Electrospun polymeric nanofibers as antimicrobial filters for a cleaner and safer environment

Renjith Sasi*, Anjaly Anil, Parvathy Valiyaveettil Rudrasenan, and Roy Joseph

ABSTRACT

Airborne particles such as particulates, spores, and hazardous bioaerosols pose a serious threat to human health. Filtration remains the most widely used method to combat deteriorating air and water quality. While conventional air filters can capture airborne particles, their inability to inactivate pathogens leads to the accumulation of bioaerosols, thereby creating a secondary source of pollution. Incorporating antimicrobial properties into air filters offers a significant advantage by not only trapping bioaerosols but also inhibiting microbial growth. Conventional air filters can be transformed into antimicrobial filters through surface coatings with antimicrobial agents such as metal and metal oxide nanomaterials, ionic liquids, quaternary ammonium or phosphonium salts, antimicrobial polymers, *N*-halamine compounds, antimicrobial peptides, antibiotics, and potent natural extracts. However, coating methods often disrupt pore structure and cause uneven distribution of antimicrobial agents, which may compromise filtration efficiency. Electrospinning is a promising alternative that enables the fabrication of uniform micro- and nanofibers capable of effectively filtering impurities from air or water. Antimicrobial properties can be introduced by incorporating antimicrobial agents directly into the spinning solution and optimizing the formulation parameters. Over the years, a wide range of polymers and antimicrobial additives have been explored for the development of antimicrobial filters using various methods. This article reviews recent advances in antimicrobial filter fabrication, with particular focus on electrospinning, and examines how antimicrobial fillers influence the structural and functional properties of electrospun nanofibers.

Keywords:
Filters; Antimicrobial; Electrospinning; Polymers; Nanofibers

***Corresponding author:**
Renjith Sasi,
renjithschem@sctimst.ac.in

How to cite this article:
Sasi, R.; Anil, A.; Rudrasenan, P.V.; Joseph, R. Electrospun polymeric nanofibers as antimicrobial filters for a cleaner and safer environment. Biomater Transl. 2025.

doi: 10.12336/bmt.25.00063

1. Introduction

Clean air and water are essential for sustaining human life on Earth.[1] Unfortunately, most air and water resources are continuously polluted due to human activities.[2] Consequently, a large portion of the global population is deprived of clean and safe air and water.[3,4] Continuous exposure to polluted air or water can cause severe health issues, such as lung diseases, cardiac ailments, neurological diseases, reproductive and developmental defects, cancer, and premature deaths.[5] Furthermore, pollution can also negatively affect the ecosystem, leading to the extinction of endangered species.[6]

A clean environment is particularly essential in hospitals, which accommodate immunocompromised patients daily.[7] Hospital-acquired infections are major contributors to nosocomial illnesses that may prolong patients' hospital stays, deteriorate their health conditions, and even result in death. Filtration is one of the oldest and most widely used approaches for purifying air and water. Its simplicity and cost-effectiveness have contributed to its widespread application in respiratory protection, air and water purification, and wastewater treatment. A well-maintained air filtration and management system is essential to avoid pathogenic contamination in critical care areas.[8,9]

Air filters have been applied for air purification in diverse settings, including hospital environments, critical care units, cleanrooms, range hoods, chemical factories, industrial facilities, furnaces, and automobile engines. Based on the requirements of specific applications, different filtration systems, filter types, and size variants have been utilized. Ionic air filters, carbon air filters, high-efficiency particulate air (HEPA) filters, and ultraviolet (UV) light air filters are commonly employed for filtration purposes.[10] Ionic air filters, or air ionizers, apply specific voltages to charge air molecules, which attract oppositely charged particles from the air stream, thereby removing contaminants. They are mainly used for conventional air purification. HEPA filters rely on trapping particulates using glass fiber mats as the filtration medium.[11] They are more efficient than ionic air filters and can remove up to 99.97% of airborne particulates. The efficiency of a HEPA filter depends on the pore diameter and fiber thickness. The filtration action of HEPA filters is mainly due to the interception, impaction, and diffusion of particulate matter (PM) in the air stream as it passes through the filter. Consequently, when PM is trapped, purified air is released.

Due to their high filtration efficiency (FE), HEPA filters are often employed in critical areas, such as hospital wards and intensive care units, to remove bacteria and prevent contamination. Carbon air filters utilize the excellent adsorptive capacity of carbonaceous materials to remove particulates and toxic gases from the air stream. Carbon filters can be activated via heat and oxygen treatments, allowing the pores to reopen and the filter to be reused. UV-light air filters employ intense UV beams (240–280 nm) to neutralize harmful particles, such as molds and bacteria.[12] However, although UV filters can remove pathogenic organisms, they cannot eliminate gaseous impurities or pollutants. Different kinds of filters employed for purifying air in the healthcare ecosystem are illustrated in **Figure 1**.

Similar to air filters, efficient water filters are essential for removing pathogens and particulates from potable water. Water filters capable of removing certain metal ions, such as calcium ions and magnesium ions, can help mitigate water hardness.[13] Moreover, the removal of heavy metal ions from potable water is crucial to prevent fatal metal poisoning and severe diseases, such as Itai-itai and plumbism, which are prevalent in rural areas.[14,15] In addition, water filters should be capable of removing disease-causing microorganisms to make water safe for ingestion. Different classes of water filters that rely on mechanisms such as mechanical separation, absorption, sequestration, ion exchange, and reverse osmosis are now available. Various water filters made of ceramic materials or natural polymers have been investigated for the sustainable removal of water contaminants.[16,17]

Recently, antimicrobial materials have gained considerable research interest due to increasing concerns regarding hospital-associated infections transmitted through direct or indirect contact. Bioaerosols (e.g., airborne microbial contaminants), biological particulate fragments, and a variety of living particles pose significant threats to air quality in the healthcare sector.[18] These microscopic particulates can travel long distances, remain suspended in the air, and induce communicable infectious illnesses, acute toxicity, allergies, and other major health risks. Bioaerosols prevalent in hospital environments can play a significant role in nosocomial infections, potentially increasing disease burden and hospital stays.[19] Although conventional filters can capture bioaerosols along with other PM, their inability to inactivate pathogens makes the filter a potential fomite, increasing the risk associated with handling bacteria-loaded filters. The viable particles may grow on the filter, forming active biofilms, and occasionally re-aerosolize, causing secondary health hazards. Hence, decontamination treatments are necessary to mitigate the health risks associated with pathogen-loaded filters.

Antimicrobial resistance (AMR) is another potential threat in the healthcare sector. The excessive use of antibiotics has led to this condition, in which microorganisms acquire resistance to conventional antimicrobial agents, such as antibiotics, and vigorously spread diseases. Thus, novel antimicrobial agents beyond conventional ones are a major focus in healthcare research and development. Antimicrobial filters obtained by incorporating such antimicrobial materials not only capture pathogenic microorganisms but also inactivate them. These antimicrobial filters can be integrated into face masks, air filters, and water filters to reduce the risk of infection from airborne and waterborne pathogens, especially for healthcare workers operating in high-risk environments.[20]

The antimicrobial agents on these filters can inhibit the growth of captured microbes, and the inhibition mechanism depends on the type of antimicrobial agent employed.[21] Antimicrobial agents can induce cell wall destruction, inhibit protein synthesis and other metabolic pathways, and rupture cell membranes, leading to cell death.[22] In one mechanism, mobile antimicrobial molecules migrate toward the microorganism and interact with it to destroy the organism. Another mechanism involves contact killing, whereby antimicrobial materials are incorporated onto a surface to eliminate microorganisms on attachment. A third mechanism operates by altering surface wettability to repel microbes and prevent attachment.[23] Antimicrobial filters primarily follow the contact-killing strategy, which enables rapid inactivation of captured microorganisms, limiting the number of viable particles ejected from the filter by the air stream.

