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Nanofibrous Polymeric Membranes for Air Filtration Application: A Review of Progress after the COVID-19 Pandemic

Roberto Scaffaro and Maria Clara Citarrella**

Air pollution is one of the major global problems causing around 7 million dead per year. In fact, a connection between infectious disease transmission, including COVID-19, and air pollution has been proved: COVID-19 consequences on human health are found to be more severe in areas characterized by high levels of particulate matter (PM). Therefore, after the COVID-19 pandemic, the production of air filtration devices with high filtration efficiency has gained more and more attention. Herein, a review of the post-COVID-19 pandemic progress in nanofibrous polymeric membranes for air filtration is provided. First, a brief discussion on the different types of filtration mechanism and the key parameters of air filtration is proposed. The materials recently used for the production of nanofibrous filter membranes are presented, distinguishing between non-biodegradable polymeric materials and biodegradable ones. Subsequently, production technique proposed for the fabrication of nanofibrous membranes, i.e., electrospinning and solution blow spinning, are presented aiming to analyze and compare filtration efficiency, pressure drop, reusability and durability of the different polymeric system processed with different techniques. Finally, present challenges and future perspectives of nanofibrous polymeric membranes for air filtration are discussed with a particular emphasis on strategies to produce greener and more performant devices.

1. Introduction

Air pollution is currently one of the major global problem. The World Health Organization (WHO) estimated that around seven million people per year die because of different medical diseases caused by air pollution,[1] including the increase of the incidence of cardiovascular and respiratory diseases and some types of cancer.[2–4] Moreover, recently, several studies confirmed a connection between infectious diseases transmission, including COVID-19, and air pollution.[5–10] According to these studies, COVID-19 consequences on human health were more severe in areas in which the presence of high levels of particulate matter (PM) was recorded.[7,11–14]

Air pollution can be described as a mixture of solid particles, gases and biological pollutants such as bacteria and viruses.[15,16] In general, air pollutants are mainly derived from fossil fuels combustion processes, vehicles emission, power generation, agriculture or waste incineration.[1] Among gases, volatile organic compounds (VOCs), carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NO_x), are some of the most dangerous pollutant for human health.[3] The solid particles, instead, are mainly composed by sulfates, nitrates, sodium chloride, ammonia, black carbon, mineral dust, and water.[17] These particles are commonly labelled as particulate matter (PM) and classified according to their size: PM_{10} identifies particles with a diameter under 10 µm, $PM_{2.5}$ ones under 2.5 µm, while particles with a diameter under 0.1 µm ($PM_{0.1}$) are considered ultrafine particles (UFPs). Their hazardousness for human health, is strongly related to their dimensions. In fact, while PM_{10} are partially blocked by nasal cavities,[1] long-term exposure to $PM_{2.5}$ and ultrafine dust particles provokes more adverse effects on human health causing serious respiratory diseases due to their rapid deposition in human lungs.[2,3] Therefore, the production of air filtration devices characterized by high filtration efficiency and ultrafine PM removal ability, has gained significant attention among researchers worldwide, especially after COVID-19 pandemic. In **Figure 1** it is reported the number of published papers present in Scopus database over the years using "air filtration" as keyword. As it is possible to notice from the graph, the interest

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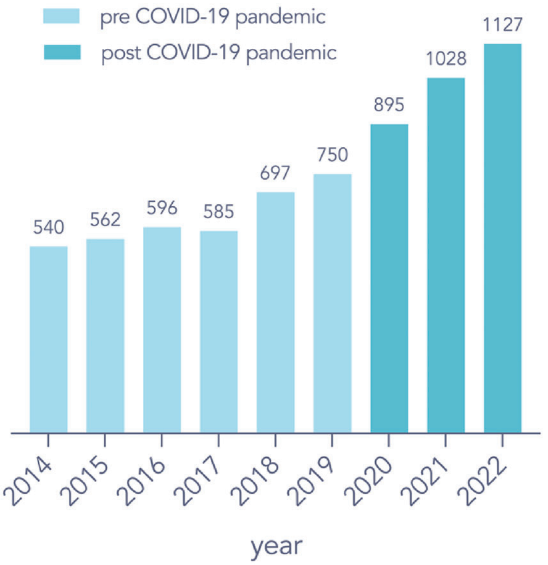

Figure 1. Number of documents found in Scopus database over the years using “air filtration” as keyword.

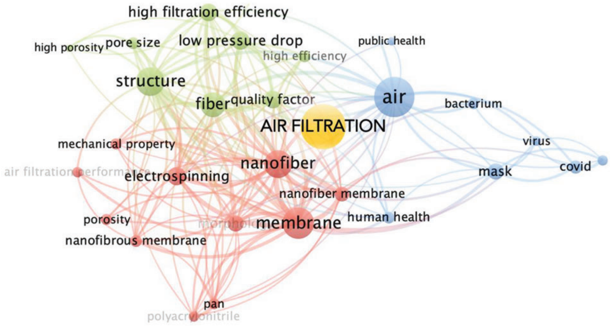

Figure 2. VOSViewer map obtained by analyzing data extracted from papers present in Scopus database from 2020 to 2023 using “air filtration” as keyword. Terms have been extracted by papers titles and abstract using a binary counting. Only terms with a minimum of ten occurrences and 60% of relevance score were taken into account.

of the scientific community has progressively increased over the years especially after the pandemic period.

Based on these data, the published paper after COVID-19 pandemic (2020-2023) were analyzed using VOSViewer software and results are reported in **Figure 2**.

Outcomes revealed that three clusters could be identify. The blue cluster includes all terms related to human health and COVID pandemic, confirming the importance of the development of efficient air filtration device in order to reduce the incidence of disease connected to air pollution. The green cluster includes all those goals that need to be archived in air filtrations, i.e., high filtration efficiency and low pressure drop. Moreover, this cluster highlights the important role of the device “structure” in reaching these goals. The analysis of the data also suggests that mats composed by “fibers” could succeed in it. The red cluster unquestionably highlights the predominance of porous nanofibrous membranes obtained by electrospinning among all the devices recently proposed for air filtration applications. Moreover, could be noted that polyacrylonitrile (PAN) is one of the most used polymers for the production of air filtration devices.

Air filtration devices appeared for the first time in 1940 and were based on glass fibers membranes.[18] Subsequently, in 1970, also activated carbon fibers were used for filter membranes production. The firsts polymeric based air filter membranes were developed in 1990s and rapidly become the most used in air purification industry thanks to their higher filtration efficiency, lower pressure drops and better durability if compared to the previous ones.[18] Polymeric fibrous membranes, in fact, are characterized by large specific surface area, small fiber diameter and high porosity. Furthermore, they are lightweight, easy to produce, cost-effective and their fibers can be easily decorated with different type of micro- and nanoparticles.[19–23]

Nowadays, air filtration membranes available on the market consist of micro-sized fibers. However, they are not efficient enough in $PM_{2.5}$ and $PM_{0.1}$ filtration and are characterize by high pressure drops, bad mechanical strength and poor thermal stability.[1,19] Therefore, is urgent to develop air filtration devices with the ability to remove also ultrafine dust from the air and contextually with low pressure drops, good mechanical properties, reusability and durability. Polymeric nanofibrous membranes have recently attracted more and more attention for the production of air filtration devices since they could allow to achieve ultrafine filtration thanks to their high porosity with interconnected pore structure, high functional surface area and customizable fiber diameter.[21,24–26] Moreover, polymeric materials have great potential for the fabrication of sensor, in fact, they have been already successfully used in different application fields.[27–32] Over the last years, also some examples of polymeric devices for air, water and soil pollution sensing have been reported.[33–37] The development of nanofibrous devices that can contextually ensure efficient air filtration and air pollution sensing is a current challenge.[35] Moreover, also the production of air filtration devices with antibacterial ability is of great interest.[38]

Nanofibrous membranes can be fabricated using different production techniques. Among them, electrospinning (ES), solution blow spinning (SBS) and their variations are certainly the most reported techniques used over the last years for the production of nanofibrous membranes for air filtration applications.[19,21,24–26,39–43] These types of technology, in fact, allow obtaining nanofibers and consequently polymeric mats with high porosity, low pressure drops, good reusability, durability and appropriate mechanical properties. Moreover, these production techniques make the incorporation of micro- or nanoparticles into fibers extremely easy allowing to enhance mechanical properties and purification efficiency of the final device.[19,44,45]

Over the last years, various reviews regarding nanofibrous membranes for air filtration application have been published especially in the recent pandemic period. Most of these works review filtering nanofibrous membranes, limited to those obtained by electrospinning, pointing to different aspects. Zhou et al.,[46] Abdulhamid et al.[15] and Russo et al.,[1] for example, discussed recent progress of electrospun membranes for air filtration highlighting advantages and disadvantages of single-polymers nanofibers and composites nanofibers. They conclude that exists a direct relation between filtration performance and fibers structure and therefore the presence of nanoparticles could improve air pollutant removal. Valencia-Osorio et al.[47] review the last 10 years progress in electrospun nanofibrous membranes for PM capture identifying three fundamental steps in ES process (i.e., solution preparation, tuning of process parameters, post-processing treatments) in order to study the influence of each step on membranes filtration performance. Lu et al.[48] deeply discussed the relationship between electrospun fibers structure, pressure drop and filtration efficiency reporting different examples of multi-structured ES membranes. Moreover, Deng et al.[49] and Lv et al.,[17] driven by the growing awareness of the importance of replacing traditional synthetic polymers with biodegradable and bio-based ones, review the last progress in the production of "green" electrospun devices for air filtration application.

