fabrication of outperforming membranes by exploiting the polymer features and the electrospinning technique.

Zhu et al. [12] utilized silica nanoparticles with superhydrophobic nature which were subsequently filled into a chitosan/poly (vinyl alcohol) (PVA) air filtration membrane via green electrospinning and UV-cured nanofibers [12]. The inorganic hydrophobic fillers were favourably added to form a rough surface and thus increase filtration efficiency. As for filtration of fine particles (between 300 and 500 nm), the filtration efficiency and pressure drop were noted to increase by increasing the basis weights, in other words, the increase of the basis weight in membranes from 1.48 to 6.2 g/m^2 resulted in an enhancement of the filtration efficiency from 42.97 % (with a pressure drop of 33.6) to 96.60 % (with a pressure drop of 305.6) for NaCl particles (**Figure 7.a**). Additionally, these membranes showed a filtration separation towards di-ethyl-hexyl-sebacate (DEHS) particles from 51% (with a pressure drop of 33) to 99 % (with a pressure drop of 296) (**Figure 7.b**). Based on authors' conclusions, this phenomenon was credited to the high basis weight, which allowed ~~confer~~ to the membranes to display more contact points while increasing tortuous airflow channels [12].

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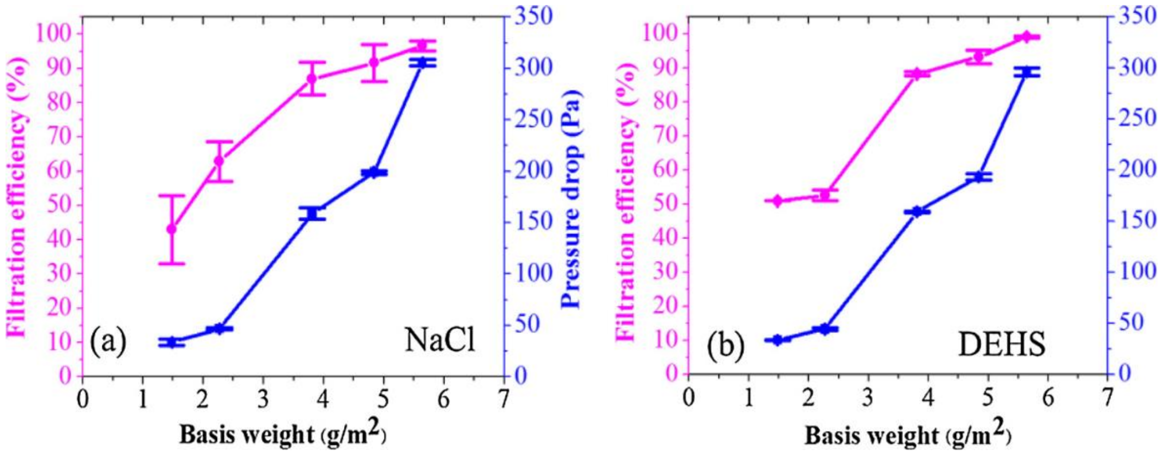

Figure 7~~6~~. Filtration performance of silica nanoparticles filled into a chitosan/poly (vinyl alcohol) (PVA) nanofibrous membranes with different basis weight investigated by using NaCl and DEHS particles. Reprint from [12] with the permission of Elsevier.

Table 3 enlists a few examples of nanofiber membranes aimed at separating different pollutants from air. In general, it can be seen that most of the nanofibers display a good performance towards environmental remediation and mask filtration which is currently an area of research related to coronavirus disease.

Table 3. Performance of various nanofiber membranes for air filtration.

Pollutants	**Materials**	**Efficiency** (%)	**Pressure drop** (Pa)	**Quality Factor (QF)** (Pa^{-1})	**Notes**	**Ref.**
$PM_{0.3}$	CNFs/PVP	86.4	17	0.117	For environmental remediation	[124]
	HNTs@CS/PVA/ NWF	96.8	143.9	0.0239	For environmental remediation	[125]
	PP	87.28	40	0.052	For environmental remediation	[126]
	PVA (nanofibers deposited on PP nonwoven)	99.1	78	-	For ideal surgical mask and dust mask	[127]
	PLA	82.156	-	-	For ideal mask filtration	[128]
	PLA/ artificially cultured diatom frustules (DFs)	99.99	-	-	For ideal mask filtration	[128]
$PM_{2.5}$	PVDF	98.16	30	0.120	For environmental remediation	[129]
	TPP/N6	99.06	253	0.018	For environmental remediation	[130]

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	PAA@ZIF-8	99.6	146.3	0.034	For environmental remediation	[131]
	PVA (nanofibers deposited on PP nonwoven)	99.9	56		For ideal surgical mask and dust mask	[127]
	PU/SiO2	95.37	126	0.001	For multilayer face masks (0.5 wt% of SiO2)	[132]
	PTFE/PP@PTFE	94.96	8	0.0348	for applications in nanogenerators, wearable electronics, medical products and other fields	[133]
NaCl aerosol particles	PMIA/PAN	99	-	-	For air pollution	[134]
	PTFE/PVA/ boric acid (BA)	98	30	-	For air pollution	[66]
	PVDF	99.2	-	-	For ideal mask filtration for SARS - COVID virus	[135]
	PVA/sodium lignosulfonate (LS)	99.44	24.5	0.212	For ideal mask filtration for SARS - COVID virus	[126]
Murine hepatitis virus A59 (MHV-A59)	PVDF	97.1	-	-	For ideal mask filtration for SARS - COVID virus	[135]
Dioctyl phthalate(DOP) aerosolparticles (0.3 μm) (TSI 3160 test)	PES/PAN	99.54	133.9	-	For ideal mask filtration for SARS - COVID virus	[136]
Diethylhexyl sebacate (DEHS) aerosols	PTFE/PP@PTFE	95.39	-	0.0358	For applications in nanogenerators, wearable electronics, medical products and other fields (DEHS size 0.200–4.595 μm)	[133]

~~5.~~ 6. Electrospun nanofibers configurations

The material properties and the operating parameters of the electrospinning technique greatly determines the configuration of nanofibers. The configuration influences ~~in~~ the construction of two-dimensional (2D) and three-dimensional (3D) networks of nanofibers [137]. Experimentally, the features of these networks are systematically analysed with the aid of different characterization techniques, such as porosimetry, which determines the pore size, while scanning electron microscopy (SEM), transmission electron microscopy (TEM), and atomic force microscopy (AFM) are used to investigate the morphology and

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surface roughness. In the case of SEM, this technique is primarily applied for the morphology study and thickness measurement of the nanofibers, while TEM tends to be more convenient for the nanofibers having a diameter less than 300nm. The AFM is commonly applied to characterize the total surface topography [138].