Similar to air, water is also susceptible to microbial contamination, which may lead to infectious outbreaks. Numerous cases of illness and death are reported annually due to waterborne pathogens, including bacteria, protozoans, helminths, fungi, and viruses.[24] Recently, membrane technologies have been preferred over conventional water treatment strategies, such as disinfection and distillation. Major limitations of conventional methods, including the requirement for additives, thermal inputs, and tedious

---

Central Analytical Facility, Biomedical Technology Wing, Sree Chitra Tirunal Institute for Medical Sciences and Technology, Thiruvananthapuram, Kerala, India

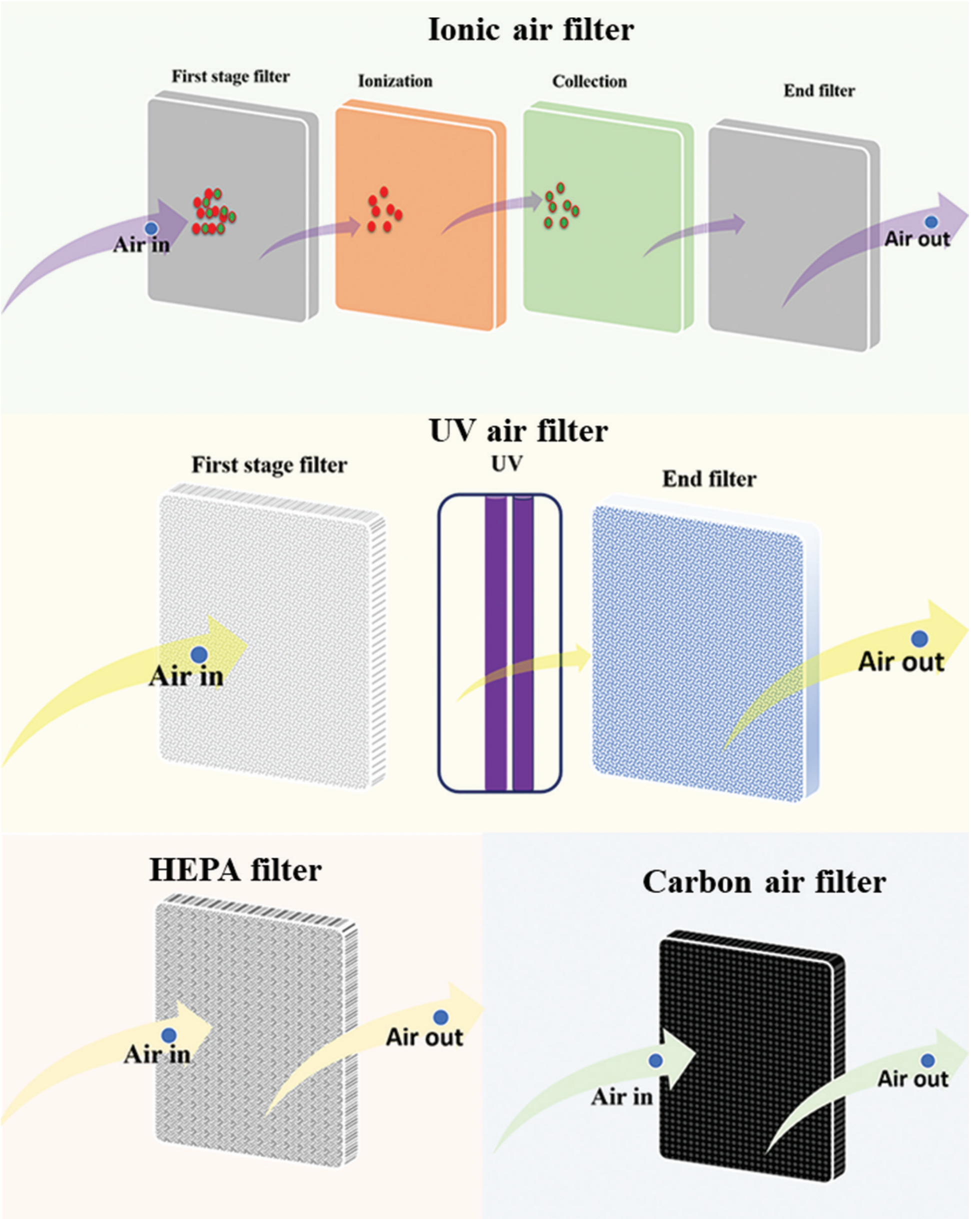

Figure 1. Types of air filters employed for air purification in the healthcare sector. Figure created by authors.
Abbreviations: HEPA: High-efficiency particulate air; UV: Ultraviolet.

regeneration of spent media, are avoided with membrane technology. Functionalization of membrane surfaces with nanoparticles is one approach to improve membrane performance. At present, biocidal filters are employed to combine disinfection with mechanical filtration.[25] This article aims to provide a brief overview of the different strategies employed in developing antimicrobial filters, with a particular emphasis on electrospinning-based approaches.

2. Antimicrobial filters

Antimicrobial filters can be generated either by coating antimicrobial agents onto conventional air or water filters or by fabricating nano- or microfibers with inherent antimicrobial properties through electrospinning.[26] A wide range of antimicrobial agents, spanning inorganic materials to organic materials, bulk compounds to nanomaterials, metallic ions to complexes, and small molecules to polymeric macromolecules, has been explored for developing antimicrobial filters.[27] Various carbon nanomaterials have also been reported to enhance the bacterial FE of filters. Recently, natural product extracts have been increasingly investigated as antimicrobial agents to impart similar properties to filters. Their lower toxicity compared with inorganic antimicrobial agents and effectiveness against both bacteria and viruses are particularly attractive features. Extracts of *Punica granatum*, *Sphaeranthus indicus*, *Andrographis paniculata*, *Acacia nilotica*, and *Allium sativum* have demonstrated antimicrobial effects.[28]

The diversity is apparent not only in the antimicrobial agents used but also in the techniques employed for their incorporation into filters. Dip coating, layer-by-layer coating, pad-dry technique, aerosol processing, electro-spraying, and spray coating are commonly employed methods to modify conventional filters into antimicrobial filters.[29,30] Electrospinning is an important fiber manufacturing technique in which polymer solutions are mixed with antimicrobial agents to produce micro- or nanoporous filters.[31] The electrospinning technique has attracted considerable attention due to its impressive characteristics.[32] Other methods are used to impart antimicrobial properties to a filter substrate with predefined filter properties and pore dynamics, whereas electrospinning generates a new fibrous system with tunable porosity and filtration properties in addition to antimicrobial functionality. This unique combination provides opportunities to fine-tune the properties and functionalities of the filter and therefore warrants comprehensive research. Incorporating antimicrobial agents through any one of the above-mentioned manufacturing methods enables the filter membranes to inactivate captured bacteria and prevent fomite formation (**Figure 2**).

3. Coated antimicrobial filters

Various polymeric membranes have long been used to filter particulates and contaminants from air and water. Polypropylene (PP), polyurethane (PU), polycaprolactone (PCL), polyvinyl alcohol (PVA), polyvinylidene fluoride (PVDF), and polylactic acid (PLA) are the most commonly used polymers for developing filter systems (**Figure 3**).[33] In addition to these synthetic polymers, filters based on natural polymers, such as cellulose, coconut fibers, and bamboo fibers, have also been reported for air and water filtration.[34] Filters can be enhanced by incorporating antimicrobial properties using suitable agents, either organic or inorganic. Organic moieties explored for this purpose often include molecules with a known antimicrobial history, such as antibiotics, antimicrobial proteins, polymers, and ionic liquids. Metal nanoparticles, carbon nanomaterials, and their composites are the most widely studied inorganic moieties for generating antimicrobial filters.

Among synthetic fibers, PP has been used in filtration systems for a long time due to its exemplary mechanical properties, stability, biocompatibility, and filtration capability.[35] PP-based filters are commonly found in face masks, particulate filters, and water filters. They have been widely employed in developing personal protective equipment and other medical fabrics. PP-based filters separate particulates and pathogens primarily through mechanical filtration. Antimicrobial filters can be generated by coating specific agents onto PP filters using suitable methods. As the polymeric backbone of PP lacks active functional groups, it is difficult to attach active moieties to the surface. However, many reports demonstrate the use of diverse antimicrobial agents to impart antimicrobial properties to PP-based filters for face masks, particulate filters, and water filters. Such coatings require specialized techniques or processing conditions to effectively integrate the antimicrobial agents.

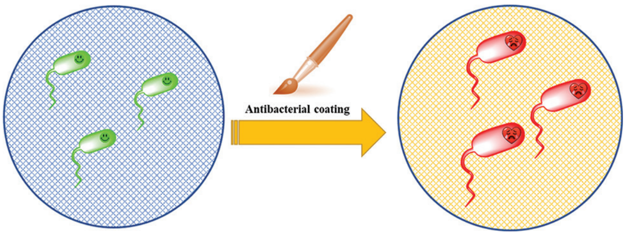

Figure 2. Antimicrobial coating imparts antimicrobial properties to the filter membrane and prevents fomite formation. Green and red bacteria indicate live and dead bacteria, respectively. Figure created by authors.