In this review, we provide an overview of the post COVID-19 pandemic progresses in nanofibrous polymeric membranes production for air filtration. Initially, the different type of filtration mechanism involved in membranes for air pollutant capture and the key parameter of air filtration were presented and the relative nanofiber features were discussed. Subsequently, the materials used for the production of nanofibrous membranes for air filtration were presented distinguishing between non-biodegradable polymeric materials and biodegradable ones. Relative additive or micro/nanoparticles were also discussed, if any. Furthermore, production processes proposed for the fabrication of nanofibrous membranes were presented. In detail, eventual advantages or disadvantages – in term of filtration efficiency, pressure drop, reusability and durability – of processing the same polymeric system with different techniques have been highlighted especially focusing on the obtainable nanofibers structure. Finally, present challenges and future perspectives of nanofibrous polymeric membranes for air filtration have been discussed.

2. Influence of Air Pollution on the Incidence and Severity of COVID-19

Several studies have highlighted that the incidence of infectious diseases is higher in areas characterized by air pollution issues.[5–10] Moreover, according to these studies, exist an association between air pollution and higher incidence and more severe consequences also of COVID-19 infection on human health in those areas in which high levels of particulate matter (PM) were recorded.[7,11–14] In fact, exposure to polluted air can adversely affect the respiratory system leading to a greater predisposition to the development of respiratory diseases. Both short- and long-term exposures to air pollution may be an important aggravating factors for SARS-CoV-2 transmission and COVID-19 severity and lethality.[50–52] Therefore, recent studies confirmed that COVID-19 mortality depends on several comorbidities, including respiratory disease such as asthma and chronic obstructive pulmonary disease.[53,54] It has been extensively reported that these latter issues are strongly connected with air pollution.[55–60] Considering that, is extremely urgent to develop efficient air filtration device in order to improve air quality and consequently reduce risk factors for human health.

3. Mechanism and Key Parameter of Nanofibers Filtration

Air filtration theory has been developed for a long time, therefore the investigations in this area are mature enough to be linked to industrial and technological developments. Before going deep into the discussion of recent progresses in nanofibrous polymeric membranes for air pollutant capturing, it is useful to briefly report filtration theory and its mechanism. According to the theory, air filtration process can be divided into two states: the steady-state and unsteady-state. In the steady-state, filtration efficiency and pressure drop are constant over the time only depending on the air filter media, particle nature and dimension and airflow velocity. On the contrary, in the unsteady-state filtration efficiency and pressure drop change over time due to particles accumulation on the filter. About this latter, there is still a lack in theoretical description because of its complexity.[61] Air filtration of nanofibrous polymeric membranes is usually considered as a steady-state process. In fact, when the concentration of PM in air is moderate, particles accumulation on the filter is minimal and does not leads to any variation in membranes thickness.[62] A schematic representation of the structure of a nanofibrous membrane and its PM filtering process is reported in **Figure 3**.

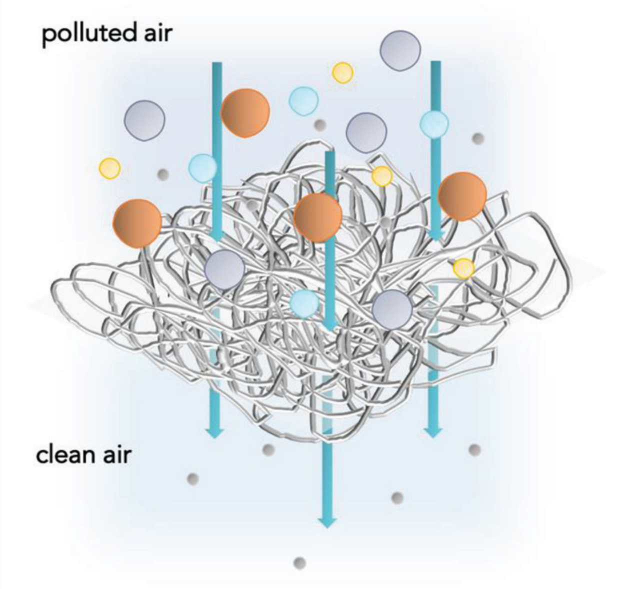

Figure 3. Graphical depiction of a typical nanofibrous membrane for air filtration application. Colored spheres represent PM of different dimensions.

The filtration theory affirms that in nanofibrous membranes particles trapping can occur following different type of mechanism: interception, inertial impaction, sieving, Brownian diffusion and electrostatic effect.[63,64]

Typically, particles tend to follow air streamlines and do not deviate from them unless there is another external force that forces them. Particles interception occurs when they get in contact with the surface of nanofibers due to the effect of van der Waals force as shown in **Figure 4**a.[65,66] Interception is recognized as primary filtration mechanism, is not affected by air flowrate and it is efficient for capturing particles with size ranged from 0.5 to 1 µm.[48,67]

UFPs, being usually smaller than the pore of the filtering mat, follow air streamlines across the nanofibrous membranes. In filtration, air streamlines are commonly tortuous due to the random orientation of the nanofibers that created extremely

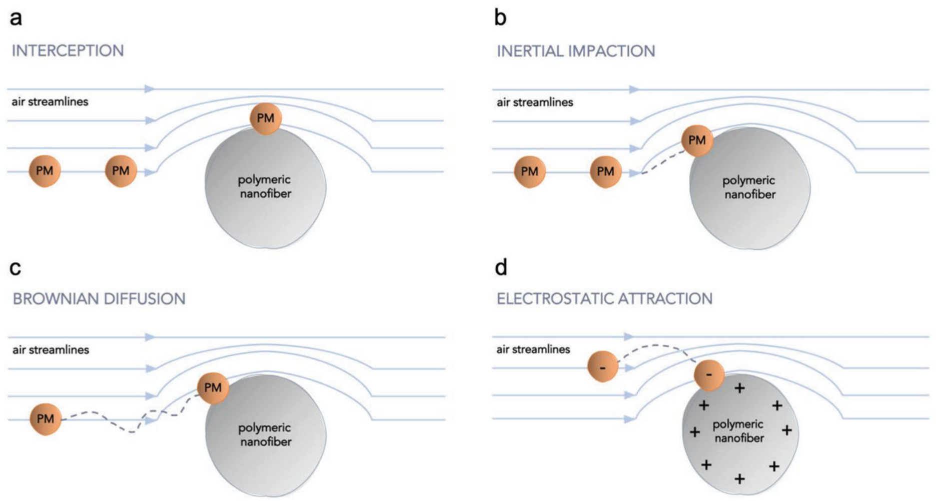

Figure 4. Graphical depiction of air filtration mechanisms of nanofibers membranes: a) interception, b) inertial impaction, c) Brownian diffusion, d) electrostatic attraction. Adapted with permission.[1] Copyright 2022, Elsevier.

complex arrangement of them in the membrane. However, due to inertia force, particles can deviate from air streamlines and impact on nanofibers surface leading to an effective filtration for inertial impaction as illustrated in Figure 4b.[68] The efficiency of filtration for inertial impaction increases on increasing the air velocity and the particle size. This filtration mechanism, in fact, is more efficient in the capture of particles larger than 0.3–1 μm.[48,67]

When the particles are larger than the pores created by fibers entanglements, a sieving mechanism occurs. In this case, nanofibers prevent particulate from passing through the membrane blocking them as soon as the particles come in contact with fibers surface. However, after a long-term usage, particles accumulation on the filter leads to a decrease in filtration efficiency but, above all, a strong increase in pressure drop. This behavior makes it challenging to recover the filter, removing the particles trapped in the filter, without destroying it, in order to reuse the same membrane as many as possible.[67,69]

Particles could also deviate from the original streamline starting to make irregular movements due to the so-called Brownian motion. Under the action of Brownian diffusion, particles could deviate from their original air streamlines, clashing with fibers and depositing on their surface as graphically described in Figure 4c.[65] Brownian diffusion typically occurs for particles smaller than 1 μm, however the effect is more significant when they are smaller than 0.1 μm in size.[67]

The force between charged bodies is conventionally called electrostatic force or Coulomb force. If the PM and/or the fiber are charged, particles could deviate from their original air streamlines, due to the electrostatic interaction (Coulombic attraction) with the fibers and deposit onto them surfaces (Figure 4d). If compared with the other forces involved in air filtration, the presence of electrostatic interaction lead to a remarkable increase in removal efficiency due to its capacity to strong attract particles also at distance. Moreover, electrostatic adsorption allows particles to adhere more firmly to the surface of the fibers[70] Electrostatic attraction can be effectively used to capture ultrafine particles such as dust and smoke.[67]

Usually, interception, inertial impaction, sieving and Brownian diffusion always occur during air filtration.[71–75] However, to archive high filtration performance it is necessary to combine all the different filtration mechanisms also exploiting electrostatic attraction.[70,76–80]

4. Parameters of Air Filtration Performance

The key parameters of filter performance include filtration efficiency, pressure drop, and the quality factor. Air filtration efficiency of nanofibrous membranes, usually represented as η, can be predicted by the Kuwabara model, as follows Equation (1):

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

where η_s is the filtration efficiency of a singular fiber, α represents the fiber volume fraction, d_f represents the average fiber diameter and L represents the membranes thickness.[81,82] This model highlights the strong dependence between filtration efficiency of the membranes and its structural and morphological properties. In detail, filtration performance decreases on increasing nanofiber diameter and is directly proportional to membranes thickness. However, this model does not consider the contribution of electrostatic effect.[46]

Figure 5 depicts a schematic drawing of the setup commonly used for performing air filtration tests. The filtration system is composed by two chambers separated by a septum in which can be insert the nanofibrous membrane. Usually, chamber (A) is equipped with a pollutant generator and a fan which push the particles towards the filtering membrane. In some configurations, the fan can be replaced by a pump connected with chamber (B). PM counters or (and) VOCs sensors are placed in both chamber in order to measure the filtration efficiency and a pressure gauge is installed between upstream and downstream side of the filter to measure membranes pressure drops.[4]

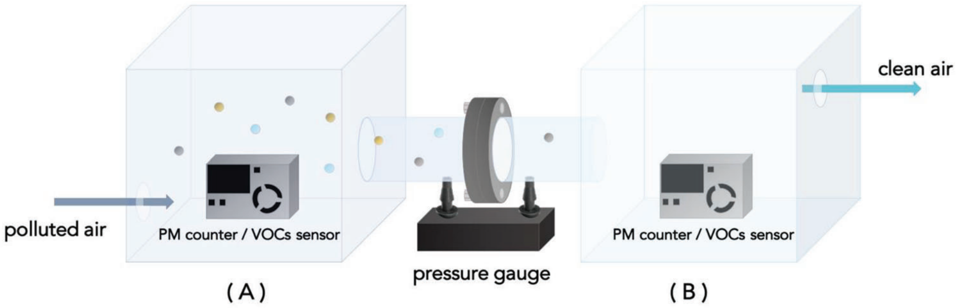

Figure 5. Schematic representation of the set-up commonly used for air filtration test for filtration efficiency and pressure drop measurement.