As for the pore size, polymeric nanofibers may present a pore size distribution ranged from tens of nanometers to several micrometres; favourably, the submicron range is suggested for better filtering efficiency. ~~Eventually,~~ A uniform and interconnected pore structure with high surface area per unit volume is preferred as well [139].

The morphology of different polymer electrospun nanofibers based on PVDF, PAA, PAN, PLA, CA is shown in **Figure 8**.

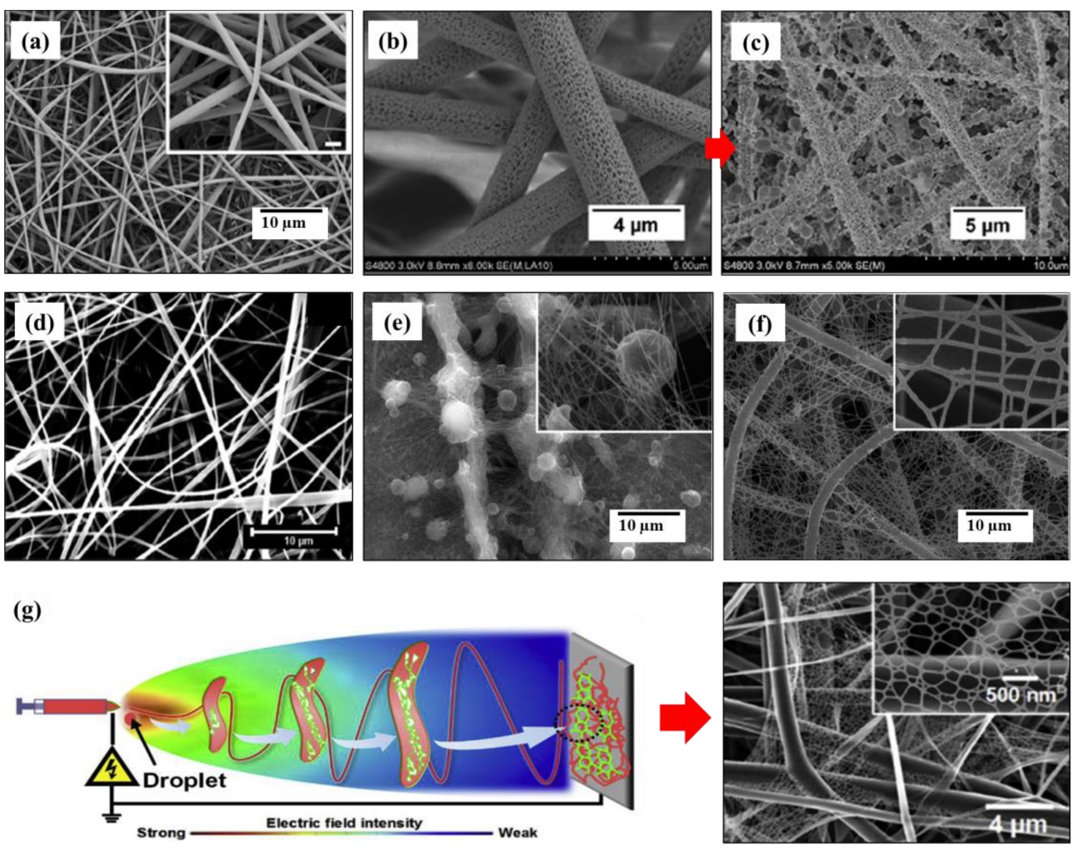

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Figure 8. Morphology of different electrospun filtration membranes based on various polymers. (a) PLA, reprinted from [140] with permission of Elsevier; (b and c) Hierarchical structured nano-sized/porous poly(lactic acid) (PLA-N/PLA-P) composite nanofibers prepared at 45% ~~RH~~ of humidity before and after filtration test, reprinted from [141] with permission of Elsevier; (d) CA nanofibers with cationic surfactant cetylpyridinium bromide (CPB), reprinted from [142] with permission of Elsevier; (e) PVDF, reprinted from [143] open access; (f) PAN reprinted from [143] open access; (g) hypothetical situation simulation of electrospinning/netting and (h) nanofiber/nets structure of poly (acrylic acid) (PAA) with 0.03 wt% of NaCl, reprinted from [144] with permission of Elsevier.

~~6~~ 7. Electrospun membrane applications for air filtration

~~6~~7.1. Individual protection devices

The current importance of electrospun membranes relies on the new perspectives for individual protection devices for air pollution or emerging infectious diseases (EIDs) including Coronavirus 2019 (COVID-19). A typical protector device for air filtration is characterized by fibrous (nonwoven filter) membranes composed by fine fibers. The mechanism of particles separation deals with an aerosol stream and entrapped between the fibers inside the filter [42]. **Table 5 ~~3~~** provides a summary of regulations and/or tests used to certify masks elaborated by Das et al. [145].

Table 5~~3~~. Regulations/test used to certify facemasks. Reprint from [145] with the permission of Elsevier.

Regulation/test	Scope	Limitation	Note

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Swedish Standard SS-EN 149 + A1:2009	Respiratory protective devices – Filtering half masks to protect against particles	At least 92% of the tested elements cannot leak N5% particles	Value taken for FFP3 device class.
NIOSH 42 CFR 84 US (NIOSH 1995)	Filtering capacity	At least 95% of the influent particles should be filtered	NaCl particles are used as surrogate particles. Typical values for N95 respirator masks.
T4D bacteriophage virus filtration, by [146]	Test the filtration property of different filter layers	1 h filtration time resulted on “infinite” T4D virus capture, while 2 h gave 1.1×10^8	Based on a FFP2 mask
Relative survivability (RS) of MS2 viruses on filters, by [147]	Test the ratio of virus survival on treated filters relative to untreated filters	1. PF PP filter (DuPont™ 01361 N): RS = 1 ± 0.1. 2. CCF coarse pore cellulose filter paper (Whatman™ Grade 54): RS = 1 ± 0.2. 3.FCF fine pore cellulose filter paper (Whatman™ Grade 50): RS = 1 ± 0.15	
ASTM F2100 – 19e1	Standard specification for performance of materials used in medical facemasks	Medical facemask materials are required to: 1. Bacterial filtration N95% 2. Sub-micron particle filtration efficiency (0.1 µm) N 95. 3. Resistance to penetration of blood N80%. 4. Flame spread Class 1	Values based on a Level 1 barrier. 1. Bacterial filtration efficiency based on Test Method F2101. 2. Sub-micron Particle Filtration based on Test Method F2299 3. Resistance to Penetration by Synthetic Blood based on Test Method F1862. 4. Flammability based on 16 CFR Part 1610

The use of polymeric nanofibers is considered ~~recognized~~ as a new generation of filter devices for enhancing the overall filtration performance in terms of efficiency and lifetime compared with conventional systems. As previously mentioned, aerosol particles can potentially be separated by different mechanisms including interception, inertial impaction, gravitational settling, electrostatic attraction, and Brownian diffusion (dominant respect others) [42]. The efficiency is dictated by the synergy of these mechanisms and it is dependent on the particles size [148]. Certainly, other factors can also ~~affect~~ influence the