In a recent study, the pad-dry technique was used to modify commercially available PP-based surgical and N95 nonwoven fabrics into antimicrobial filters by incorporating 1-chloro-2,2,5,5-tetramethyl-4-imidazolidinone. The modified filters displayed excellent bactericidal activity against both Gram-positive and Gram-negative bacteria.[36] Similarly, the chemical metallization approach was adopted to incorporate silver nanoparticles (AgNPs) onto melt-blown PP tape to confer antibacterial and antifungal properties. In addition, the modified filter was effective against the SARS-CoV-2 virus.[37] The conventional dipping/washing method has also been used to functionalize PP-based HEPA filter fabrics with tannic acid (TA) (**Figure 4A**). The TA-functionalized HEPA filter demonstrated an in-solution influenza virus capture efficiency of up to 2,723 pfu/mm^2 within 10 min, significantly higher than that of unmodified filters.[38]

In another approach, an ultrathin hybrid coating of graphene oxide (GO) and polydopamine was applied to PP filters by spray-coating, improving FE (**Figure 4B**). Furthermore, the coating enabled anchoring cationic polymer brushes on the surface, which enhanced the bactericidal activity of the PP filters.[39] In another approach, zinc pyrithione was coated onto conventional heating, ventilation, and air conditioning filters to impart antimicrobial properties. The results showed that antibacterial activity was successfully incorporated, with no degradation in filtration performance.[40]

Ionic liquids are well-known antimicrobial agents due to their mobile polar units, which can penetrate and disrupt bacterial cell walls. In a recent study, the surface of PP filters was modified

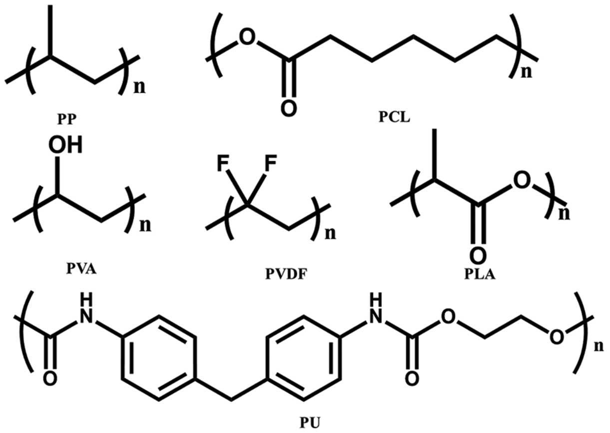

Figure 3. Chemical structures of common polymers used in filter fabrication. Figure created by authors.

Abbreviations: PCL: Polycaprolactone; PLA: Polylactic acid; PP: Polypropylene; PU: Polyurethane; PVA: Polyvinyl alcohol; PVDF: Polyvinylidene fluoride.

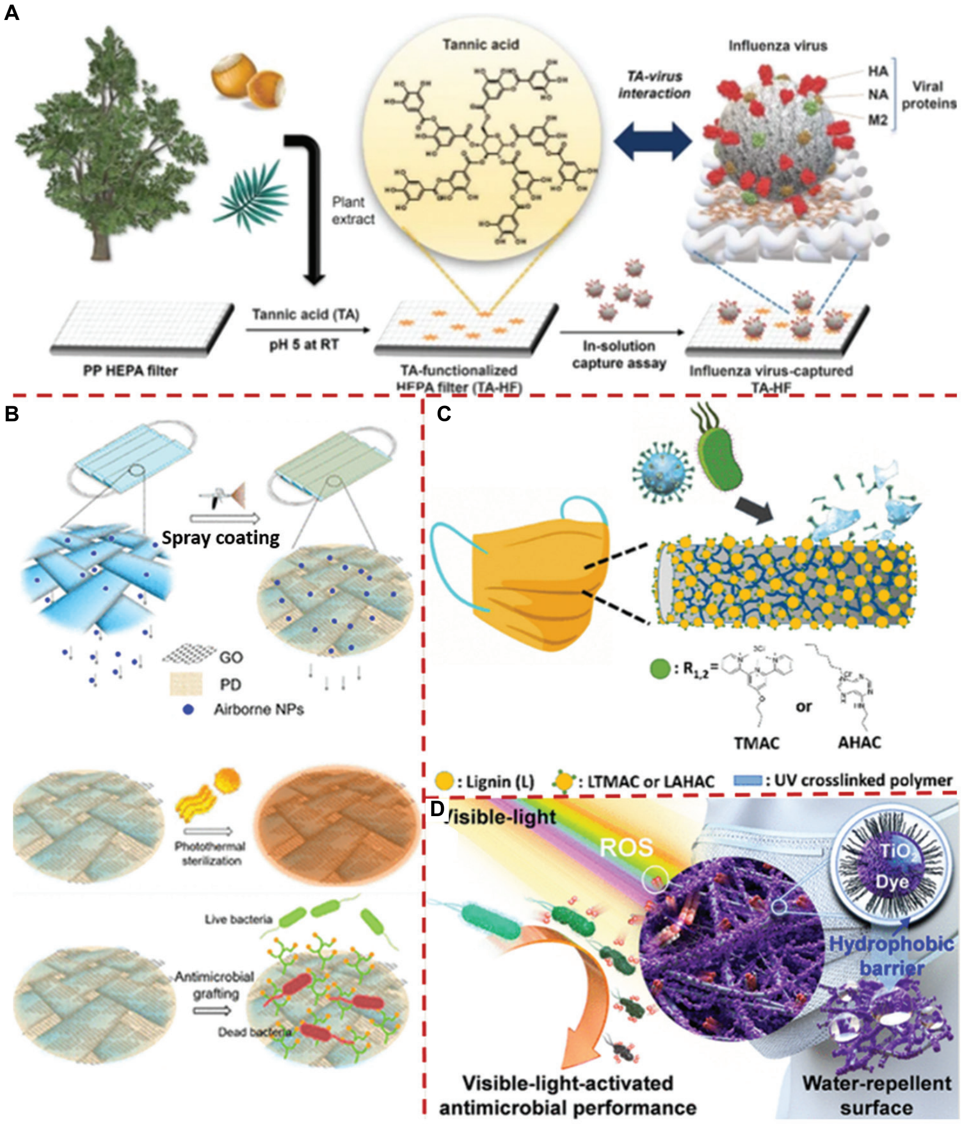

Figure 4. Filters with antimicrobial coatings. (A) Tannic acid-functionalized HEPA filter for viral filtration (adapted from Kim *et al.*[38]). (B) PP-based masks coated with GO and PD to generate antimicrobial masks (adapted with permission from Kasbe *et al.*[39]; license number: 6097540000542). (C) Quaternary salt-conjugated lignin coatings for antimicrobial and antiviral face masks (adapted with permission from Kumaran *et al.*[42]; license number: 6097531306864). (D) Crystal violet-functionalized TiO_2 coatings for visible light-activated antimicrobial filters (adapted with permission from Heo *et al.*[51]; license number: 6097540224434).

Abbreviations: AHAC: Adenine hexyl ammonium chloride; GO: Graphene oxide; HEPA: High-efficiency particulate air; LAHAC: Lignin adenine hexyl ammonium chloride; LTMAC: Lignin 2,2′,4′-terpyridine methyl ammonium chloride; NP: Nanoparticle; PD: Polydopamine; PP: Polypropylene; ROS: Reactive oxygen species; RT: Room temperature; TiO_2: Titanium dioxide; TMAC: Terpyridine methyl ammonium chloride; UV: Ultraviolet.

with ionic liquids through interfacial self-assembly to generate antimicrobial PP filters.[41] The stability of antimicrobial filters can be enhanced if the active ionic liquids are chemically linked to the filter surface. Suitable grafting methods can incorporate ionic liquids and similar quaternary salts onto the filter surface. In a recent report, quaternary salts were conjugated onto lignin through epoxide chemistry and employed as antiviral and antibacterial face mask coatings (**Figure 4C**). These UV-induced, easy-to-apply coatings displayed activity against viruses and bacteria, including PR8 H1N1 influenza virus, HCoV-229E, HCoV-OC43, and *Klebsiella pneumoniae.*[42] Polyionic liquids also exhibit antimicrobial properties due to their abundant charge centers, and their flexibility is advantageous for deployment as simple coatings. Ren *et al.*[43] introduced polymerizable ionic liquids onto PP nonwoven fabrics through surface grafting and photo-crosslinking to generate polyionic liquid-grafted PP filters. These modified filters exhibited excellent antimicrobial activity and could absorb dyes and oils.