In filtration test, in fact, the filtration efficiency is measures as the ratio between the amount of pollutant (PM, VOCs, etc.) captured by the device from the airstream and the total amount of pollutant that get in contact with the filtering membranes, as described by the following Equation (2):

$$\eta = \left[1 - \frac{C_{\text{downstream}}}{C_{\text{upstream}}}\right] \times 100 \tag{2}$$

where C_{upstream} is the amount of particles detected by PM counters (or VOCs sensor) of chamber (A) before the filtration and $C_{\text{downstream}}$ is the number of particles detected by PM counters (or VOCs sensor) of chamber (B) after the filtration process.[83,84]

Filtration performance of fibrous membranes are also affected by pressure drop, which characterizes their air resistance. The pressure drops can be considered as the decrease in air pressure due to its passage through the filtering membrane. Pressure drop, in fact, refers to the difference between upstream and downstream air pressure of the filter.[85] In nanofibrous membranes, pressure drop across the filter are generated by air flowing resistance of the singular fiber. Membranes with high porosity, need to be preferred in order to minimizing pressure drop. Moreover, pressure drop is inevitably and strongly influenced by membranes thickness.[85–88]

However, the influence of membranes structural factors on filtration efficiency (η) and the pressure drop (ΔP) are often contradictory. The increase in membrane thickness, for example, promotes filtration efficiency but increase pressure drop. Because of that, a quality factor (QF) was established to assess the overall performance of the nanofibrous membranes, as described by the following Equation (3):

$$QF = -\frac{ln\,(1-\eta)}{\Delta P} \tag{3}$$

where η is the filtration efficiency (%) and ΔP is the pressure drop (Pa), therefore a higher-quality factor indicates a better filtration performance.[79,89]

Therefore, in general, membranes with high porosity and small fibers diameters should be preferred for air filtration applications. However, also fibers physical, chemical and electrostatic interaction with particles influence filtration performance. Will be detailed in the following paragraphs that by properly selecting materials, additives, production technique and the operative parameters of the process it is possible to tune membranes morphology and fibers-particles interaction in order to enhance filtration performances.

5. Materials for Polymeric Air Filtration Devices

Polymeric materials are actually the most used for the production of air purification device thanks to their superior filtration performances.[18] Synthetic polymers (non-biodegradable), in particular, are widely used for the fabrication of air filtration devices. Thanks to their property, in fact, they can ensure good reusability, durability, appropriate mechanical properties and thermal stability to the filter membrane. In detail, as already shown in Figure 2, polyacrylonitrile (PAN) is the most reported polymeric material for “air filtration” topic after COVID-19 pandemic period. However, recently, due to the current need of solve environmental pollution and resources shortage issues, the development of filtration devices based on biodegradable polymeric material has become an attractive topic.[17,49] Moreover, always more often, composites polymeric membranes were proposed for air filtration application. In fact, when nanoparticles are successfully imbedded into polymeric nanofibers, they could enhance membrane filtration efficiency and contextually improve its mechanical and thermal stability.[90]

5.1. Non-Biodegradable Polymers

Among the wide range of non-biodegradable existing polymers, polyacrylonitrile (PAN), polyvinylidene fluoride (PVDF), polypropylene (PP), polyamide (PA) and polyvinyl pyrrolidone (PVP) are some of the most recently used ones for the production of air filtration devices, as listed in **Table 1**.

Could be easily noted that polyacrylonitrile (PAN), as already seen in VOSViewer map (Figure 2), is the most reported polymeric material for air filtration device production. PAN nanofibers, in fact, due to the presence of polar chemical group on their surface, induced dipole-dipole intermolecular attraction forces with PM ensuring high capture efficiency.[41,91,100] Moreover, PAN is characterized by adequate mechanical and thermal properties.[101] However, it is possible to increase the number of functional groups on PAN fibers surface and therefore improving filtration efficiency, by combining PAN with other polymers or by adding appropriate additive of functional nanoparticles (NPs). Lv et al.,[21] for example, presented a PAN based multifunctional

Table 1. Non-biodegradable polymers recently used for the production of nanofibrous filter membranes.

Polymers	Polymer conc. [wt.%]	Filler	Filler conc [wt.%]	Year	Ref.
PAN	12	–	–	2020	[41]
PAN	12	–	–	2022	[91]
PAN	18	–	–	2019	[92]
PAN & CS	12 & 1	Fe_3O_4	5	2020	[21]
PAN	10	ZnO & Ag NPs	0.5 & 0.5	2021	[45]
PAN & PI	10 & 6	GO	0.05	2021	[19]
PAN	14	g-C_3N_4	3	2021	[93]
PAN & PCL	12 & 11	β-CD & ZnO NPs	50 & 27	2021	[94]
PAN & PVDF/PDMS	10 & 2.5 / 2.5	–	–	2023	[44]
PVDF	16	–	–	2020	[95]
PVDF	10	–	–	2022	[96]
PVDF	16.5	Fe_3O_4	1	2020	[76]
PP	(melt)	–	–	2019	[97]
PP	(melt)	–	–	2022	[98]
Nylon-6/PEO	10 / 0.2–0.4	–	–	2023	[99]

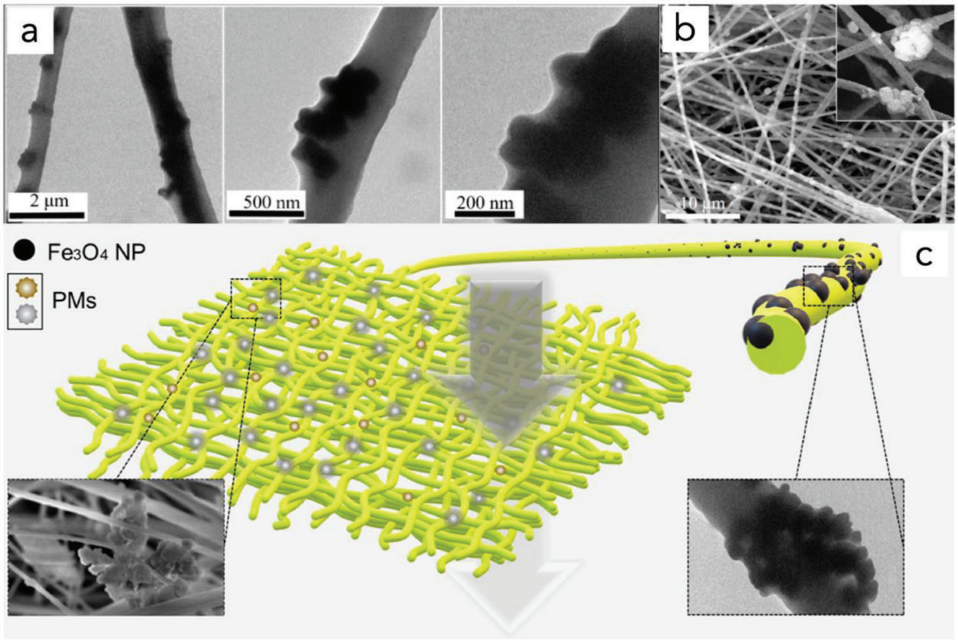

Figure 6. a) Transmission electron microscopy (TEM) images, b) scanning electron micrographs (SEM) image after PM filtration, and c) pictorial description of PMs filtration mechanism of Fe_3O4@PAN/CS membrane. Reproduced with permission.[21] Copyright 2020, American Chemical Society.

nanofibrous membrane, reporting that the addition of chitosan (CS) to PAN provide more functional groups to nanofibers ensuring a robust interaction with pollutants. Moreover, iron oxide nanoparticles (Fe_3O_4 NPs) agglomerate (**Figure 6**) promoted the formation of a 3D porous structure improving Fe_3O_4@PAN/CS membrane filtration efficiency and also allowing antibiotic absorption. Thermal stability was also increased after the incorporation of Fe_3O_4 NPs.