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facemask efficiency including the facial fit of individual wearers and different mask types commercially available [149]. As for HEPA masks, i.e., without the presence of electrostatic attraction from the polymer fibers, an efficiency as high as 99.97% was demonstrated at 0.3 microns [42]. It is well known that PP, PA, PAN, PVDF, and PTFE are among the common polymers used for the production of facemasks. In a very recent study, Shen et al. [150] developed PVDF/PTFE fiber layers and implemented them in ~~the~~ facemasks, which were later evaluated for the removal ~~efficiency~~ of PM with different sizes (from 0.3 µm to >10 µm). The outcomes demonstrated that for facemask wearers, the exposure to $PM_{2.5}$~~2.5~~ concentrations in the air could be reduced by less than 20%. To improve the electret performance and the uniformity of fiber structures, the perspectives are oriented toward the design of novel network of nanofibers containing nanoparticles [151], i.e., hybrid polymeric fibers [152]. However, the usage of nanoparticles may bring another structural issues, for example, depending on the nanoparticles properties, a potential agglomeration issue can be originated which can be translated to a non-efficient separation performance [153].

Regarding the electric properties, these can be estimated by the electric intensity ($\bar{E}$) of the fibers from surface potential ($\bar{U}$) analysis. The intensity can be calculated as follows (4):

$$\bar{E} = \frac{\lambda}{2\,\Pi\,\xi 0\,\mathrm{L}}\,\frac{\bar{U}}{\Pi\phi(1-p)(\sqrt{R2+H2-R})L} \tag{4}$$

where λ corresponds to the charge density of a single fiber, ξ_0 refers to the dielectric constant, L is the distance, ϕ and p correspond to the thickness and porosity of fibrous

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membranes. R and H regard the radius of tested samples and distance, respectively [152,154].

The Ē parameter varies in an hybrid PS/PVDF nanofibers, and such a variation has been investigated by Li et al. [152]. In general, such variation of Ē parameter in the hybrid PS/PVDF fibers was highlighted in a colour map for single PS and PVDF fibers. The different surface potential of the materials was considered. As for PS, the red zone proved the high electret effect on dielectric property ascribed to a positive surface potential (Ē positive); on the contrary, the graph for PVDF was characterized by negative Ē values credited to its negative surface potential, presumably for its polar nature.

During the development of anti-bacterial/antiviral materials for personal protective equipment (PPE), photoactive chemicals were examined as effective for producing antimicrobial electrospun membranes due to the possibility to produce oxidative biocidal reactive oxygen species (ROS). TiO_2, ZnO and Ag are considered as photoactive nanoparticles used in the preparation of polymeric nanofibers that inactivate both Gram-positive and Gram-negative bacteria [155,156]. Salam et al. [155] added the viroblock (combination of silver and lipid vesicles) agent into a PAN/ZnO electrospun hybrid membrane for a novel antiviral personal protective equipment (PPE). This viroblock is a white viscous liquid that acts as an antiviral as well as an antibacterial agent. The antibacterial efficiency for PAN/ZnO nanofibers loaded with 5% VB was 92.59% and 88.64% in the case of *Staphylococcus Aureus* and *Pseudomonas Aeruginosa*, respectively. In a recent work, Zhang et al. [157] blended the Vitamin Ks (VKs) for producing antiviral electrosun PAN membranes (VNFMs). The prepared VNFMs exhibited robust photoactivity in generating reactive oxygen species (ROS) under both daylight (D65,

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300−800 nm) and ultraviolet A (UVA,365 nm) irradiation, resulting in high antimicrobial and antiviral efficiency (>99.9%) within an exposure time of 90 min (**Figure 9.a**).

Wang et al. deeply described the benefits of the embodiment of SiO_2–TiO_2 porous nanofibrous membrane (STPNM) with Ag [158]. Interestingly, the inorganic nanofibers were prepared by electrospinning the precursors of SiO_2 and TiO_2 followed by a step of calcination, whereas Ag nanoparticles were embedded into the electrospun STPNM porous nanofibers through an impregnation process (**Figure 9.b**). The Ag@ STPNM electrospun membrane showed an efficiency of 98.84% in $PM_{2.5}$ removal with a pressure drop of 59 Pa coupled with an inhibition of the growth of *E. coli* of 95.8% (**Figure 9.c**).

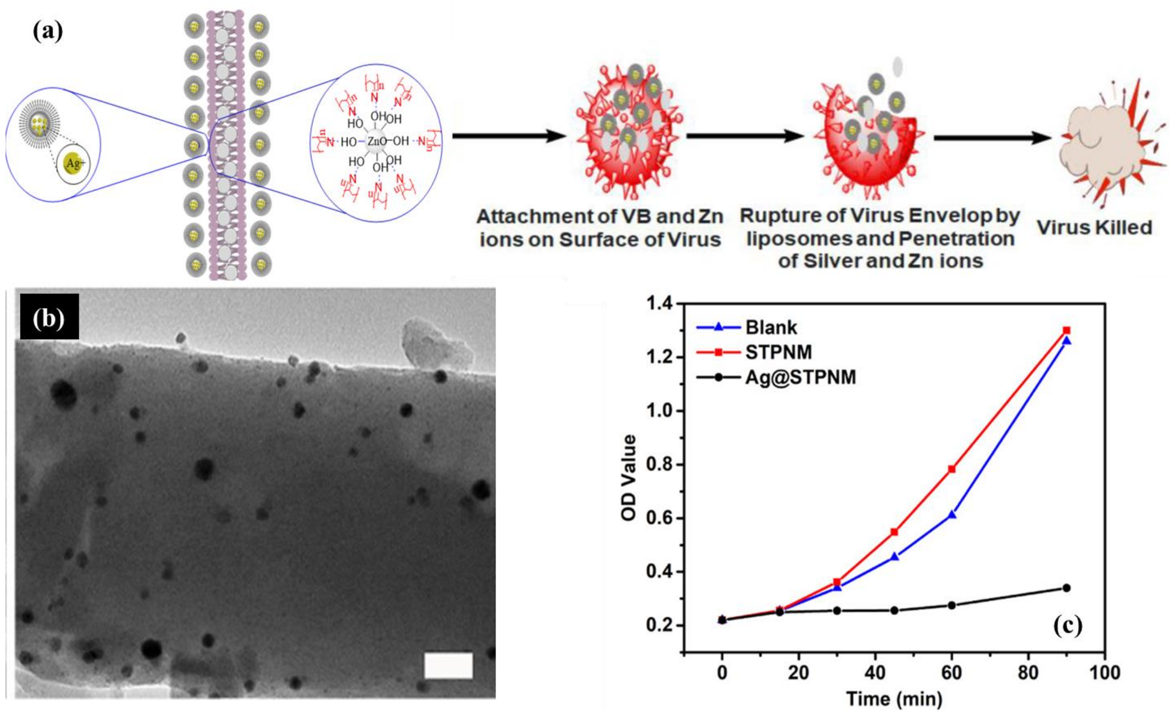

Figure 9. a) Suggested mechanism of working of antiviral activity of VB-loaded PAN/ZnO electrospun nanofibers [155]. This work is licensed under a Creative Commons Attribution 4.0 International License. b) TEM image and c) antibacterial performance of Ag@STPNM. Reprinted (adapted) with permission from [158]. Copyright 2019 American Chemical Society.