Unlike PP, many polymer filters possess suitable functionalities for the effective incorporation of antimicrobial agents. Jeong *et al.*[44] incorporated PU filters with natural sea salt particles through an aerosol process to develop antimicrobial filters. Natural sea salt particle-coated filters displayed superior bactericidal activity (>98%) and FE (95–99%) against aerosolized bacterial particles of *Staphylococcus epidermidis* and *Escherichia coli*. Chlorhexidine digluconate is another well-known antimicrobial and antifungal agent. Watson *et al.*[45] modified MK3 filters with chlorhexidine digluconate to achieve significant antifungal and antimicrobial effects without impeding airflow through the filter.

In addition, many studies have employed plant extracts with biocidal activity to generate antimicrobial filters. For example, AgNPs were generated *in situ* on polyacrylamide polymer using lignin as a biodegradable reducing agent through solvent-free ball milling mechanochemistry. The resulting antimicrobial water filter exhibited antimicrobial activity against various bacteria.[46] Hwang *et al.*[47] fabricated antimicrobial filters with excellent activity against *S. epidermidis* and *Micrococcus luteus* by coating a PU resin fiber filter with natural *Euscaphis japonica* nanoparticles. The natural extract-modified filters displayed an average FE of >95%.

Metal or metal oxide nanoparticles have been reported to possess excellent antimicrobial properties and impart antimicrobial traits to filter membranes. Among them, AgNPs are the most commonly reported material in antimicrobial systems. AgNPs are typically employed alone or in combination with binding materials to ensure stable incorporation into filter systems. In a recent study, hybrid nanosystems with synergistic activity against both Gram-negative and Gram-positive bacteria were developed by incorporating monodisperse silica nanoparticles with AgNPs and successfully incorporated into air filtration systems to achieve approximately 95% FE.[48]

Similarly, AgNPs were coated onto carbon nanotubes (CNTs) using a unique aerosol technique involving both nebulization and thermal evaporation/condensation in a continuous one-step preparation, and the resulting hybrid nanosystem exhibited antimicrobial activity when coated onto filter units (FE > 90%).[49] Furthermore, copper nanoparticles (CuNPs) were generated *in situ* within a melamine–formaldehyde resin sponge to produce CuNP-decorated melamine sponge air filters, which demonstrated antibacterial activity against *E. coli*.[50]

The antimicrobial activity of semiconducting nanoparticles, such as titanium dioxide (TiO_2) and zinc oxide (ZnO), has been reported previously. Incorporation of such semiconducting nanomaterials allows photoactivation, owing to their excellent photoactivity. Surface functionalization of TiO_2 with crystal violet (CV) yields photoactive nanocomposites whose antimicrobial activity can be modulated by visible light. The visible light-activated antimicrobial air filters developed by coating TiO_2–CV nanocomposites exhibited approximately 99.9% FE and an approximately 99.98% inactivation rate against various bioaerosols (**Figure 4D**).[51]

Apart from metal nanoparticles, various carbon nanostructures have also been reported to possess antimicrobial activity. Dong *et al.*[52] used different carbon nanomaterials, including multi-walled CNTs, single-walled CNTs, and carbon quantum dots, to modify trimethylolpropane trimethacrylate millipore (polycarbonate) membranes for bacterial removal from aqueous solutions (FE >95%). Musico *et al.*[53] developed cellulose nitrate membrane filters modified with polymer nanocomposites of poly(vinyl carbazole) and graphene or GO for microbial filtration. In another approach, the cellulose filter was chemically oxidized through periodate oxidation. The FE (>90%) and bacterial inactivation performance of the resulting dialdehyde cellulose filter against airborne and waterborne bacteria and viruses were reported.[54] Various coated antimicrobial filters and their applications are summarized in **Table 1**.

Although coated antimicrobial filters are effective in removing pathogens from air or water streams to a considerable extent, they present several limitations. Coating methods often reduce the pore size of the base filter, thereby lowering FE. In addition, exposure to harsh solvents or high temperatures during the coating process can compromise the mechanical integrity of the filter material. The long-term stability of the antimicrobial coating on the filter surface is another critical concern. These drawbacks have prompted the global research community to explore alternative strategies, among which the development of electrospun nanofibers has emerged as a particularly promising solution.

4. Electrospun nanofibers

Electrospinning is an advanced method for generating uniform fibers with diameters ranging from nanometers to micrometers. In this method, electrically charged jets of polymer are generated under the influence of a high-voltage electric field, then collected and solidified to produce uniform fibers. Polymer solutions with suitable solvents or polymer melts can be used to generate charged jets.[55] During electrospinning, the spinning solution extruded from the spinneret forms droplets due to the surface tension of the solution, which becomes charged in the applied high-voltage electric field. The electrostatic repulsion between identical surface charges on the droplet transforms it into a conical shape, often known as a Taylor cone. The charged jet of the spinning solution ejected from the Taylor cone initially extends along a linear path and then deviates into a bending path owing to bending instability.

After attaining a certain diameter, the fiber solidifies rapidly and deposits on the grounded collector. Thus, electrospinning proceeds through four consecutive steps: (i) Charging of the liquid droplet and Taylor cone formation; (ii) linear extension of the charged jet; (iii) thinning and bending of the charged jet (whipping instability); and (iv) solidification and collection as solid fibers on the grounded collector. The schematic illustration of the electrospinning process is shown in **Figure 5**. Electrospun nanofibers have a large surface area-to-volume ratio, an adjustable porous structure, and tunable properties by modifying the combination of spinning solutions. Therefore, electrospun nanofibers have gained increasing attention in air filtration applications. Electrospun nanofibers obtained through direct or coaxial electrospinning display excellent performance compared with conventional microfibers. An ideal electrospun air filter should have very fine fiber diameters and high porosity, ensuring effective particle capture and minimal airflow resistance.[56]

Table 1. Coated antimicrobial filters and their applications

Base polymer	Antimicrobial agent	Coating method	Applications	References
Non-woven PP	1-chloro-2,2,5,5 tetramethyl-4-imidazolidinone	Soaking followed by pad-drying	Air filtration in masks and air filters	36
Melt-blown PP tape	Ag nanoparticles	Chemical metallization	Antibacterial, antifungal, and antiviral air filtration	37
HEPA filters (PP)	Tannic acid	Dipping/washing	Influenza viral capture filter	38
PP	GO and PD	Spray coating	Antibacterial filter	39
HVAC filter	Zinc pyrithione	Impregnation coating	Antifungal and antibacterial air filter	40
PP	1-Hexyl-3-methyl imidazolium iodide	Interfacial self-assembly	Antimicrobial filter	41
PP face masks	Quaternary salt conjugated lignins	Photopolymerization coating	Antimicrobial coating for multifunctional face masks	42
Nonwoven PP	Poly (ionic liquid)	Photopolymerized coating	Antimicrobial filter and dye/oil separator	43
PU	Natural sea salt particles	Surface coating	Antimicrobial filter (FE>98%)	44
MK3 filter	Chlorhexidine digluconate	Solution coating using an automated treatment system	Airborne pathogens filtration	45
Polyacrylamide	Ag nanoparticles	*In situ* mechanochemistry	Multidrug-resistant antibacterial filters	46
PU resin fiber filter	*Euscaphis japonica* nanoparticles	Nebulization thermal drying	Antimicrobial air filters (FE>95%)	47
Glass fiber filter	Ag nanoparticle-decorated silica nanoparticles	Aerosol coating	Antimicrobial air filters	48
PU resin fiber filters	Ag/CNT	Aerosol coating	Antimicrobial air filters (FE>90%)	49
Melamine–formaldehyde resin sponge	Copper nanoparticles	*In situ* nanoparticle coating	Antimicrobial air filters (FE>95%)	50
Commercial mask filter	Titanium dioxide/crystal violet	Aerosol coating	Antimicrobial air filters (FE approximately 99.9%)	51
Polycarbonate (TMTP) filters	CNTs/quantum dots	Solution coating	Antimicrobial water filters (FE>95%)	52
Cellulose nitrate	PVK/GO	Vacuum dispersion coating	Antimicrobial water filters	53
Cellulose	Dialdehyde cellulose	Chemical oxidation	Antimicrobial water and air filters (FE>90%)	54

Abbreviations: Ag: Silver; CNT: Carbon nanotube; FE: Filtration efficiency; GO: Graphene oxide; HEPA: High-efficiency particulate air; HVAC: Heating, ventilation, and air conditioning; PD: Polydopamine; PP: Polypropylene; PU: Polyurethane; PVK: Polyvinylcarbazole; TMTP: Product code of isopore membrane filters of Millipore Sigma.