Multifunctional PAN based nanofibrous membrane have been also prepared by adding Zinc oxide nanoparticles (ZnO NPs) on one side of the mat and silver nanoparticles (Ag NPs) on the other side. The addition of the two NPs allowed obtaining a Janus membrane with improved filtration efficiency (if compared to neat PAN one prepared with the same procedure), organic contaminant removal ability and antibacterial properties.[45]

Dai et al.,[19] in 2021, prepared nanofibrous polymeric filter membranes by adding polyimide (PI) and graphene oxide (GO) into a solution containing PAN aiming to obtain a mask can be used for avoiding COVID-19 infection. If compared to neat PAN nanofibrous membranes obtained with the same procedure, PAN/GO/PI mat showed higher efficiency in capturing $PM_{2.5}$ pollutants, lower pressure drop, improved thermal stability and

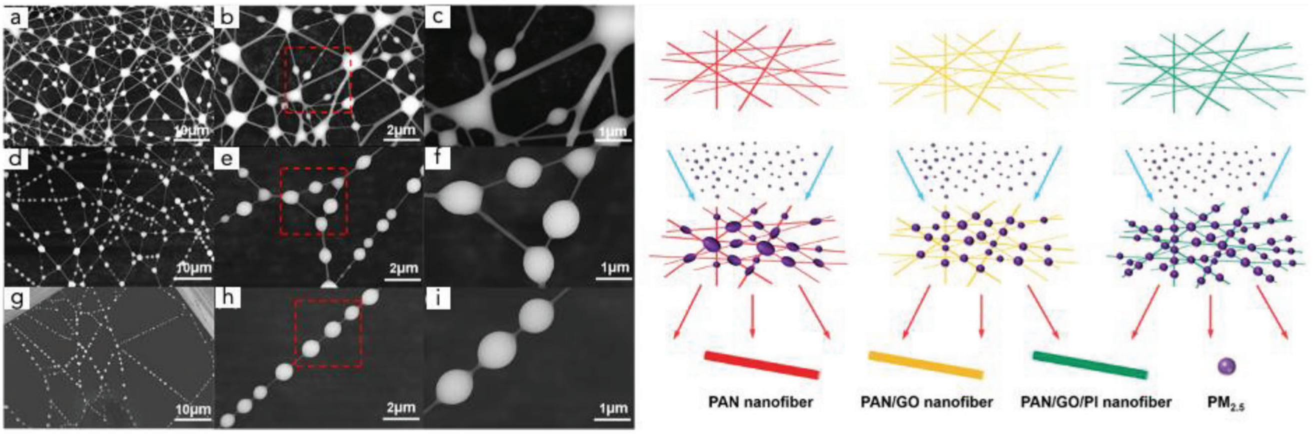

Figure 7. a–c) SEM images and illustration of PAN, d–f) PAN/GO, and g–i) PAN/GO/PI-6 nanofibers after PM2.5 adsorption. Reproduced with permission.[19] Copyright 2021, Elsevier.

mechanical properties. PAN/GO/PI nanofibers could adsorb $PM_{2.5}$ more uniformly and in spherical (rather than elliptical) shape if compared to neat PAN ones, as shown in **Figure 7**. According to the authors, this behavior can be reasonably ascribed to the abundant hydrophilic functional groups on the PAN/GO/PI nanofibers introduced due to GO and PI addition.

In the same year, Cui et al.,[93] added graphite carbon nitride (g-C_3N_4), a photocatalytic degradation material, to PAN solution obtaining a composite nanofibrous membranes. Air pollutant capture ability of PAN@g-C_3N_4 filter membrane was investigated and outcomes reviled that the addition g-C_3N_4 effectively improved filtration efficiency of $PM_{2.5}$. This behavior has been explained by the authors considering that the addition of g-C_3N_4 lead to an increase in nanofibers surface roughness and therefore to an increase in the chance of collision between the fibers and the intercepted contaminant. Moreover, g-C_3N_4 is also a good electret which allows nanofibers charging and therefore particles electrostatic attraction, further improving filtration efficiency. Furthermore, g-C_3N_4 dispersed on nanofibers surface, under light irradiation, could oxidizes and degrades formaldehyde molecules to achieve catalytic degradation of the pollutant, making the membrane multifunctional.

Xu et al.[94] prepared multifunctional Janus membranes that can filter particulate matter (PM) and volatile organic compounds (VOCs) simultaneously. One side (the hydrophilic one) was prepared by adding β-cyclodextrin to PAN, while, in the other side, zinc oxide (ZnO) was embedded in polycaprolactone (PCL) nanofibers in order to increase their roughness and enhance membrane hydrophobicity. The multifunctional Janus nanofibrous membrane achieved higher PM removal efficiency, lower airflow resistance and effective VOCs adsorption if compared to single side neat PAN ones.

Polymeric microbeads have been used for obtaining hydrophobic layers on filter membranes. Kim et al.,[44] for example, coated PAN nanofibrous membranes (**Figure 8**a) with polymeric microbeads based on a polyvinylidene fluoride (PVDF) and polydimethylsiloxane (PDMS) 50:50 solution (Figure 8b). Outcomes revealed that the decorated membrane showed high filtration efficiency. Moreover, the PVDF/PDMS coating effectively created a hydrophobic layer conferring water droplet cleaning ability to the membrane. When water droplets roll off membrane surface, they carry captured dust particles with them, see Figure 8c,d. This behavior allowed to renew membrane filtration performance multiple times, as it is possible to notice in Figure 8e. After three filtering stages, filtration efficiency remained stable, while the pressure drop gradually increased. However, after the cleaning stage, the pressure drop was almost completely restored. The reusability and durability of this membrane leads to clears economic and environmental advantages reducing maintenance cost and waste production.

Polyvinylidene fluoride (PVDF) is the second most reported polymer for the production of air filtration device. PVDF is characterized by unique properties such as good flexibility, good chemical resistance and high thermal stability.[102,103] Moreover, PVDF nanofibrous membranes have demonstrated excellent air filtration performance thanks to their electret effect that lead to a more effectively and firmly attachment of PM on fibers.[95,96] Liu et al.,[76] prepared a composite filter membrane by adding Fe_3O_4 NPs to PVDF solution aiming to exploiting the electret effect (given by PVDF) and the magnetic effect (given by metallic NPs) for obtaining high filtration efficiency. Thanks to the synergy of the two effects, in fact, PVDF/Fe_3O_4 showed higher filtration performance if compared to neat PVDF ones.

Polypropylene (PP) based materials have also been reported for the fabrication of air purifiers. In detail, PP is commonly used for the production of nanofibrous mat to be employed for the production of surgical face mask used for preventing COVID-19 infection. PP membranes, in fact, are characterized by high filtration efficiency and low pressure drop.[97,98]

Among the non-biodegradable polymers Nylon-6 was also investigated for the production of devices for the filtration of UFPs. Zhang et al.,[99] prepared a multilayer nanofibrous membrane based on a blend of Nylon-6 and polyethylene oxide (PEO) in different concentration. The obtained filter, due to chemical functional groups of Nylon-6 molecules, exhibited extremely high filtration performance and overall optimal filtering performance. The membrane was also characterized by relatively high mechanical performance. Moreover, these membranes provided users more comfortable wearing experience and stable protection performance against COVID-19.

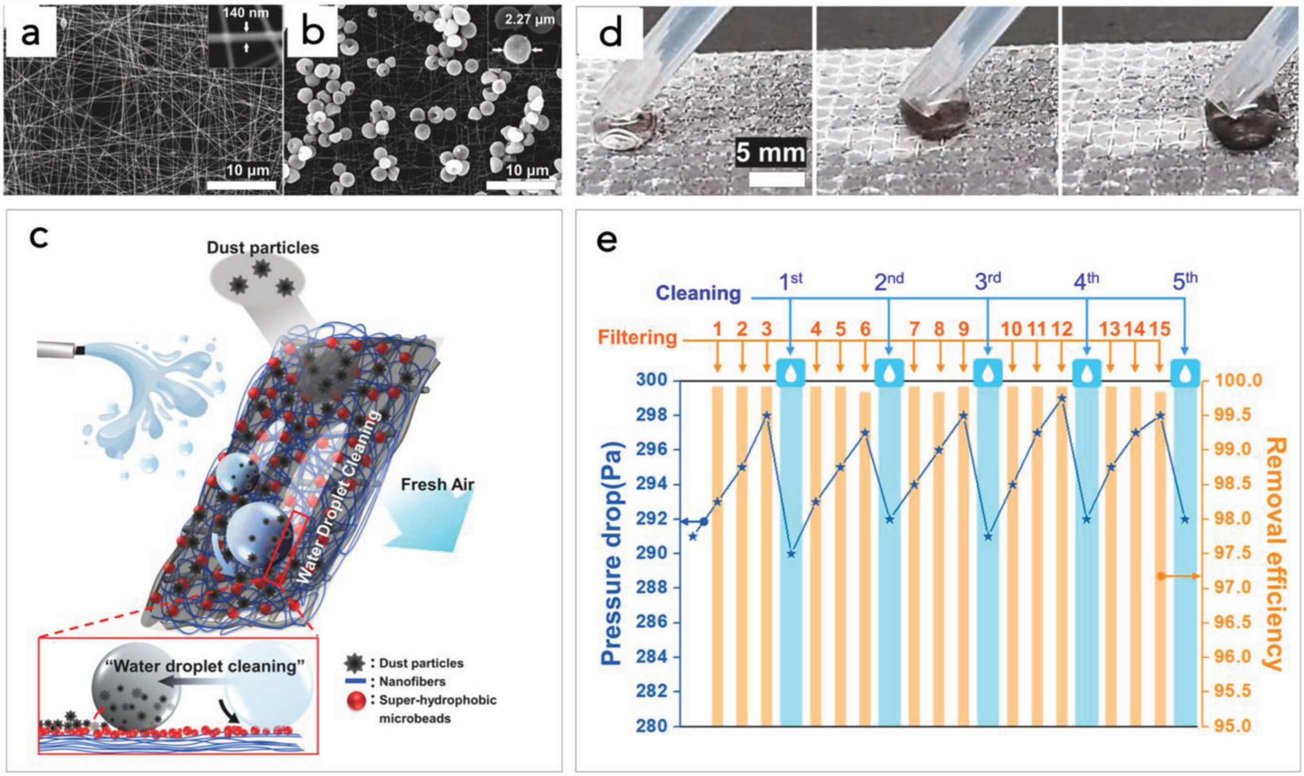

Figure 8. SEM images of PAN nanofibrous membrane before a) and after b) the PVDF/PDMS microbeads coating; pictorial description c) and photograph d) of filter and water droplet cleaning mechanism; filtration efficiency and pressure drop of PAN/PVDF/PDMS membrane during repetitive filtering and cleaning stages e). Reproduced with permission.[44] Copyright 2023, Elsevier.