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Wang et al. [62] produced high-performance filtration membranes with structural alternatives by using different concentration of silica nanoparticles (SNP) into the electrospinning PAN solution. The presence of SNP on the filtration performance contributed to a high probability of particle capture due to the extended specific surface area and ~~can~~ acted as stagnant zones for airstream, generating low air resistance. The compromise between filtration efficiency and pressure drop was monitored by modifying the SNP content using the NaCl aerosol particles as reported in **Figure 10.**

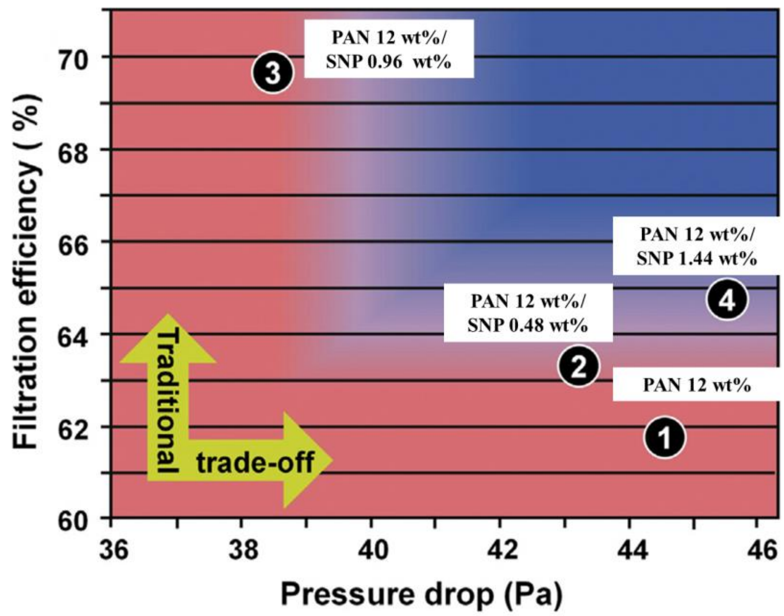

Figure 10. Trade-off between filtration efficiency and pressure drop of relevant PAN/SNP electrospun membranes. Reprint from [62] with the permission of Elsevier.

~~6~~7.2. The role of electrospun nanofibers in environmental remediation

The air pollution increment in highly populated cities necessitates the development and implementation of new efficient air filtering systems. Electrospun membranes, due to their outstanding properties, represent an effective alternative to be applied in these types of separation. Patanaik et al. [121], for instance, evaluated various types of PEO for the

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synthesis of electrospun membranes, followed by their testing in air filtration applications. Particularly, it was observed that by increasing the polymer concentration, from 3 to 6 w/v, the diameter of the fibers increased from 85 to 125 nm, while improving their uniformity. In air filtration testing, dust particles with size between 0.6-180 nm and fed at the constant air velocity of 4 m/s, the membranes presenting the highest PEO concentration demonstrated better performance in terms of dust particles retention of approximately 88%. This latter outcome was ascribed to the fact that the polymer concentration increase conducted to a reduction of membrane mean pore size (17 μm at 6 w/v of PEO) enabling the membrane to retain more. Additionally, the membranes prepared at higher PEO concentrations, resulting in a larger diameter, showed a lower pressure drop (17 Pa at 6 w/v of PEO) compared with the membranes having smaller diameter (28 Pa at 3 w/v of PEO). In a different work, Canalli Bortolossi et al. [159] interestingly fabricated PAN electrospun fibers containing particles at different concentrations (from 0 to 50 wt.%), and deposited on a non-woven substrate. The main purpose was to design ~~a~~ nanofibers with the ability to remove particles from the air. The final electrospun nanofibers owned a diameter of approximately 250 nm except for the ones containing 10 wt.% of silver, displaying a larger diameter (about 400 nm). This latter fact was basically ascribed to the change in conductivity and solution viscosity caused ~~provoked~~ by the embodiment of the silver nanoparticles. Concerning to the air filtration test, the efficiency was initially analysed in terms of pressure drop. The use of silver nanoparticles (up to 10 wt.%) resulted in an increase in pressure drop (about 225 Pa) and consequently a decrease in the void space which hindered the air permeation. Unfortunately, higher content of silver nanoparticles (50 wt.%) resulted in a lower pressure drop (68 Pa). Such an explanation was justified

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considering that the membranes containing the highest concentration of silver, thanks to the higher solution viscosity, ~~were revealed a~~ resulted in a lower nanofibers deposition rate on the collector. When the membrane yield was determined to separate nanoparticles ranging from 9 to 300 nm, a complete removal, ca. 100%, was obtained for the samples doped with a silver concentration up to 10 wt.% but, as mentioned previously, with a high-pressure drop; however, a slight decrease in removal efficiency (approximately 98.6%) was observed ~~seen~~ for the sample containing ~~with~~ the highest silver concentration (50 wt.%) but with a much lower pressure drop as said above. Considering the obtained outcomes and regulation established by the European Union Standard for EN 18222 filters, the membrane lacking in silver loading could be categorized as H13, denominated as High-Efficiency Particulate Air Filters - HEPA>99.95% collection efficiency. On the other hand, membrane presenting 1 and 10 wt.% of silver, display the same performance as E12 (Efficiency Particulate Air Filters – EPA > 99.5% collection efficiency), while membranes with 50 wt.% of silver meet the requirements for E11 filters (EPA > 95% collection efficiency). Promisingly, credited to the presence of silver, the resulting silver/PAN nanofibers proved also compelling antibacterial activity towards various *E. coli* bacterial strains.

The fabrication and subsequent implementation of polycarbonate (PC) electrospun nanofibers for the removal of PM from the air was investigated by Li et al. [160]. In this study, it is relevant mentioning that researchers conducted the air filtration experiments using real polluted air (full of PM) collected from the outdoor campus of Zhengzhou University (China). Unlike most investigations reported in literature where the air filtration performance is determined using air models containing aerogel NaCl particles, which are far to mimic, in terms of complex chemical composition, the PM dispersed in the polluted

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air, in Li’s study [160], researchers selected three levels of pollution varying in PM concentration: 50, 110, and 220 mg/m^3. The filtration experiments notified how PC membranes were capable to separate and ~~this~~ retain the PM with an almost complete efficiency (approximately 100%), as reported in **Figure 11**. In addition to this, a good air permeability (78.36 ± 11.48 L/cm^{2}h) was observed in such membranes. Taking into account that most of the PM owned a dimension lower than 0.3 μm, the membranes successfully operated in an outperforming way.