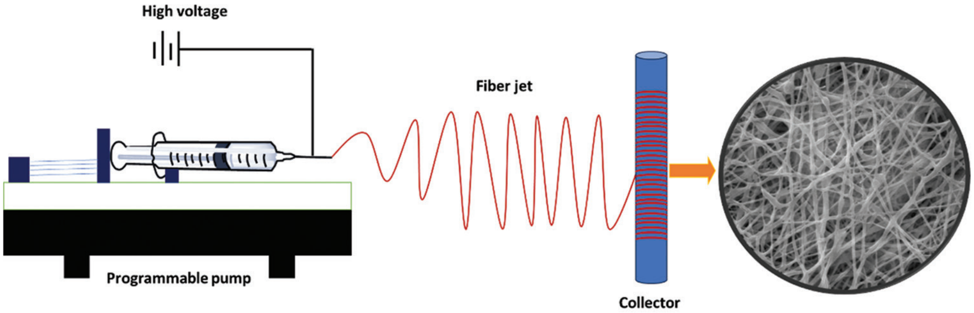

Figure 5. Schematic representation of the electrospinning setup used for developing micro- and nanofibers suitable for filter applications, along with a scanning electron micrograph image of an electrospun polycaprolactone membrane displaying an interconnected nanofibrous network. The figure is created by authors, and the SEM image is part of the author's unpublished work.

Electrospinning is a versatile and effective method used to create nanofibers with sizes ranging from nanometers to micrometers. These nanofibers are utilized in a variety of industries, including tissue engineering; drug delivery, filtration, and energy storage, due to their high surface area-to-volume ratio, porous structure, and functional properties.[57] In recent years, a variety of polymers have been electrospun into ultrafine fibers, mainly from liquid solvents and, in some cases, from molten polymers. Polymers such as PU, PCL, PVDF, PVA, and PLA have been electrospun into nanofibers for a variety of applications.[58]

Electrospinning facilitates the incorporation of functional filters into the spinning solution, allowing the impartation of antibacterial and antiviral properties into nanofibers, enhancement of mechanical properties, implementation of self-sterilization mechanisms, and integration of stimuli-responsive or energy-harvesting properties. Electrospun membranes are capable of retaining surface charges without additional treatments and exhibit electrostatic behavior similar to electret filters. The electrospun nanofibrous membranes have smaller fiber diameters and finer pore sizes suitable for mechanical filtration, making them superior to conventional microporous filters.

Electrospun nanofibers can be prepared using a wide range of natural and synthetic polymers.[59] The straightforward equipment setup, flexibility in starting materials, capability for mass production, and tunability of fiber characteristics make electrospinning a preferred method for nanofiber production.[60] The properties of electrospun nanofibers, including diameter, composition, morphology, and shear alignment, can be tuned by modifying the composition of the spinning solution, applied voltage, and distance between spinneret and collector. In addition, it is possible to adjust fiber diameter, surface area-to-volume ratio, surface functionalities, and mechanical performance (e.g., stiffness and tensile strength) by optimizing the spinning parameters. The flexibility of fiber generation and ease of incorporation of antimicrobial agents make electrospinning an excellent approach for developing antimicrobial filters. Various polymeric systems used to generate antimicrobial filters via electrospinning and their applications are detailed in the following sections.

5. PVDF nanofibers

PVDF nanofibers exhibit several remarkable properties, including exceptional chemical stability, ease of processing, superior mechanical strength, wear resistance, heat resistance, and stability against hydrolysis and UV radiation.[61] Thus, PVDF is particularly well-suited for a wide range of applications, including piezoelectric devices, tactile sensors, the aviation and aerospace industry, radio-electronic devices, drug delivery systems, tissue engineering, gas and liquid separation through membranes, energy storage systems, and erosion-resistant coatings in the construction sectors.[62] Due to its impressive properties, PVDF nanofibers produced through electrospinning and related techniques have been widely explored for various applications. For instance, phase inversion and electrospinning have been frequently utilized to create ultrafiltration and microfiltration membranes using PVDF and its copolymers.[63]

PVDF has been extensively used for filtration applications. The diameter and areal weight of nanofibers generated through electrospinning depend on the polymer solution concentration. The structural parameters of PVDF fibrous membranes, such as fiber diameter, pore size, pore distribution, porosity (or packing density), thickness, and areal weight, play significant roles in the FE and permeability of the membranes.[64] PVDF, either alone or in combination with other polymers, is commonly used for the separation of complex mixtures. For instance, PVDF-co-hexafluoropropylene (PVDF-HFP) has been combined with polytetrafluoroethylene membranes for water-in-oil emulsion separation. The membrane was prepared via a thermally induced phase separation method using dibutyl phthalate and dioctyl phthalate as mixed diluents.[65] In a previous study, robust oil–water separation membranes were fabricated by electrospinning a composite mixture of PVDF-HFP and fluorinated polyhedral oligomeric silsesquioxane (FPOSS). The hybrid membranes, which displayed highly hydrophobic and superoleophilic behavior, efficiently separated low-viscosity oil from water in a single step. The researchers recommended employing PVDF-HFP-FPOSS nanofiber membranes for real-time industrial wastewater treatment.[66] Wang *et al.*[67] fabricated a bead-on-string type smart membrane by electrospinning TiO_2-doped PVDF nanofibers. The unique bead-on-string structure with hierarchical surface roughness endowed the membrane with superwetting and liquid-resisting properties, enabling reversible separation of oil/water mixtures by allowing only one liquid to pass through (**Figure 6A**). The fabricated membrane also displayed superior antifouling and self-cleaning capabilities owing to the photocatalytic TiO_2 incorporated in the hybrid structure.

The hybrid membranes fabricated by co-spinning two dissimilar polymers often exhibit the synergistic properties of their individual components. Recently, smart membranes were fabricated by integrating hydrophobic PVDF polymers with the hydrophilic cellulose acetate polymer and co-electrospinning nylon-6. The interplay between the hydrophilicity and hydrophobicity of the individual polymers enables these smart membranes to mitigate biofouling, providing an innovative strategy to control biofouling during wastewater treatment applications.[68] In another study, beadless, uniform, and straight polyacrylonitrile (PAN) and PAN/PVDF nanofibers were produced using the electrospinning method. These nanofibrous membranes were proposed for use in air filtration applications.[69]

Antimicrobial PVDF nanofibers can be generated by incorporating agents with microbial inhibition capability into the PVDF spinning solution. Various inorganic nanomaterials and organic molecules with bactericidal activity have been utilized for this purpose. Electrospinning of PVDF solutions containing different concentrations of AgNPs yielded antimicrobial nanofibers. The bacterial FE and anti-bacterial activity of the filters were evaluated against *Staphylococcus aureus* and *E. coli*. The results demonstrated a 99.86% bacterial FE for Ag–PVDF fibers, providing valuable insights for clean air management.[70]

The introduction of ZnO nanoparticles along with different compositions of vermiculites and chlorhexidine into the PVDF solution was reported to have a pronounced influence on the wettability, mechanical properties, and bactericidal performance of the generated nanofibers.[71] Spasova *et al.*[72] developed superhydrophobic antimicrobial filtration mats using PVDF and PVDF-HFP by electrospinning with ZnO nanoparticles featuring a silanized surface and a model drug, 5-chloro-8-hydroxyquinolinol. Another study employed magnesium oxide (MgO) as an inorganic functional additive for the development of antimicrobial nanofibers and obtained excellent antimicrobial activity against *E. coli* and *S. aureus*.[73]

The loading of antimicrobial drugs such as enrofloxacin is another approach to impart antimicrobial behavior to PVDF-based nanofibrous mats.[74] These drug-loaded nanofibrous