Combining two or more polymers with different properties has been reported as a successful strategy for the obtainment of nanofibrous membranes with high filtration performance due to the possibility of combine the respective strengths.[104] Wang et al.,[40] for example, fabricated porous nanofibers using a PVP/PTFE blend in which PVP was used as a sacrificial phase. Thanks to the extremely porous nanofibrous membrane high filtration efficacy and ultralow pressure drop were achieved.

5.2. Biodegradable Polymers

The fabrication of environmentally friendly air filtration membranes with high filtration performance is still a big challenge. Most of the polymers mentioned above, in fact, need to be dissolved in toxic or, otherwise, harmful solvents and could not be biodegraded after their use. Therefore, solvents evaporation during nanofibers formation and the final disposal of the devices could induce second pollution.[17,49] Moreover, environmental impact of COVID-19 was very significant also due to the tons of raw materials exploited and plastic waste produced due to mask and indoor air filter extensive consumption.[105] The develop of air filtration devices based on bio-based and (or) biodegradable polymers would contribute to reduce these environmental issues. Although, biodegradable filters cannot ensure extensive durability or reusability they can be widely used for replacing traditional ones in all those applications in which single use only is mandatory.[106] Stimulated by these environmental needs, different nanofibrous devices based on green solvents and/or biodegradable polymers have been recently reported, as listed in **Table 2**.

Polyvinyl alcohol (PVA) is one of the most reported biodegradable polymers used for the production of nanofibrous filter membrane. Therefore, PVA is a water-soluble polymer characterize by excellent mechanical property, thermostability and biocompatibility. Kim et al.,[107] for example, fabricated a double layer device (PVA nanofibers/PP-based non-woven fabric) exploiting PVA water solubility to produce a nanofiber filter membrane that could be environmentally friendly disposed. In detail, as shown in **Figure 9**, after the filtration process, the devices could be immersed in water in order remove the PVA layer saturated with filtered particles. Subsequently, the non-woven fabric could be dried and a new PVA filtering layer could be added.

In order to expand its application, it is possible to stabilize PVA membranes through a thermal or chemical induced crosslinking. Glutaraldehyde.[24] and citric acid.[109] are commonly used as green additive for stabilizing PVA nanofibers. Li et al.,[73] add up to 70 wt.% of zein (denatured in acetic acid/water solution) to PVA solution in order to prepare nanofibrous membrane for air filtration. Water Contact Angle (WCA) test reviled that on increasing zein amount the hydrophobicity of PVA membranes increase. Moreover, zein containing membranes showed higher air pollutant removal efficiency if compare to neat PVA ones. According to the authors, this behavior could be reasonably ascribed to

Table 2. Biodegradable polymers recently used for the production of nanofibrous filter membranes.

Polymers	Solvents	Polymer conc. [wt.%]	Filler, additive	Filler, additive conc. [wt.%]	Year	Ref.
PVA	water	7	–	–	2021	[107]
PVA	water	10	zein	0 – 70	2020	[73]
PVA/CS	water/acetic acid	10 / 2	–	–	2020	[24]
PVA/CS	water/acetic acid	10 / 3	SiO_2, Ag NPs	4	2019	[108]
PVA/KGM	water	10 / 1	ZnO NPs	1	2019	[109]
PLA	EA/DMF	10	–	–	2022	[110]
PLLA	DCM/DMF	10	DC	2.5	2023	[111]

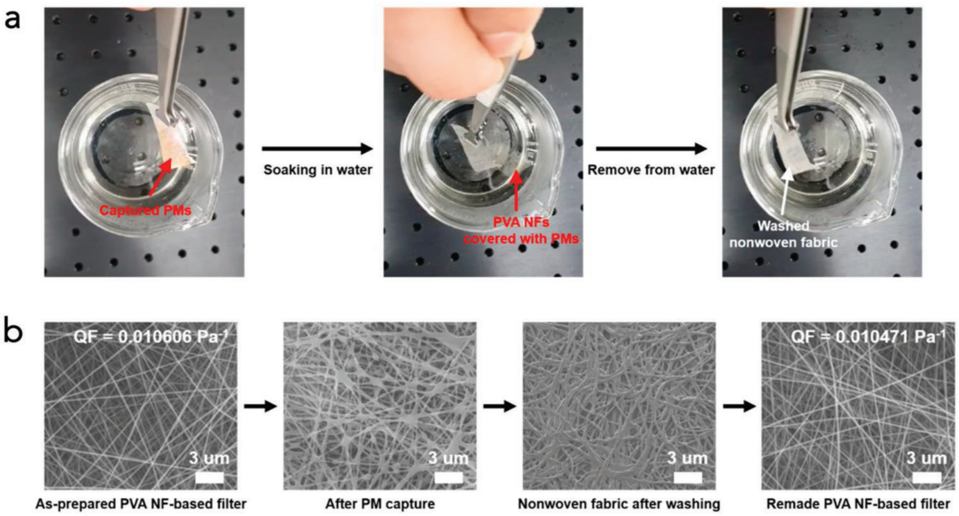

Figure 9. a) Removal of PVA layer in water after filtration and b) SEM images of the surface of the device during the restoring process. Reproduced with permission under the terms of the CC-BY license.[107] Copyright 2021, the Author(s). Published by MDPI.

zein higher interaction with pollutants if compared with PVA. After the denaturation in acetic acid, in fact, zein exposed active group increased guaranteeing an effective interaction with pollutant of different nature. Furthermore, zein addition, leading to a decrease in solution viscosity, provoked a decrease in nanofibers diameters, resulting in an increase of their specific surface that positively contributing to membranes filtration performance.

In 2020, Zhang et al.[24] fabricated a multilayer structured membrane with excellent mechanical properties, air filtration performance and antibacterial ability by assembly PVA/CS nanofibrous membranes onto both sides of a N-halamine biopolymer fibrous mat. Zhu et al.,[108] similarly, exploited antibacterial activity of CS to produce PVA based filter membrane. Moreover, in this study, Ag and SiO_2 NPs were added to the nanofibrous membrane with the aim of enhance antibacterial ability and filtration performance, respectively.

Lv et al.,[109] successfully encapsulated ZnO NPs into PVA/konjac glucomannan (KGM, a natural polymer) nanofiber. Outcomes revealed that the presence of ZnO NPs into PVA nanofibers allow to enhance filtration performance (as shown in **Figure 10**) of the device, conferring also antibacterial and photocatalytic ability to the composite membranes.

Polylactic acid (PLA), is another biodegradable polymer widely used for the production of environmentally friendly air filtration device.[71,112–114] However, PLA is commonly dissolved using harmful organic solvents such as dichloromethane (DCM), chloroform, 1,1,1,3,3,3-hexafluoro-2-propanol (HFIP) in order to obtain nanofibers. Therefore, preparing PLA nanofibrous membranes without using toxic solvent is an urgent issue. Han et al.,[110] for example, prepared PLA based nanofibrous membranes selecting two relatively green alternative non-halogenated solvents: ethyl acetate (EA) and N, N-dimethylformamide (DMF). According to the authors, if compared to the others possible solvents (see **Figure 11**), EA/DMF mixture could significantly reduce secondary pollution related to membranes production. Moreover, once optimized the PLA concentration and the solvents ratio, the obtained morphology achieved outstanding removal efficiency and extremely low pressure drop. Filtration performance of the membrane was significatively higher to those reported for commercial masks used for avoiding COVID-19 infection.

Wanwong et al.,[111] added cyclodextrins (CDs) to poly(L-lactic acid) (PLLA) in order to obtain a mask based of nanofibrous membrane that could contextually filter PM and VOCs. In fact, piezoelectric and triboelectric property of PLLA lead to an increase in membrane PM capturing ability due to the high electrostatic interaction between PLLA nanofiber and PM. On the other hand, CDs, due to their peculiar conic structure composed by a

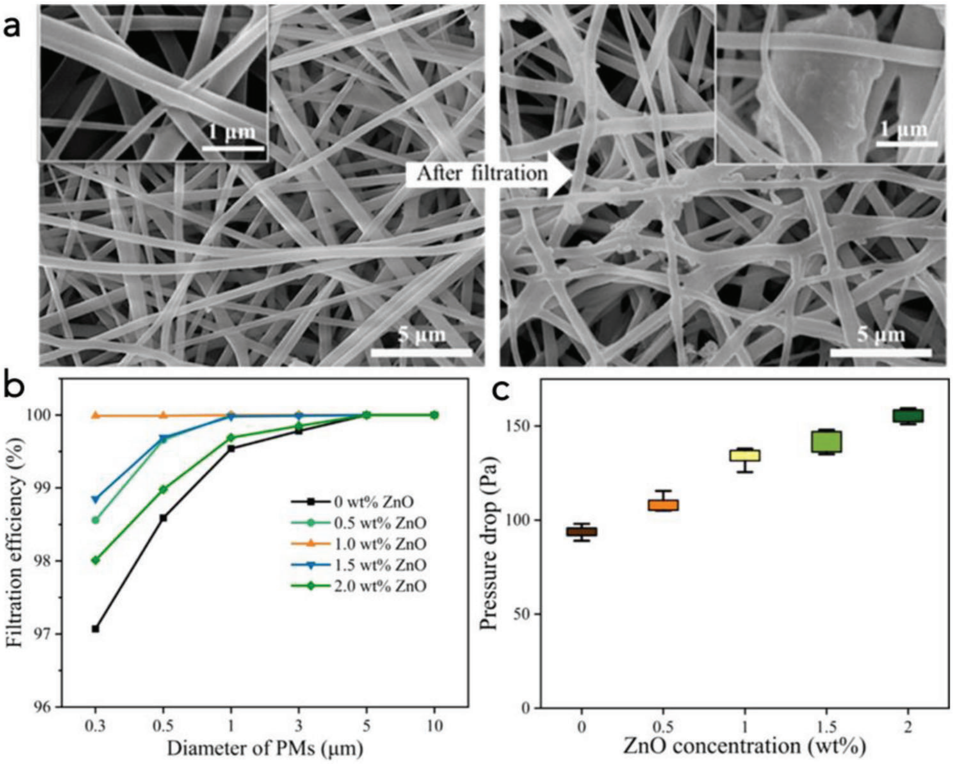

Figure 10. a) SEM images of ZnO@PVA/KGM nanofiber membrane before (left) and after (right) filtration; b) filtration efficiency at different PM dimensions, and c) pressure drop of membranes with different ZnO concentrations. Reproduced with permission.[109] Copyright 2019, American Chemical Society.