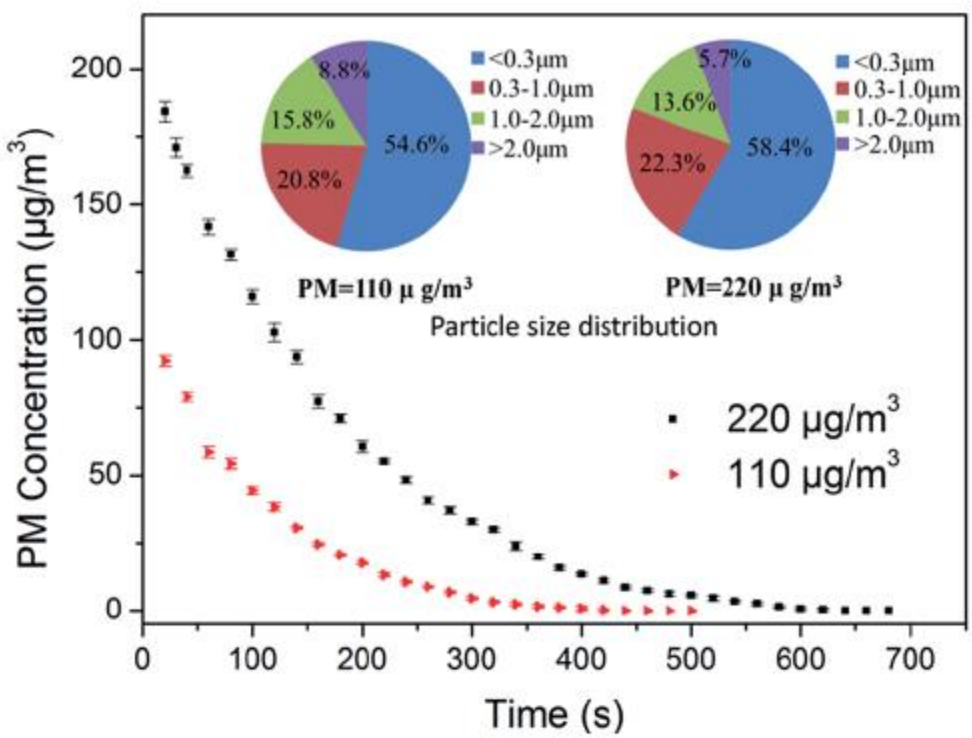

Figure 11. Filtration performance of PC membranes at different PM concentration and as a function of time. The particle size distribution is reported in the inserted pie charts. Reprinted from [160] with permission of Elsevier.

By comparing the filtration performance of PC membranes with PVA and polystyrene membranes, it was concluded that the first ones were the most efficient to remove PM from

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the air [160]. Favourably, it was found that the removal efficiency increased when the polarity of polymers repeating units increased as well. Herein, it is quite possible that the high dipole moment of PC membranes could have improved the binding of PM with polymer nanofiber surface by means of dipole-dipole or induced-dipole interactions.

In a recent work, Cao et al. [161] prepared bead-free ~~polyacrylonitrile (~~PAN~~)~~ nanofibers with diameter lower than ~~of <~~100 nm to filter $PM_{2.5}$~~2.5~~ emissions from burning cigarettes and from fused deposition modeling (FDM) three-dimensional (3D) printing. The experiments were carried out by using two-chamber filtering devices. In the case of filtration of cigarette smoke particles, the device consisted of two chambers as reported in **Figure 12.a**. The dimension of smoke particles was in the range of 0.3-10 µm and the rate of number emission was 3.9×10^{11} particles/min and the $PM_{2.5}$~~2.5~~ emission rate was 2690 µg/min. In the case of particles filtration from FDM 3D printing, the device was prepared by using an interior chamber with a hole covered by the layer of PAN nanofibers membrane and an exterior chamber as reported in **Figure 12.b**. The emission rate of this type of particles was fixed to $1\text{-}61 \times 10^{10}$ particles/min. In these experiments, the efficiency was calculated by using the equation (5):

$$\text{Filtration efficiency} = (1 - C/C_0) \times 100\% \qquad (5)$$

where C_0 is the PM concentration from Detection 1 (**Figure 12.a and 12.b**) and C is the PM concentration from Detection 2 (**Figure 12.a and 12.b**).

The results confirmed a~~n~~ $PM_{2.5}$~~2.5~~ removal efficiency of 99.26% in the cigarette smoke particles filtration experiment and 81.16% in the case of particles sequestration experiment from FDM 3D printing.

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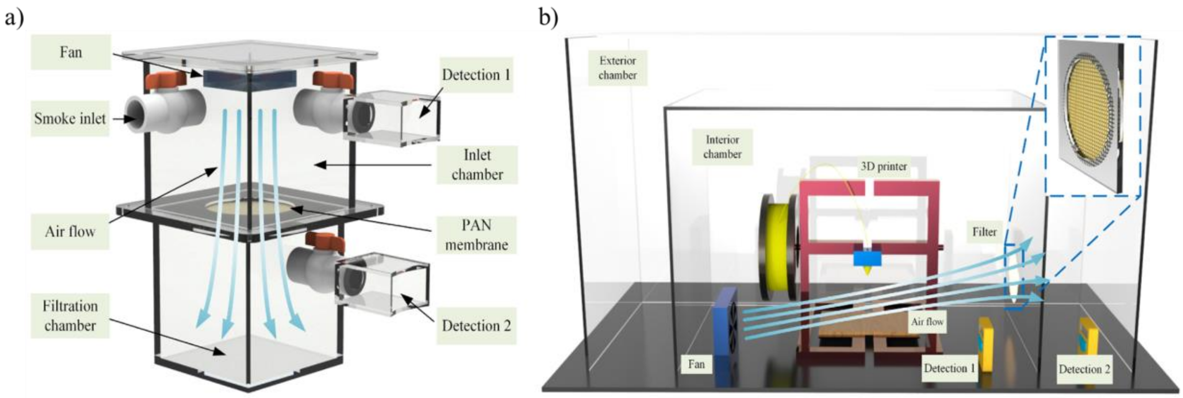

Figure 12. Set-up for a) cigarette smoke particles filtration experiment and b) particles filtration experiment during 3D printing. Reprinted from [161] with the permission of Elsevier.