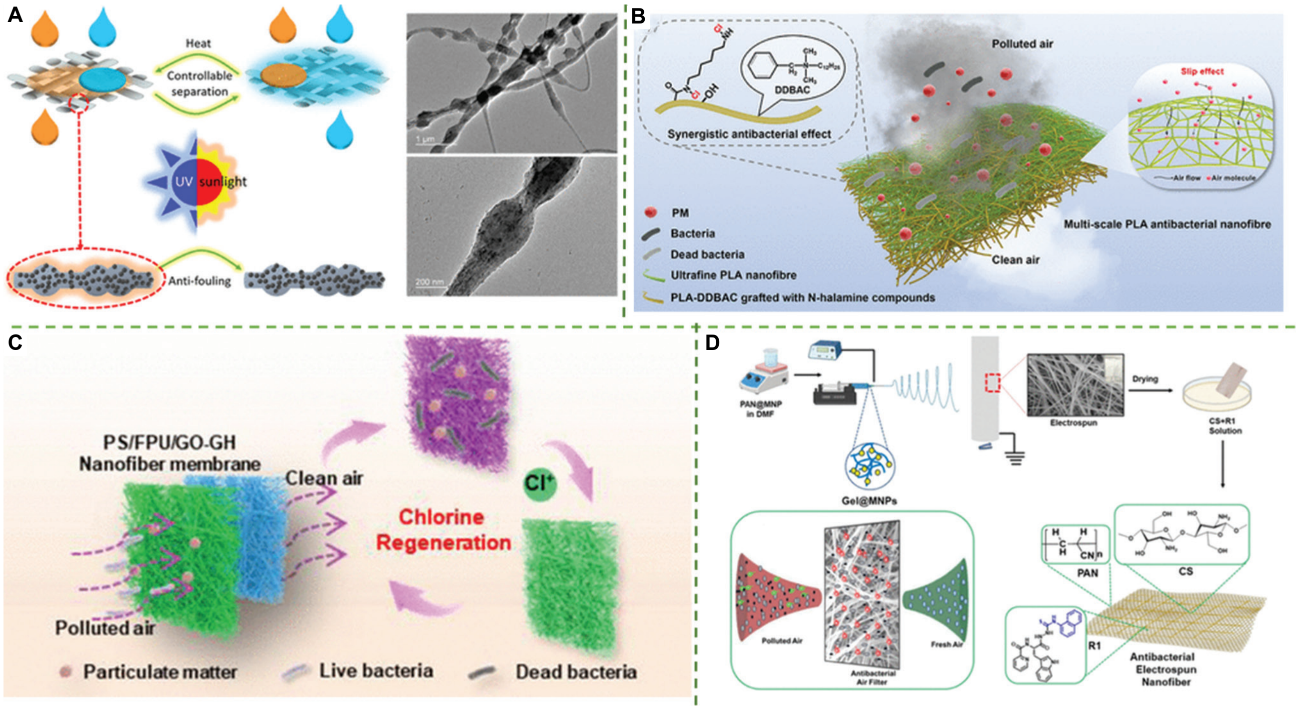

Figure 6. Electrospun nanofibers as antimicrobial filters. (A) Titanium dioxide-incorporated beaded polyvinylidene fluoride nanofibers for photocatalytic, self-cleaning, and antifouling filters (adapted with permission from Wang *et al.*[67]; license number: 6097500905140). (B) PLA nanofibers incorporated with quaternary ammonium salts and *N*-halamine derivatives exhibiting a synergistic antimicrobial effect (adapted with permission from Shao *et al.*[114]; license number: 6097501454814). (C) PS/FPU nanofibers doped with GH for mechanically strong antimicrobial air filters (adapted with permission from Shao *et al.*[123]; license number: 6097501354148). (D) Metal-doped PAN nanofibers complexed with pseudopeptide thiourea to generate an antimicrobial and antioxidant air filter (adapted with permission from Devi *et al.*[150]; license number: 6097540539057).

Abbreviations: CS: Chitosan; DDBAC: Dodecyl dimethyl benzyl ammonium chloride; FPU: Fluorinated polyurethane; GH: Graphene oxide–halamine; GO: Graphene oxide; MNP: Metal nanoparticle; PAN: Polyacrylonitrile; PLA: Polylactic acid; PM: Particulate matter; PS: Polystyrene; UV: Ultraviolet.

mats can be used as promising wound dressing materials. Similarly, well-known antimicrobial agents such as quaternary ammonium salts and ionic liquids have also been explored to impart antimicrobial behavior to PVDF nanofibers. Capkova *et al.*[75] introduced dodecyl trimethyl ammonium bromide as an antimicrobial agent into the spinning solution, and investigated its effect on the structure, morphology, adhesion, and antimicrobial properties of the fibers.

In another study, electrospun PVDF-HFP nanofibers were subjected to UV-induced surface graft copolymerization with 4-vinyl pyridine, followed by quaternization with 1-bromohexane. The resulting membranes exhibited excellent antimicrobial activity against both Gram-positive and Gram-negative bacteria.[76] Interestingly, the piezoelectric behavior of PVDF provides another pathway for antimicrobial action without the addition of external bactericidal agents. It was observed that charge generation on the electrospun PVDF mat under mechanical perturbation inhibited the growth of *Klebsiella pneumoniae* colonies.[77] This area of research is expected to gain considerable attention in the future.

In summary, the unique properties of PVDF support the fabrication of hydrophobic, piezoelectric nanofibrous membranes. By incorporating functional fillers—such as antimicrobial agents, wettability modulators, photoactive materials, and semiconducting nanomaterials—these membranes can be tailored into versatile, multifunctional filters of air and water purification, as outlined in **Table 2**.

6. PCL nanofibers

PCL is one of the earliest polymers to be synthesized in the laboratory. Its unique mechanical properties, high miscibility, excellent blend compatibility, low melting point, and biodegradability make PCL an attractive biomaterial. This aliphatic, semicrystalline thermoplastic polyester has been approved by the United States Food and Drug Administration for applications in regenerative medicine and biomedical engineering. PCL has been extensively studied for use in diverse biomedical areas, including tissue engineering, drug delivery systems, and implantable biomaterials.[78] However, PCL exhibits limited cellular affinity due to its hydrophobic nature. In addition to surface wettability, the stiffness of membranes also contributes to cell proliferation, which can be tuned by adjusting the fiber thickness to generate membranes with enhanced cytocompatibility.[79]

Electrospinning of PCL solutions is an effective method for generating nanofibers with tunable dimensions for various applications, such as wound healing, tissue engineering, drug delivery systems, and medical devices.[80] Kodali *et al.*[81] employed force spinning technology to produce PCL microfiber scaffolds suitable for drug delivery applications. For the use of PCL

Table 2. Electrospun polyvinylidene fluoride filters and their characteristics

Base polymer	Antimicrobial agent	Fiber diameter	Applications	References
PVDF	TiO_2	~120 nm	Oil-water separation filter	67
PVDF, cellulose nitrate, and nylon	-	880 nm	Antibiofouling filter	68
PVDF and PAN	-	~250 nm	Air filtration	69
PVDF	AgNPs	136 nm	Antimicrobial air filter (FE 99.86%)	70
PVDF	ZnO–vermiculite–chlorhexidine	~108 nm	Antimicrobial membranes, filters	71
PVDF and PVDF–HFP	ZnO and 5-chloro-8-hydroxyquinolinol	~110 nm	Superhydrophobic antimicrobial membranes	72
PVDF	MgO		antimicrobial membrane	73
PVDF	Enrofloxacin	~470 nm	Antimicrobial wound dressing	74
PVDF	Dodecyl trimethyl ammonium bromide	~260 nm	Antimicrobial air filters	75
PVDF–HFP	Poly (4-vinyl-N-alkylpyridinium bromide)	NA	Antimicrobial membranes	76
PVDF/TPU	-	~211 nm	Piezoelectric antimicrobial membranes	77

Abbreviations: AgNP: Silver nanoparticle; HFP: Hexafluoropropylene; MgO: Magnesium oxide; NA: Not available; PAN: Polyacrylonitrile; PVDF: Polyvinylidene fluoride; TiO_2: Titanium dioxide; TPU: Thermoplastic polyurethane; ZnO: Zinc oxide.

nanofibers in biomedical applications, spinning parameters and conditions must be carefully optimized to eliminate any possibility of toxicity or contamination. The solvent ratio, polymer concentration, tip-to-collector distance, and applied voltage should be optimized to generate PCL nanofibers with the desired structural and functional properties.[82]

Hybrid nanofibers involving other polymers exhibit improved functional properties compared with unmodified PCL fibers. The addition of hydrophilic polymers and nanoparticles could overcome the deficiencies of unmodified PCL and improve its performance in targeted applications. For instance, Kao *et al.*[83] fabricated PCL nanofibers by integrating them with chitosan and observed an enhanced cellular response of mesothelial cells. Similarly, PCL/gelatin nanofibers loaded with *Pinus radiata* bark extracts demonstrated improved biocompatibility.[84] Moreover, PCL nanofibers were fabricated with different concentrations of the antibiotic drug tetracycline hydrochloride (2–5%) and employed for controlled drug delivery applications.[85] In another study, a biocompatible PCL nanofiber-mediated transdermal delivery system was developed for the sustained release of the hydrophilic drug vitamin B12.[86] The mechanical properties of PCL can be improved by fabricating composite electrospun membranes in combination with cellulose nanofibrils. The mechanically robust membranes were used for water filtration, resulting in enhanced water quality in terms of turbidity, conductivity, and metal ion removal.[87]