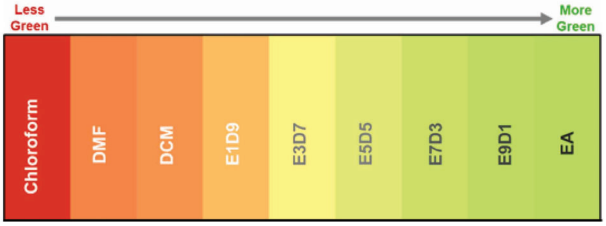

Figure 11. Greenness comparison of solvents. Reproduced with permission.[110] Copyright 2022, Elsevier.

hydrophobic central cavity and a hydrophilic outer surface, entrap higher amounts of VOCs, including aniline and benzene vapors.

It can be concluded that the choice of the polymeric matrix, together with the appropriate selection of additives and fillers, make the difference in term of filtration performance of the final nanofibrous device regardless production techniques. The addition of functionals NPs, in particular, seems to be a successful strategy to produce nanofibers with improved filtration efficiency and (or) to make membranes multifunctional.

6. Polymeric Membranes for Air Filtration Production

The structures of polymeric filter materials have been developed over the last few years. Different examples of porous polymeric filter membranes with high filtration efficiency but low porosity, poor hole connectivity and, therefore, high air resistance have been reported.[46,115–118] However, by processing the same polymeric systems with alternative production techniques it is possible to obtain different structures with higher porosity and, therefore, improved filtration performance.[119–121] In detail, polymeric membranes with nanofibrous structure turn out to perform better for air filtration if compared to other porous structure.[67,122] This behavior confirms the strong influence of the membrane structure on filtration efficiency and, therefore, the importance of production technique choice. **Table 3** enlist the filtration performance of various polymeric nanofibrous membranes obtained with different production technique.

6.1. Electrospinning

Electrospinning (ES) is one the most frequently reported technique to prepare nanofibrous mats.[121] and its set-up is shown in **Figure 12**.

ES apparatus is mainly composed by a collector, a spinneret, a high voltage power supply and a syringe pump. The polymeric solution is loaded into a syringe pump with a needle tip (the spinneret) and due to the supply high voltage power is charged. If the applied voltage is enough to overcome the solution tension surface a Taylor cone will be formed and polymeric fibers will overlay the grounded metal collector.

As it is possible to notice from Table 3, ES is widely used to prepare membranes for air filtration application, allowing to

Table 3. Filtration performance parameters of polymeric nanofibers devices obtained with different production techniques.

Technique	Polymers	Structure	PM [µm]	η [%]	ΔP [Pa]	QF [Pa^{-1}]	Ref.
ES	PVA	nanofibers	0.5	86.81	191	0.011	[107]
ES	PAN@g-C_3N_4	nanofibers	2.5	99.76	43	0.121	[93]
ES	PAN/GO/PI	nanofibers	2.5	99.5	92	0.058	[19]
ES	PVDF@Fe_3O_4	nanofibers	2.5	99.95	58	0.130	[76]
ES	PVA/KGM@ZnO	nanofibers	0.5	99.99	130	0.070	[109]
ES	PLLA/DCs	nanofibers	2.5	96.84	43	0.105	[111]
ES	PAN	NF/nanonet	0.3	99.99	110	0.100	[92]
ES	PVDF	NF/nanonet	0.3	99.99	93	0.110	[95]
ES	PVDF	branched NF	0.3	99.99	126	0.090	[96]
ES	PLA	bead-on-string	2.5	98.56	29	0.140	[110]
ES	PVA/CS	multilayer	0.5	99.30	183	0.027	[24]
ES	PVA/CS@SiO_2/Ag	hierarchical	0.5	96.60	306	0.011	[108]
ES	PAN@ZnO/Ag	Janus NF	0.3	80	32	0.050	[45]
ES	PAN/CD-PCL/ZnO	Janus NF	0.3	99.99	156	0.059	[94]
ES double-disc	PAN	well-ordered NF	2.5	99.60	62	0.090	[91]
ES and electrospray	PAN/PVDF/PDMS	microbeads on NF	2.5	99.80	110	0.057	[44]
centrifugal ES	PVP/PTFE	porous fibers	0.3	99.72	90	0.065	[40]
solution blow spinning	PAN	nanofibers	2.5	92.90	58	0.046	[41]
solution blow spinning	PAN/CS@Fe_3O_4	hierarchical	0.3	99.98	48	0.123	[21]
solution blow spinning	Nylon-6/PEO	multilayer	0.25	99.50	144	0.066	[99]
melt blown spinning	PP	nanofibers	0.3	99.20	29	0.170	[98]

electrospinning (ES); nanofibers (NF); particulate matter (PM); filtration efficiency (η); pressure drop (ΔP); quality factor (QF

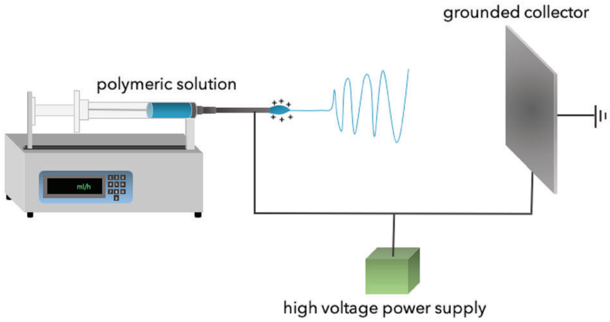

Figure 12. Schematic representation of electrospinning set-up.

easily produce uniform, randomly oriented or aligned fibers with homogeneous diameters and leading to the fabrication of highly and interconnected porous membranes. Kim et al.,[107] for example, using ES, fabricated eco-friendly air filter membranes based on PVA nanofibers. However, filtration performance of the devices was relatively low, reporting a filtration efficiency of 86.81% and a quality factor of 0.11 Pa^{-1}.

As mentioned above, the presence of functionals NPs could improve membranes filtration efficiency. ES has the great advantage of easily allowing fabrication of composite nanofibers just by adding NPs to the polymeric solutions and electrospun them. Lui et al.,[76] for example, fabricated electrospun PVDF mats containing up to 1.5 wt.% of Fe_3O_4 NPs, as is possible to notice from TEM image in **Figure 13**a. When 1 wt.% of Fe_3O_4 NPs is added, the membranes achieved the best filtration performances (filtration efficacy of 99.95% and pressure drop of 58.5 Pa) as reported in Figure 13b,c.

Similarly, also Cui et al.[93] and Dai et al.[19] in 2021, correctly embedded graphite carbon nitride (g-C_3N_4) and graphene oxide (GO), respectively, into PAN electrospun nanofibers leading to an increase in membranes filtration performances if compared to the neat PAN ones. As regards biodegradable polymers, Lv et al.[109] fabricated PVA based filtering membranes through green electrospinning and ecofriendly thermal cross-linking. They successfully loaded ZnO NPs into PVA nanofibers during the spinning process achieving a filtration efficiency higher than 99.99% for UFPs. Moreover, recently, Wanwong et al.[111] electrospun PLLA solutions in which up to 10 wt.% of CDs were added with excellent results. 2.5 wt.% CDs containing membranes showed the best air filtration performance if compared to neat PLLA (16% higher) and other composites membranes with different CDs amounts. More in detail, 2.5 wt.% CD/PLLA displayed filtration efficiencies of 96.84% and 99.38% for $PM_{2.5}$ and PM_{10} capturing respectively.

Electrospinning is a very versatile technology. By tuning solution composition and concentration, processing and (or) ambient parameters it is possible to modify electrospun fibers morphology and consequently to obtain membranes with complex structure and improved properties. Liu et al.[92] in 2019, for example, fabricated PAN nanofiber/nanonet fluffy membranes (**Figure 14**a) for air filtration application by introducing cationic surfactant tetrabutylammonium chloride (TBCA) in the polymeric solution, using a humidity-induced electrospinning/netting technique. In detail, PAN/TBAC charged droplets

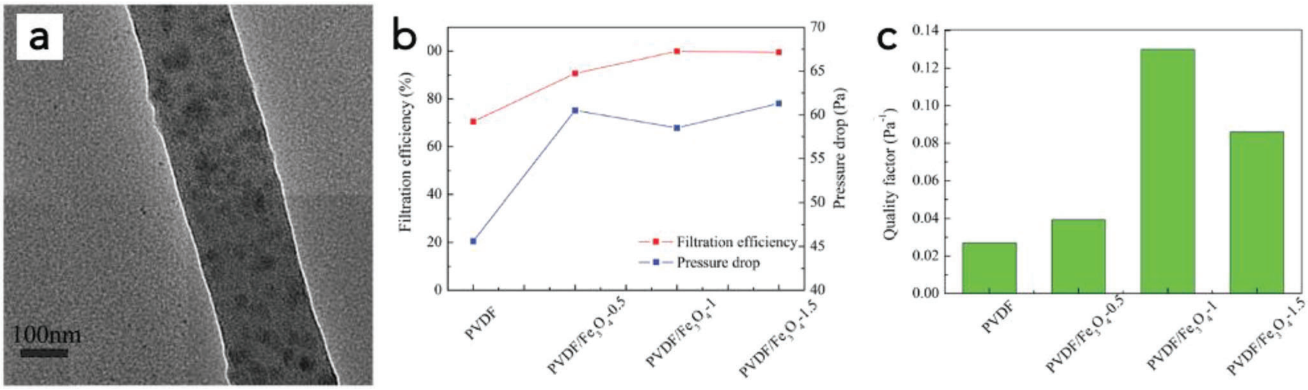

Figure 13. a) TEM image; b) filtration performances, and c) quality factor of PVDF/Fe3O4 membranes. Reproduced with permission.[76] Copyright 2020, Wiley-VCH GmbH.