~~6~~7.3. Electrospun nanofiber in recovering volatile organic compounds (VOCs)

The emissions of VOCs into the environment requires to be strictly regulated by legal limits ~~since~~ due to their negative contribution to the production of polluted waste gas flows, and to their harmful effects on plants, human beings and animals' health. Thereby, the control and regulation of their emissions is a major worldwide concern. VOCs, methane, ethane, tetrachloroethane, BTX, formaldehyde, acetaldehyde and acetone are among the most common atmospheric pollutants, which are the resulting emission of various chemical and petrochemical industries [162]. ~~Towards~~ For the recovery of VOCs, the techniques are primarily categorized in two macro areas: process equipment modifications and add-on-control techniques [162]. Within the second category, ~~we can find~~ it is possible to find membrane processes ~~engineering~~ that represents an interesting alternative to separate VOCs from gaseous streams. This is because membranes ~~processes~~ own several advantages in terms of ~~the~~ high chemical stability ~~of specifically designed membranes~~ in

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the presence of chlorinated compounds, together with the possibility to be operated at mild temperatures, thus reducing the overall energy consumption [163]. The main property of polymer membranes ~~implemented~~ used in membrane contactors for VOCs recovery ~~deal with~~ is their high ~~permeable properties~~ permeation to VOCs ~~while substantially hindering the~~ and low permeation to air [164]. Polydimethylsiloxane (PDMS) and polyimide (PI) are typical membrane materials for the removal of VOCs, including acetone, toluene, and xylene, from air or N_2. ~~As for~~ PDMS, for instance, displays~~ a~~ selectivity values ranging from 11 to 25 in separating acetone [163,165], a selectivity of approximately 84 for toluene ~~removal~~ and a~~n~~ CO_2/N_2 ideal selectivity of 21 [166]. Rebollar-Perez et al. [167]~~, for instance,~~ investigated the application of PDMS/α-alumina membranes for vapor permeation, constructing a device to remove VOCs from air currents (at feed pressure: 3 bar and temperature: 21°C). The preliminary outcomes proved that the membrane was able to reduce the VOC content as high as 95%.

Scholten et al. [70] in their study fabricated and assayed electrospun polyurethane-based fibers for the separation of VOCs from air, in which particularly was observed a complete reversible VOCs absorption and desorption using a purge with N_2 at room temperature. The final fibers exhibited a sorption capacity comparable to active carbon, which is commonly used for vapor adsorption.

~~6~~7.4. Electrospun nanofiber in ventilation and climate control aspects

Over the last two decades, membrane technology has attracted the attention in the field of Heating, Ventilation and Air Conditioning (HVAC). From the environmental point of view, the energy requirements of chillers and air conditioners are responsible for around

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40–50% of the world's greenhouse gas emissions. Since the World Health Organization declared the coronavirus disease 2019 (COVID-19) as a Public Health Emergency of International Concern [168], it is highly needed to develop and implement new and highly efficient filtration systems for air purification in closed spaces.

Vacuum membrane dehumidification, and membrane evaporative cooling and humidification represent some of the HVAC membrane-aided processes, in which each process operates differently in terms of inlets and outlets, together with different types of membranes [169].

In the light of membrane-based air dehumidification process, the required membranes must be dense with hydrophilic nature; requiring a driving force as the vapor pressure gradient between the feed and permeate sides. In the case of membrane-based evaporative cooling and membrane-based evaporative humidification process, they are categorized as low-cost and energy-efficient technologies for the control of the evaporative cooling and the humidity within the rooms, respectively [169].

Nanofibers based filters aimed for the filtration of small aerosols are usually produced by electrospinning. Presently, Ju et al. [170] explored polyamide-6 polymer for the fabrication of electrospun nanofibers containing silver nanoparticles. It is a common practice to evaluate different operating parameters during the electrospinning. In this study, the investigated parameters were the distance between needle and sample collector (18 cm), processing temperature (40 °C), the voltage (18 kV), and the average flow rate (0.5 mL/h). The aim of the research was also to evaluate their effect on the antibacterial and antiviral properties of resulting air filter membranes for a high-efficiency PM removal. The membranes displayed $PM_{2.5}$~~2.5~~ filtration efficiency as high as 99.99%, concurrently with

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the removal of multiple aerosol pollutants and bacteria, such as *Escherichia Coli* and *Staphylococcus Aureus*.

Photosensitized electrospun nanofibrous membranes were tailored by Shen et al. [135], who aimed to capture and inactivate coronavirus aerosols. In this case, the rose bengal dye was employed as a photosensitizer thanks to its exceptional reactivity in virucidal generation. The electrospun membranes presented a pore size of ca.1.5 µm and a diameter of approximately 200 nm. Finally, the filtration tests were performed using different virus types, such as murine hepatitis virus MHV-A59, a coronavirus surrogate for SARS-CoV-2. The findings evidenced a rapid inactivation of 98.9% after 15 min irradiation of simulated reading light.

8. Upscaling potential of nanofiber air filters and current companies for nanofiber production

Over the course of this review, we have reviewed one of the many applications of electrospun nanofibers. To date, most of the research in electrospun membranes has been done at a lab scale. Thanks to the outperforming separation of nanofibers for air filtration, there is a current need of producing nanofibers on a large scale. However, the key challenges in developing large-scale production of nanofiber rely on establishing accuracy and reproductivity of the fabrication processing while satisfying the large volume processing. Additionally, such processes must also meet important safety and eco-friendly aspects of electrospinning. In this regard, centrifugal electrospinning [171], for instance, owns the characteristics for large scale production at industrial level, along with high speed and low cost [172]. It has been reported that such technique is able to tailor fibres with diameters down to 100 nm [173]. Towards reaching scaling processes, higher flexibility

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towards the materials and processing with multifunctional properties can be potentially reached via co-axial and multi-axial technologies. Additionally, it has been documented that ambient conditions drastically influence on the properties of electrified jets and consequently on the resultant electrospun materials; to some extent, even small environmental changes have demonstrated to have an effect on fiber features. Therefore, several suppliers of commercial electrospinning devices have developed climate-controlled electrospinning systems, assuring temperature and humidity control. For instance, IME Technologies, recently named as Vivolta, https://www.vivolta.com/) fabricates laboratory-scale systems for medical purposes, presenting electrospinning chambers and control of air conditions, water filtration and automatization system.

In terms of industrial-scale equipment market of electrospinning devices, several companies and suppliers have emerged satisfying this field, such as Elmarco (www.elmarco.com), NaBond (www.electro-spinning.com), Holmarc Opto-Mechatronics (www.holmarc.com), E-SpinNanotech (www.espinnanotech.com), Linari Engineering (www.linaribiomedical.com), Kato Tech (www.keskato.co.jp), Mecc Co. (www.mecc.co.jp), Toptec (www.toptec.co.kr), Electrospinz (www.electrospinz.co.nz), Electrospunra (www.electrospunra.com), Vivolta Technologies (https://www.vivolta.com/), Yflow (www.yflow.com), and Ino-venso (www.inovenso.com). Importantly, electrospinning at industrial scale majorly implied a rotating drum or on substrates using winding-unwinding systems, while laboratory set-ups are based on needle-type electrospinning.