Antimicrobial filters based on PCL nanofibers can be generated by incorporating antimicrobial agents during electrospinning. Silver (Ag)-incorporated PCL nanofibers were obtained through *in situ* reduction of Ag^+ introduced into the spinning solution. PCL–Ag nanofibers exhibited antimicrobial activity against Gram-positive and Gram-negative bacteria and were suitable for addressing drug-resistant bacterial infections.[88] Other studies have also investigated the incorporation of AgNPs into PCL nanofibers to develop antimicrobial filters.[89,90] These nanofibers can be used not only as antimicrobial wound dressings but also as filtration media. Jaisankar *et al.*[90] incorporated AgNPs and 5-fluorouracil into electrospun PCL mats to achieve dual functionality of controlled anticancer drug delivery and antimicrobial activity. Permyakova *et al.*[91] developed self-sanitizing membranes from biodegradable PCL nanofibers by integrating AgNPs within the matrix. Other agents such as gold nanoparticles, ZnO nanoparticles, tetracycline, polyphenols from pomegranate peel extract, spearmint essential oil, and fibronectin/gentamycin have also been explored to develop electrospun PCL nanofibers.[92-96]

Electrospun PCL nanofibers with antimicrobial capability have been reported to be effective in air or water filters. Nanomeshes of electrospun PCL fibers have demonstrated excellent FE for use in face masks.[97] ZnO nanoparticles were grown on plasma-treated PCL nanofibers to generate antimicrobial filters with superior respiratory protection, suitable for a wide range of applications. ZnO-coated filters were capable of filtering both bacteria and fungi from the air stream.[98] Ferreira *et al.*[99] replaced ZnO with copper oxide and MgO nanoparticles to develop antimicrobial face mask filters based on electrospun PCL meshes. In another study, PCL nanofibers modified with poly(dopamine) were incorporated into a microfluidic device to remove *E. coli* from contaminated water.[99] Poly(dopamine)-incorporated PCL membranes were reported to remove up to 90% of *E. coli* from contaminated water.

Thus, an array of electrospun PCL nanofibers with antimicrobial characteristics has been developed by incorporating various antimicrobial agents into the spinning solution (**Table 3**). Most PCL-based nanofibrous membranes have been employed as tissue engineering scaffolds, wound dressing materials, drug delivery systems, and efficient filtration media for removing contaminants and pathogens from air and water streams.

7. PLA nanofibers

PLA is a synthetic biopolymer obtained through the polymerization of lactic acid, which has recently attracted significant attention due to its biodegradability and thermoplasticity. As an aliphatic polyester thermoplastic, PLA is biodegradable, bioabsorbable, and biocompatible, and exhibits excellent mechanical and thermal performance.[100] Electrospun PLA-based nanofibrous structures have drawn increasing interest. By adjusting solution parameters,

Table 3. Electrospun polycaprolactone nanofibrous membranes and their characteristics

Base polymer	Antimicrobial agent	Fiber diameter	Applications	References
PCL	Tetracycline	~825 nm	Drug delivery system	85
PCL: cellulose nanofibers	-	1.70 μm	Water filters for heavy metal filtration (FE~99%)	87
PCL	AgNPs	~160 nm	Antimicrobial membranes	88
PCL	Ag NPs	~834–634 nm	Antimicrobial membranes	89
PCL	Ag NPs and 5-fluorouracil	~295 nm	Antimicrobial membranes for anticancer drug delivery	90
PCL	AgNPs	~270 nm	Antimicrobial membranes	91
PCL	AuNPs and spearmint oil nanoemulsion	~320 nm	Antimicrobial fibrous mat	92
PCL	Oxytetracycline and ZnO	~350 nm	Antimicrobial membranes for periodontal drug delivery	93
PCL	Pomegranate peel extract	~278 nm	Antimicrobial wound dressings	94
PCL	Essential oils	700–1100 nm	Antifungal membranes	95
PCL	Fibronectin, gentamycin, AgNPs	~270 nm	Antimicrobial wound dressing	96
PCL	ZnO NPs	NA	Antimicrobial protective filter	98
PCL	MgO and CuO NPs	~481 nm	Antimicrobial filter	99
PCL/PMMA	Polydopamine	~274.7 nm	Antimicrobial water filter (FE~90%)	100

Abbreviations: AgNP: Silver nanoparticles; AuNP: Gold nanoparticle; CuO: Copper oxide; FE: Filtration efficiency; MgO: Magnesium oxide; NA: Not available; NP: Nanoparticle; PCL: Polycaprolactone; PMMA: Polymethyl methacrylate; ZnO: Zinc oxide.

processing conditions, and electrospinning techniques, the morphological, physical, mechanical, and biological properties of PLA-based nanofibrous materials can be tailored for specific applications.[101] The use of electrospun PLA-based nanofibrous structures as sutures, artificial blood vessels, wound dressings, scaffolds for tissue engineering, and drug delivery vehicles has been thoroughly studied.[102] The pore diameter and dynamics of electrospun PLA fibers can be tuned via solvent treatment (e.g., acetone treatment) to enhance their absorptive capability.[103] However, the potential for hydrolytic degradation of electrospun PLA nanofibers must be carefully considered when employing them in biomedical applications.[104]

Like other polymer nanofibers, PLA has also been explored for filtration applications. Ge *et al.*[105] developed electrospun PLA nanofibers using green solvent mixtures of *N*, *N*-dimethylacetamide (DMAc) and dimethyl carbonate (DMC) and employed them in air filtration systems. The DMC/DMAc mixed solvent combines environmental friendliness with excellent solubility, making it a more sustainable alternative to conventional solvents such as chloroform and more effective in dissolving PLA than anhydrous ethanol. The difference in the volatility and dielectric constants of the component solvents resulted in the production of surface-roughened, beaded fibers. Karabulut *et al.*[106] developed a novel face mask filter medium using electrospun PLA nanofibers with bactericidal and virucidal characteristics, capable of providing protection against COVID-19 by employing acidified PLA as the spinning solution. The antimicrobial performance of the filters was further enhanced by the addition of non-toxic, naturally derived terpenoids extracted from manuka oil.

The presence of functional groups on the polymeric backbone enables the chemical modification of PLA with multifunctional polymers or small molecules to generate smart membranes with antibacterial properties. In a previous study, biodegradable and antibacterial PLA fibers were developed by incorporating a versatile bio-based polymer synthesized via radical polymerization, followed by a click chemistry reaction. The presence of triazole and hydantoin groups in the resultant polymer facilitated subsequent functionalization with antimicrobial agents. These fibers demonstrated antibacterial activity against both Gram-positive and Gram-negative bacteria.[107] The incorporation of moieties bearing host cavities, such as cyclodextrins, can improve the FE, as they can encapsulate particulates, volatile organic compounds, and pathogens. Cyclodextrin-functionalized electrospun PLA nanofibers exhibit excellent adsorptive properties due to their unique hydrophobic interior cavity and hydrophilic outer surface.[108]

The incorporation of semiconducting metal oxide nanoparticles, such as ZnO and TiO_2, in the spinning solution further enhances the functional properties of the resulting membranes. These nanoparticles possess both antimicrobial and photocatalytic activities, thereby imparting additional functionality to the resulting fibers.[109] In a recent study, PLA and PLA–TiO_2 composites were fabricated using a conjugate electrospinning approach to generate membranes with a bimodal diameter distribution. In addition, zeolitic imidazolate frameworks were grown *in situ* on the fibers to impart antibacterial activity against both Gram-positive and Gram-negative bacteria.[110]

The incorporation of titanium carbide (MXene) into the PLA spinning solution led to the development of functionalized PLA nanofibers with an excellent capacity for the adsorptive removal of toxic nickel ions from aqueous solutions.[111] Ke *et al.*[112] incorporated zinc-doped TiO_2 nanoparticles (Zn–TiO_2) into the PLA spinning solution to generate electroactive antimicrobial nanofibrous membranes for air purification in the healthcare sector. The hybrid membranes containing 10 wt% of Zn–TiO_2 exhibited approximately 99% FE toward $PM_{0.3}$ and effectively inactivated *E. coli* and *S. epidermidis.*

Shao *et al.*[113] developed multiscale PLA nanofibrous membranes incorporating quaternary ammonium salts and *N*-halamine derivatives, demonstrating long-lasting bacteriostatic behavior along with impressive particulate FE. The excellent antimicrobial activity exhibited by the multiscale nanofibers was attributed to the synergistic effect of the quaternary ammonium salts and *N*-halamines (**Figure 6B**). A similar approach, involving plasma activation of commercially available PLA membranes followed by the anchoring of quaternary groups, was employed by Chen *et al.*[114] to develop antimicrobial water filters with excellent FE.