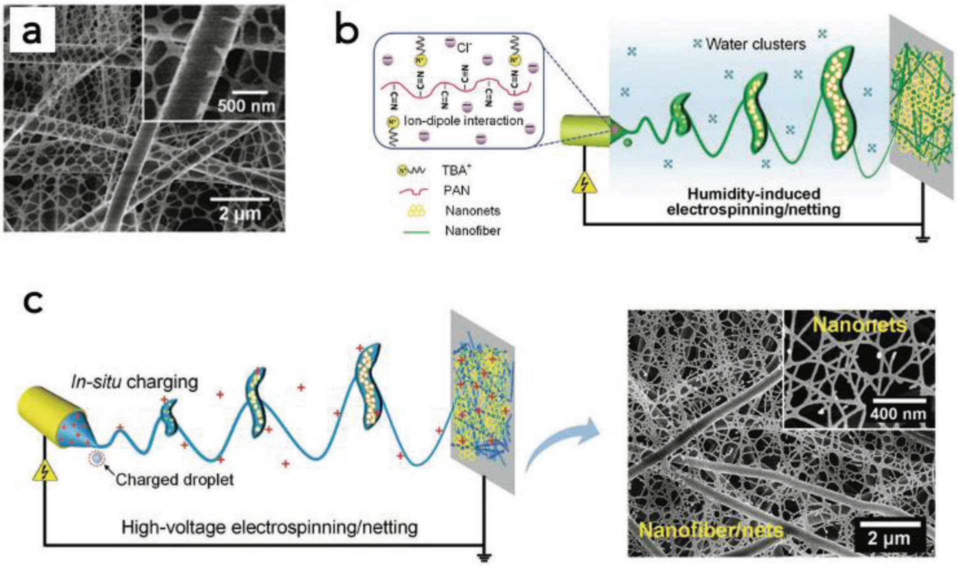

Figure 14. a) SEM image and b) graphical description of fabrication process of PAN nanofibers/nanonet membranes. Reproduced with permission.[92] Copyright 2019, Wiley-VCH Gmb. c) Graphical description and SEM image of PVDF nanofibers/nanonet membranes. Reprodcued with permission.[92] Copyright 2019, Wiley-VCH GmbH.

were formed at the exit of the needle tip due to the ion–dipole interaction between the polymer and the surfactant. Subsequently, under high-voltage electric field and humid controlled atmosphere the droplets turn in 2D nanonets due to phase separation effects, as graphically descripted in Figure 14b. According to the authors, thanks to the synergistic effects of nanonet and fluffy nanofiber, membranes showed extremely high filtration efficiency (99.99%) for $PM_{0.3}$ and ultralow air resistance (110 Pa). The same authors, in 2020, tested other polymeric systems in order to obtain the same nanofiber/nanonet membranes structures.[95] More in detail, by using electret PVDF was possible to exploit electrostatic attraction to produce the nanonet (Figure 14c,d), keeping filtration efficiency at 99.99% and decreasing pressure drop to 93 Pa if compared with the previously obtained PAN membranes.

TBCA was also used with PVFD by Zaarour et al.,[82] in order to obtain electrospun branched nanofibers. The extremely small diameter of branched nanofibers, in fact, improves van der Waals attractive forces between particles and nanofibers leading to a very high filtration efficiency (99.99%) and a quality factor of 0.09 Pa^{-1}.

Han et al.,[110] fabricated electrospun membranes with bead-on-string structure by tuning the solvent ratio of PLA solution. Thanks to this complex structure, membranes achieving an outstanding removal efficiency (98%) for $PM_{2.5}$ and an extremely low pressure drop of 29.3 Pa.

Moreover, different complex structures have been obtained by electrospinning. Zhang et al.,[24] for example, reported that PVA based multilayer and multifunctional nanofibrous membranes (for air filtration mask) have been prepared by consecutively electrospun superimposed different polymeric solutions. The multilayer membranes showed a high filtration efficiency of 99.3% and a relatively low pressure drop of 183 Pa for $PM_{0.5}$. On the other hand, Zhu et al. fabricated hierarchical PVA/CS based electrospun nanofibrous membrane by adding SiO_2 and Ag NPs in order to increase nanofibers surface roughness to further improve

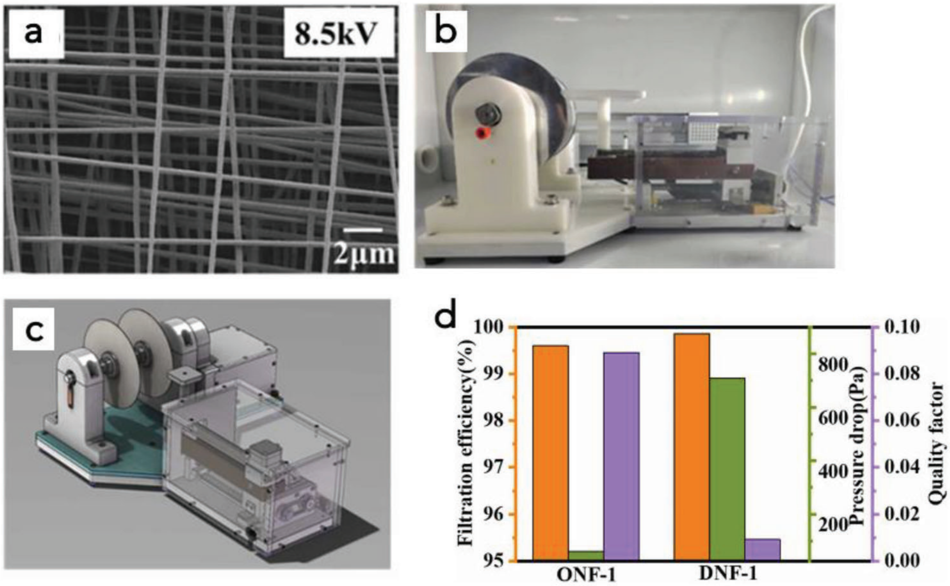

Figure 15. SEM image of a) ONF membrane; b) picture, and c) schematic description of double-disc collecting device; d) air filtration performance of ONF and DNF membranes. Reproduced with permission.[91] Copyright 2022, Elsevier.

membranes air filtration performance and to give antibacterial ability to the device. The membranes could effectively serve as a personal protective mask also for COVID-19 infection.

It has been reported that ES technique allow to produce Janus membranes also for air filtration application.[45] Xu et al.,[94] for example, prepared, by electrospinning, PAN/PLA based cyclodextrins and ZnO containing Janus nanofibrous membranes aiming to obtain a mask with contextually high filtration performances and VOCs adsorption ability. More in detail, the Janus membranes were obtained by consecutively electrospun superimposed PAN/β-CDs solution and PCL/ZnO one. PAN/β-CD/PCL/ZnO device reported a filtration efficiency of 99.99% and a pressure drop of 156 Pa for $PM_{0.3}$, moreover, it effectively absorbed aniline.

By appropriately designing the grounded collector shape it is possible to modify nanofibers morphology and, therefore, the structure of the membranes in order to improve their filtration performances. Cheng et al.,[91] for example, succeeded in the obtainment of well-ordered PAN nanofibrous membranes (**Figure 15**a) by using a double-disc collecting device, reported in Figure 15b,c. The well-ordered nanofibers membranes (ONF) showed a relatively high filtration efficiency of 99.60% and extremely low pressure drop of 62 Pa. According to the authors, the more ordered fibers arrangement trapping particles more effectively if compared to a disordered nanofiber membrane (DNF). But, predominantly, the well-ordered structure allows to decrease significantly the air resistance (see Figure 15c) and improve stability over long periods of time, potentially allowing continuous air-purification applications.

Combine ES with other similar techniques has been proved to be a successful strategy for obtaining multifunctional membranes with high filtration performance. Kim et al.[44] in 2023, for example, combined ES with electrospray (conceptually identical to ES but microbeads instead of fibers are ejected) in order to fabricate filter membranes with water droplet cleaning ability. A dual-layer structure consisting of hydrophilic PAN nanofibers coated with hydrophobic PVDF/PDMS microbead was obtained. Membranes reported a filtration efficiency higher than 99.8% and the pressure drop was recovered by 99% after each cleaning cycle, ensuring filter reusability.

ES standard set-up can be easily modified and implemented in order to obtain different fibers morphologies, improved production rate or new functionalities. Many variations of ES are reported in the scientific literature and electro-centrifugal spinning (ECS) is one of these.[43,123,124] Wang et al.,[40] for example, reported that through ECS (the process is schematized in **Figure 16**a) and a subsequent sintering calcination was possible to improve fibers production rate and obtain ultrafine porous PTFE fibrous membrane (shown in Figure 16b) that exhibited excellent air filtration performance – with a filtration efficiency of 99.72% and a pressure drop of 90 Pa – and reusability, as shown in Figure 16c.