According to the experts in the field, to reach a fully implementation of electrospinning systems at industrial scale, several aspects should be satisfied [173], as follows:

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- As in most of emerging technologies, a substantial reduction in cost is highly needed. This can be achieved as soon as potential skateholder may be interested at implemented electrospun nanofibers in commercial air filters.
- Multi-functional set-up should be fabricated, which is a current challenge since it is difficult to offer ‘‘all-in-one’’ set-ups to reach different requirements from the customer.
- Compactness in the devices is required since they need to be installed in limited space.
- Productivity demand is also a current matter for large-scale electrospining since the nanofiber volume may be required by in many sectors.

When dealing with the industrialization and availability, various companies have released electrospun products, such as Donaldson (www.donaldson.com), DuPont (www.dupont.com), Ahl-strom Corporation (www.ahlstrom.com), Espin Technologies (www.espintechnologies.com), Esfil Tehno AS (www.esfiltehno.ee), Finetex Technology (www.finetextech.com), Hemcon Medical Technologies, Inc (www.hemcon.com), Hollingsworth (www.hollingsworthvise.com), to mention just a few, in which the nanofiber air-filter market has grown drastically [173].

To some extent, electrospinning devices should be also developed according to the needs in terms of desired nanofiber properties, feedstock and items and, more importantly, materials used for the fabrication of the nanofibers. In this latter aspect, new functional materials are currently being developed to overcome the limitations of existing materials. In this sense, bio-functional nanomaterials based on biomolecules, copolymers, and polymer blends have been synthetized, such as fibroin in water-soluble polymers,

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PCL/gelatin, poly(L-lactide acid)/gelatin blends, protein-based and chitosan-poly(ethylene oxide)(PEO) blend [174–177], among others. Importantly, such materials produced from natural sources have been proposed to face the eco-friendly weaknesses of chemically synthetized polymers. Especially, natural protein nanofibers have shown high efficiency filtration towards particulates, pollutants and toxic gases from polluted air [177]. However, typical polymers produced via chemical synthetized are still the preferred ones for fabrication of electrospun mats for air filtration, as evidenced by Inovenso Ltd. Co. [178]. It is worth mentioning that air filters presenting electrospun nanofibers are usually applied in several applications, such as pulse-clean cartridges for Dust Collection., nanofiber filter media in Cabin Air Filtration of Mining Vehicles, and specialized face mask fabrication, among many others [179]. All these applications will eminently foster the establishment of electrospinning technology at industrial scale in near future.

9. Grand challenges for electrospun membranes for air filtration

The bottleneck of electrospun nanofibers is the technology transfer from the lab scale to the mass production. In fact, the limited production rate of traditional electrospinning equipped with a single needle has hindered the practical implementation of nanofiber for air filtering at large scale (typically the flow rate of the polymeric solution is in the range of 1–5 $mL \cdot h^{-1}$ with a production rate of the nanofibers lower than 1 $g \cdot h^{-1}$) [180].

The employment of an auxiliar electrode could enable the ejection of up to 12 nanofibers from a single needle [181], but safety issues have limited the feasibility of this route to intensify the electrospinning process. As a manner of fact, the productivity of the electrospinning process increases as a function of Taylor cones. This has stimulated the

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development of multi-spinnerets where numerous needles are arranged in linear or two-dimensional arrays (es. circular, elliptic, hexagonal or triangular)[182] expanding the jet number up to 38,880 [183]. Moreover, an interesting advantages of multi-needle configurations is the opportunity to produce multi-component mat made of polymers not soluble in the same solvent [184].

Unfortunately, heterogeneous mat are often obtained with multi-needle spinnerets because of: i) the high density of needles which compromises the uniformity of the external field and ii) the Coulombic repulsions among the nascent fibers [185]. Several studies have been focused on the optimization of the multi-needle electrospinning focusing on the design (geometry, needle-to-needle distance, number of needles) of the spinnerets to: i) uniform the electric field, ii) minimize the interactions between the nascent fibers and iii) avoid their fusion during the flight from the needle to the support [186,187]. These critical issues have been also minimized by using polypropylene (PP) as dielectric material on the tip of the nozzles [188]. Another emerging and promising practice to mitigate the reciprocal interferences among the jets is the employment of a sheath gas in laminar regime (**Figure 13.a**) which secured an improvement of the productivity of ca. 30-50 folds with respect to single needle configuration [184].

Just to give an example about the scalability of the electrospinning of nanofiber with multi-needle spinneret, Inovenso Inc. has commercialized an industrial electrospinning system equipped with 110 needles able to produce up to 5 kg of nanofibers per day [189].

Unfortunately, the improvement of the number of needles drastically increases the risk of clogging of the nozzles. A possible solution is to provide the polymeric solution to the outside surface of the needle. According to this strategy , thermoplastic polyurethane

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(TPU) has been electrospun with production rate of ca. 50 $g \cdot h^{-1}$ obtaining a network of nanofibers with a diameter of 145 nm and a $PM_{2.5}$ filtration efficiency of 99.9% [182]. Recently, needless spinnerets able to eject nanofibers directly from the surface of the polymer solutions have been purposed (**Figure 13.b**). The mechanism of working of needless electrospinning-which is not influenced by the capillary effect- is based on the self-organization of the liquid solution at mesoscopic scale induced by electromagnetic field able to induce the expulsion of the nanofibers [190]. This strategy has the potential to ensure the industrialization of nanofibrous membranes for air filtering as demonstrated by technology developed by Elmarco Inc. using a wire electrode to eject multiple nanofibers which guaranteed an annual productivity of 20,000,000 m^2 (0,03 $g \cdot m^{-2}$ of fibers of 150 nm of PA6)[191].