6.2. Solution Blow Spinning

Solution blow spinning (SBS) is a new technology that allow to produce polymeric fiber by using a simple and cost-effective set-up, showed in **Figure 17**.[125] In SBS, in fact, pressurized air is used to stretch the polymeric solution and disperse the solvent in order to obtain fibers.[121] Compared to electrospinning, solution blow spinning has no high-voltage requirement, therefore not only is safer for the user and greener for the environment but also allow to process polymeric solution with low conductivity, expanding the application range.[126] However, usually, membranes obtained with SBS suffer from poor morphology presenting irregular fibers diameter distribution, fibers bundle and fibers in the micro-scale range.[126]

Nevertheless, this non perfectly homogeneous structures achieved relatively high filtration performance,[99] especially

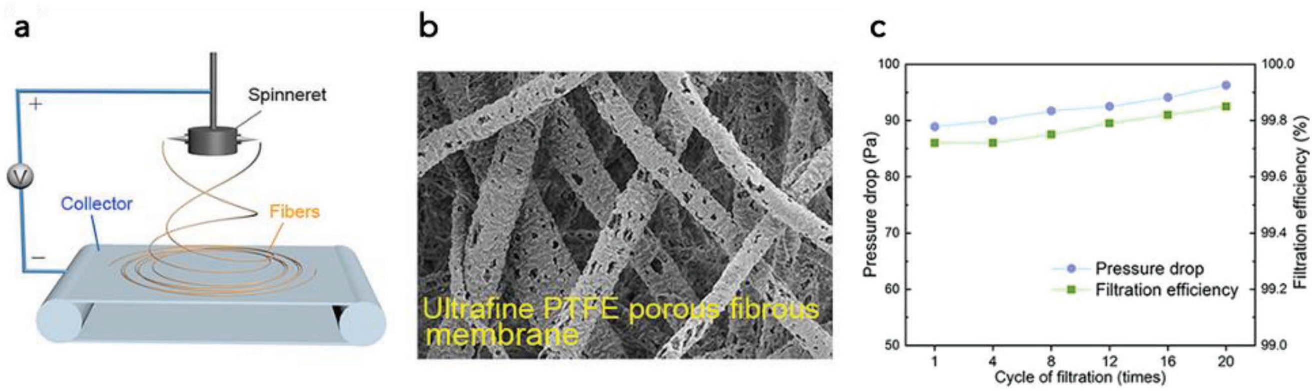

Figure 16. a) Schematic representation of ECS fabrication process; b) SEM micrograph of porous fibers; c) membranes filtration performance. Reproduced with permission.[40] Copyright 2021, Elsevier.

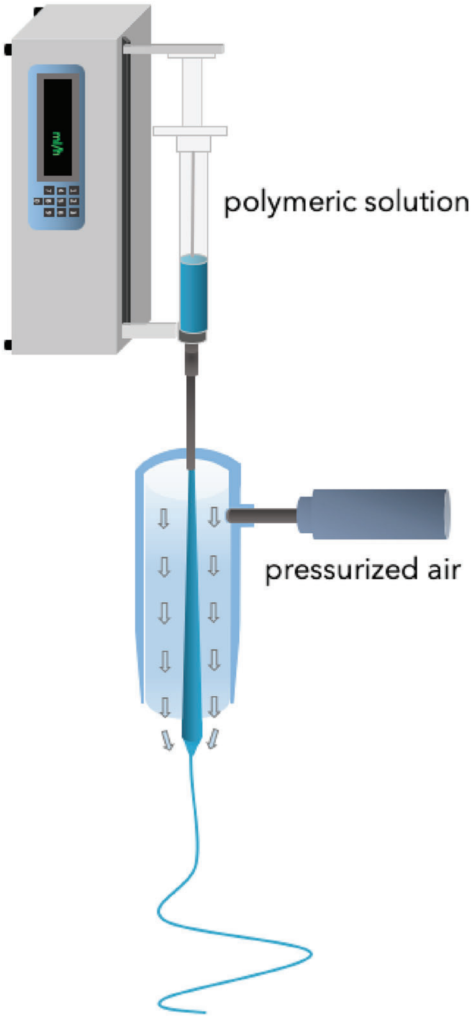

Figure 17. Schematic representation of SBS set-up.

when NPs are embedded in the fibers and a wrinkled surface is obtained. Lv et al.,[21] for example, used SBS technique (**Figure 18**a) aiming to fabricated ultrathin nanofiber membranes with high porosity, interconnected pore and hierarchical structure for filtration application (Figure 18b). In detail, they prepared multifunctional polyacrylonitrile/chitosan@Fe_3O_4 based membranes that, due to the high fibers surface roughness (achieved thanks to the presence of NPs), showed an extremely high filtration efficiency (99.98% for $PM_{0.3}$ and almost 100% for PM_1) and pressure drop of only 48 Pa. Moreover, PAN/CS@Fe_3O_4 membranes proved their reusability and durability demonstrating the potential long-term application.

Moreover, SBS allow large-scale fabrication ensuring good industrialization prospect that, however, has not been reached up so far. Song et al.,[41] for example, used SBS in order to successfully fabricate, in continuous production, 500 mm wide nanofiber membranes that exhibited filtration efficiency of 92.90%, pressure drop of 58 and a consequent quality factor of 0.046 Pa^{-1}.

6.3. Melt Blow Spinning

Not all polymers can be processed for electrospinning or solution blow spinning, aiming to produce nanofibers, since not all polymers can be solvated. PP, for example, is one of these. However, PP fibrous mats were successfully fabricated for melt blow spinning (MBS).[97,98,127–129] In MBS, fibers are created through hot and high-speed air jets that stretch the extruded molten polymer. Melt blow spinning has the great advantages of no voltage requirement, can allow large-scale fabrication and is suitable to process wide range of polymers.[126] For these reasons, MSB is actually a common method used in industry for producing microfibrous mat.[130] However, this technique is not very used for the production of innovative air filtration device since is not possible to easy obtain fibers in the nanoscale range and we have already widely discussed how the obtainment of small fiber diameter (leading to membranes with large specific surface area and high porosity) is high desirable in air filtration in order to obtain good filtration performance. In order to solve this limit, Yang el al.[98] developed a laser-assisted melt-blown (LAMB) spinning technique (illustrated in **Figure 19**) to produce PP nanofibers for fabricate facemask with a quality factor of 0.17 Pa^{-1}.

7. Conclusion and Future Perspectives

The production of polymeric nanofibrous membranes for air filtration has gained a lot of interest over the last years especially

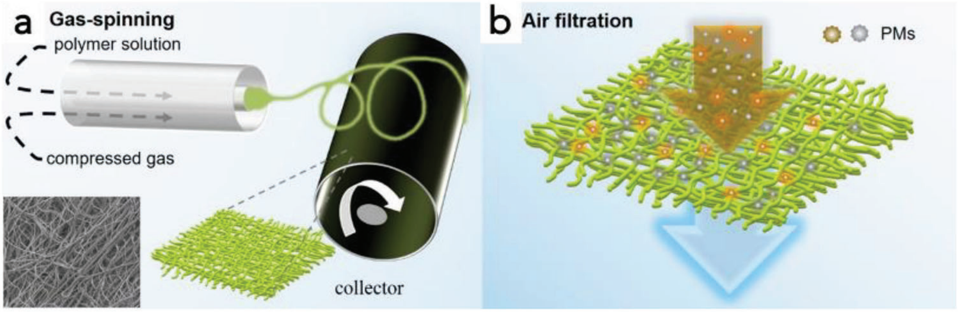

Figure 18. Schematic representation of SBS technology a) for the production of nanofibers membranes for air filtration application b). Reproduced with permission.[21] Copyright 2020, American Chemical Society.

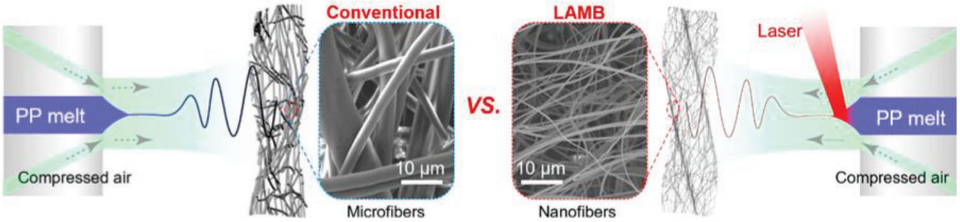

Figure 19. Pictorial description and SEM images of conventional melt blow spinning and laser-assisted melt blow spinning. Reproduced with permission.[98] Copyright 2022, American Chemical Society.

after COVID-19 pandemic period. In detail, electrospinning is the most reported technique for the fabrication of these devices allowing to obtain complex structure and to easily incorporate NPs. Membranes with complex structures (nanonets, branched fibers, beads on fibers, well-ordered, Janus or hierarchical) demonstrated superior filtration efficiency if compared with simple nanofibers. The same behavior has been recorded when NPs were added to the polymeric nanofibers, enhancing their roughness. However, new technologies, such as solution blow spinning and melt blow spinning have been implemented aiming to improve fibers production rate and to expand the range of usable polymers. Also in these cases, the crucial role of the membranes structure and NPs presence have been highlighted. Therefore, further investigate new process techniques and implement them with new set-up and (or) new tool the known ones are an interesting challenge that would allow to fabricate innovative composite polymeric membranes with complex structure aiming to obtain high filtration performance.

Moreover, during the COVID-19 pandemic period, production and usage of face masks and other filtering devices significantly increased generating million tons of plastic wastes.[131,132] Driven by the increasing awareness on second pollution related to air filtration membranes, different examples of green and (or) biodegradable filter membranes are reported over the very last years. Moreover, due to the current need to solve environmental pollution and resources shortage issues, the development of filtration devices based on waste material has recently become an attractive topic.[133–135] In fact, the use of scraps material and (or) the recycle of polymeric ones for the production of innovative air filter would promote the transition to a circular economy model, minimizing environmental pollution and materials usage and improving waste management.[136–140] Moreover, the addition of natural wastes as filler in biopolymeric matrices, that have been already successfully exploited for other applications,[141–149] could be an interesting challenge aiming to fabricated green and biodegradable filter membranes with wrinkled nanofibers and, therefore, high filtration performance.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

air filtration, air pollution, COVID-19, fibers, nanofibers membranes, particulate matter, polymeric membranes

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