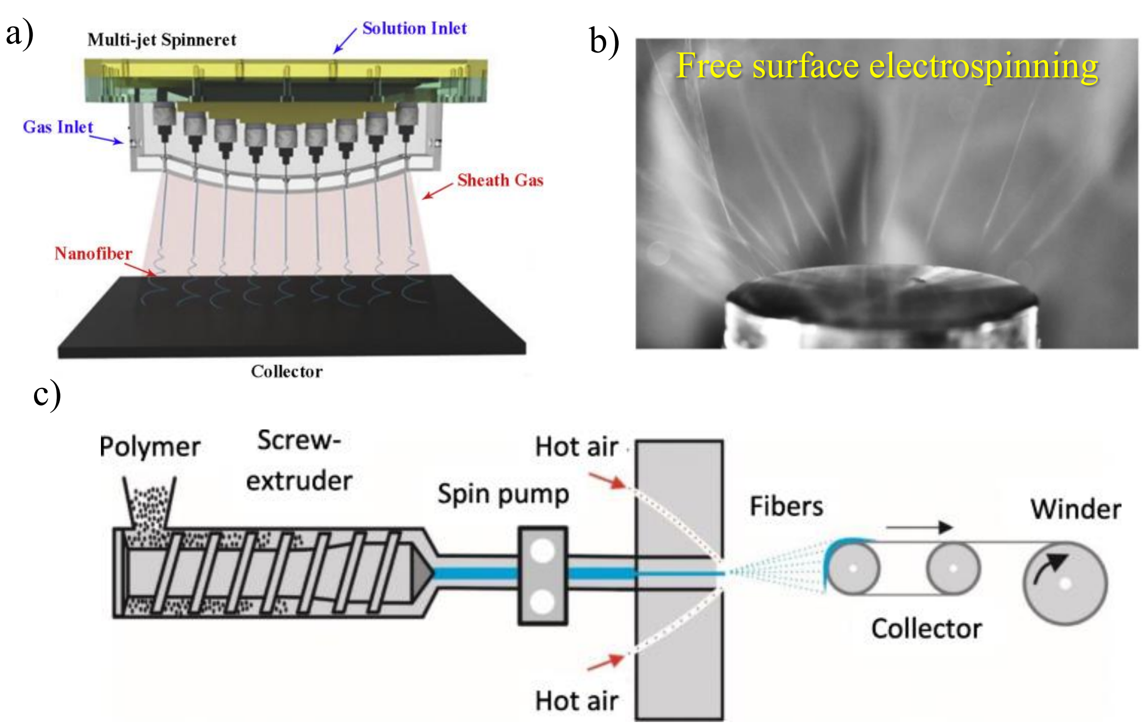

Figure 13. a) Multi-jet electrospinning with sheath gas for the intensification of the nanofiber production. Reprinted from [192]. This work is licensed under a Creative

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Commons Attribution 4.0 International License. b) PAN nanofibers ejected from a self-made free surface electrospinning with a spherical section. Reprint from [193] with the permission of Elsevier. c) Scheme of a melt-electrospinning system. Reprinted from [194]. This work is licensed under a Creative Commons Attribution 4.0 International License.

Another significant Achilles heel in the industrialization of nanofibers is the environmental impact. Tendentially, nanofibers are ejected from diluted polymeric solutions with a viscosity below than 20 poise (solvent content >70wt %) [138,195] and they are obtained upon the evaporation of the solvent during the flight from the needle to the support. Thus, mass production of electrospun nanofibers implies the use of enormous volumes of solvent raising serious concerns about the environmental footprint of nanofibers. Thus, it is necessary to introduce circular economy strategy to collect and recycle the solvent during the production of membranes via electrospinning. Noteworthy, common solvents used for electrospinning process are restricted by the Chemical Control Regulation in the European Union (REACH), such as halogenated (e.g. chloroform, trifluoroethanol) and toxic solvents (e.g. dimethylformamide) [196]. Beyond the employment of green solvent for the environmental-friendly production of nanofibers (**see Section 3.4**) , melt electrospinning (**Figure 13c**)- the process of spinning polymers from their melts- guarantees the solvent-free preparation of nanofibrous air filters [197]. Interestingly, melt electrospinning secure the preparation of i) nanofibers without residual of solvents [198] and ii) air filters of non-soluble polymers, such as polypropylene (PP) and polyethylene (PE) [199]. For instance, PP nanofibers with a diameter ranging from 7 µm to 14 µm were deposited on PP nonwoven support via melt-electrospinning. After post-treatment (i.e. hot-pressing), a mat of 0.42 mm of thickness showed a filtration efficiency above of 95% filtration for oil particles (size of 2.0 µm) and an air permeability of 54.69 $mm \cdot s^{-1}$[200].

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~~7~~ 10. Conclusions ~~and future perspectives~~

~~The growth of the human population, the increase of urbanization, and industrialization have brought the decrement of air quality over the last few decades. Air pollution starts to be a major issue that can result in serious risks for human health. In addition to this, microorganisms and natural contaminants suspended in the air can potentially provoke a great damage to human life.~~ ~~Looking for~~ Being considered efficient and reliable technologies, electrospun membranes are gaining a lot of interest in a plethora of applications in air filtration sectors ~~represent a viable tool and have been pointed out~~ for their ~~potential at enhancing~~ capacity to effectively improve the air quality ~~by~~ through a relatively simple filtration mechanism. Electrospun membranes ~~on their own~~ display ~~possess~~, in fact, a number of advantages in terms of small nanofibers diameters, high active surface area, tuneable morphology, and interconnected pore structure. This review has provided an overview and discussed the potential trapping mechanisms which can occur in electrospun membrane filtration, as well as their effect on membrane separation performance. ~~We also reviewed~~ A number of applications reporting the successful ~~application~~ use of electrospun membranes for air filtration, and their comparison with commercial filters, was also reported ~~for such a purpose~~. The ~~removal~~ performance of electrospun membranes in removing different types of contaminants has been evidenced as high as 100% with a low-pressure drop up to 68 Pa.

Although many developments and advances have been done in this field, many challenges still remain open and are waiting for potential solutions. Unfortunately, some of the bottlenecks of electrospun membranes comprise their poor mechanical stability which

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frequently demands their deposition on a suitable support, along with their compromised application under harsh conditions. An interesting finding in this review reveals that the reduction of fibers diameter certainly improves the filtration efficiency, but compromising unfavourably the mechanical properties.

For wide exploitation of electrospun fiber, there is a need to turn ~~develop~~ the spinning technique into an easy and affordable technology ~~as easy as possible~~ with an applicability on a large scale [7]. Within the preparation processes, there is also an interest to replace traditional toxic solvents, that are typically used for the fabrication of electrospun membranes, ~~herein, the latent~~ with more benign alternatives, ~~are~~ the so-called green solvents [111,201]. This aspect becomes relevant when dealing with environmental protection and human safety. Some research groups have already started to explore new solvents to make the electrospinning process more sustainable and eco-friendly [79,202] outlining the importance of this aspect in developing the next generation of membranes aimed for environmental remediation.

As a recommendation for the new researchers in the field: ~~great~~ important advances in nanofibers synthesis, either polymeric or composite, have been done over the last years; however, they were limited to model tests on small lab scales. ~~this review timely finds the need to initiate the~~ The testing of electrospun membranes ~~for~~ with real air samples, as evidenced by Li et al. [160], is, therefore, crucial. ~~Most researches tend to use~~ Air model samples for performance evaluation can reveal, in fact, a good approximation but ~~a~~ more realistic outcomes, on real case studies, will be ~~determine the feasibility of new concepts of nanofibers.~~ fundamental to prove the efficiency of nanofiber-based membranes in air filtration processes.

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