Metal-organic frameworks (MOFs) were also explored to impart antimicrobial activity to PLA nanofibrous systems. Recently, Zhu *et al.*[115] patterned PLA nanofibers with zeolitic imidazolate framework-8 by electrospinning solutions containing both components in different weight ratios and reported impressive particulate FE and bacterial inhibition in the nanopatterned PLA-based MOF filters. Composite filters exhibiting both antibacterial and antiadhesive properties were fabricated by electrospinning a composite solution of poly(butylene adipate-co-terephthalate), PLA, and AgNPs.[116]

Thus, electrospun nanofibrous membranes derived from PLA as the base polymer can be used for a wide range of biomedical applications. The biodegradability of the base polymer aligns well with the development of sustainable and next-generation materials. The characteristics of PLA-based electrospun nanofilters employed for water and air purification applications are outlined in **Table 4**.

8. PU nanofibers

PU nanofibers can be synthesized through the chemical reaction of polyisocyanates with hydroxyl-containing compounds (polyols). PUs with tailored properties can be synthesized by adjusting the type of isocyanate and polyol used. The inherent intermolecular interactions and biocompatibility of PUs make them suitable for a wide range of applications, including adhesives, coatings, foams, and medical devices. Due to their excellent chemical stability, mechanical strength, and efficient mass transport characteristics, PUs are often used in the fabrication of nanofibers. Unlike thermosetting PUs, thermoplastic PUs are more suitable for manufacturing processes due to their temperature-dependent behavior.[117] Electrospun PU nanofiber mats with superior mechanical properties can be used in a wide range of applications, including high-performance air filters, wound dressing materials, protective fabrics, biomedical devices, sensors, and drug delivery systems.[118]

Recently, PU/silicon nitride-based electret nanofiber membranes, with an average diameter of approximately 350 nm and a narrow diameter distribution—fabricated via electrospinning—have been developed for use as HEPA filters in window screens.[119] The demand for safe and biodegradable polymers has increased due to growing concerns over plastic pollution. A safe, biodegradable, and waterborne PU was synthesized via melt polymerization of biocompatible monomers and subsequently electrospun to generate fibrous mats suitable for sustainable food packaging.[120] Similarly, a honeycomb-like polysulphone/PU nanofiber filter was developed via electrospinning for the removal of organic and inorganic contaminants from air streams.[121] The composite fibers exhibited enhanced mechanical strength, FE, and quality factor in comparison with conventional filters.

The incorporation of antimicrobial nano- or microparticles of CuO into PU spinning solutions facilitates the development of antimicrobial filters with improved antibacterial activity. In another approach, GO–halamine was incorporated into polystyrene/fluorinated PU nanofibers to improve their mechanical properties and impart antimicrobial characteristics against a wide range of bacteria (**Figure 6C**). These fibers demonstrated bacteriostatic behavior even after 10 filtration cycles, making them suitable for use in reusable antibacterial filters.[122] Electrospun PU-based membranes loaded with GO–montmorillonite complex exhibited the capability to remove dyes as well as micro- and nanoplastics from industrial wastewater.[123]

Table 4. Electrospun polylactic acid nanofilters and their characteristics

Base polymer	Antimicrobial agent	Fiber diameter	Applications	References
PLA	-	26–353 nm	Particulate air filter (FE>90%)	106
PLA	Multifunctional bio-based polymer, *P* (DMHI)	~1.5–2.0 μm	Antibacterial polymer membranes	107
PLA	Cyclodextrin	530–990 nm	Particulate (FE>98%) and VOC filter	108
PLA	TiO_2	1.3–1.4 μm	Antimicrobial air filter (FE>99.9%)	109
PLA	TiO_2 and MOF	0.53–1.06 μm	Antimicrobial air filter (FE~96%)	110
PLA	Ti_3C_2	1.07–1.19 μm	Adsorptive removal of Ni ions from water	111
PLA	Zn–TiO_2	264 nm	Antimicrobial air filter (FE>99.9%)	112
PLA	*N*-halamine and quaternary ammonium salt	157–285 nm	Antimicrobial air filter (FE>99.9%)	113
PLA	Quaternary ammonium salt	NA	Antimicrobial water filter (FE>99.99%)	114
PLA	ZIF-8 MOF	447 nm	Antimicrobial air filter (FE 97.1%)	115
PBAT/PLA	Ag NPs	253 nm	Antimicrobial water filter (FE~99.99%)	116

Abbreviations: AgNP: Silver nanoparticles; FE: Filtration efficiency; MOF: Metal–organic framework; NA: Not available; *P*(DMHI): Multifunctional click polymer containing dimethyl hydantoin (DMH) and itaconate (I) moieties; PBAT: Poly (butylene adipate-co-terephthalate); PLA: Polylactic acid; Ti_3C_2: Titanium carbide; TiO_2: Titanium dioxide; VOC: Volatile organic compound.

9. PVA nanofibers

PVA nanofibers have long been considered an important synthetic thermoplastic commercial polymer that is low-cost, easy to produce, optically transparent, and mechanically durable.[124] Technological advances in electrospinning, similar to those achieved with other electrospun nanofibers, have created new opportunities for the development of novel nanostructured materials. PVA fibers can be synthesized through a simple electrospinning process. Electrospun PVA nanofibers exhibit a porous morphology and possess chemical functionalities that enable particulate adsorption from air and smoke.[125] PVA can function alone or in combination with suitable substrates or additives to generate composite membranes with excellent FEs.

Electrospinning of PVA onto spunbonded polyethylene terephthalate, followed by crosslinking with citric acid, used as a green crosslinker, yielded air filters capable of withstanding humid environments.[126] Similarly, composite air filters with FEs comparable to those of HEPA filters were obtained by electrospinning PVA fibers over nonwoven fabric for the filtration of sodium chloride nanoparticles.[127] The use of nonwoven PP fabric as a substrate for PVA electrospinning can yield eco-friendly air filters with effective particulate capture.[128] PVA composite filters incorporated with cellulose nanocrystals were reusable after heat treatment for the removal of PM from airflow.[129,130] In another study, PVA nanofibers were doped with AgNPs to obtain efficient filter materials for removing virus-sized particles from the air stream. The incorporation of AgNPs imparted the filters with improved FE and antimicrobial properties without compromising membrane breathability, making this an attractive approach for the development of an antimicrobial face mask.[131]

Electrospun hybrid membranes composed of PVA and other polymers, such as cellulose acetate and chitosan, along with antimicrobial AgNPs, exhibited superior filtration performance suitable for use as antimicrobial air filters.[132] Des Ligneris *et al.*[134] utilized copper as an antimicrobial agent to develop mixed-matrix PVA electrospun microfilters with antibacterial functionality. Multifunctional nanofibrous membranes composed of PVA, chitosan, hydrophilic silica, and AgNPs have demonstrated excellent performance in air filtration systems.[133] Multilayered antimicrobial membranes composed of PVA/chitosan nanofibers and PVA/*N*-halamine nanofibers exhibited high FE and superior antibacterial activity.[134] Electrospinning of PVA solutions with other metallic additives, such as gold and MXene, has also been reported to generate functional nanofibrous systems.[135,136] Recently, antimicrobial air-conditioning filters suitable for electrically powered portable tractors were developed by incorporating 1–2% Ag solution into the PVA spinning solution.[137]

In addition to metallic or semiconducting nanoparticles, other antimicrobial agents have also been explored in the development of antimicrobial PVA nanofibers. In a previous study, an aqueous antimicrobial agent, Aquacure—composed of copper ion and zinc ion—was introduced into the electrospinning solution to produce antimicrobial fibers. These fibers exhibited excellent bactericidal activity against Gram-positive and Gram-negative bacteria.[138] Similarly, Muniz *et al.*[139] introduced a tetracarboxylic acid as a crosslinking agent and benzalkonium chloride as a biocidal agent in the spinning solution to generate nanofibers on a melt-blown PP substrate. The resulting composite membrane exhibited improved bacterial FE and provided protection against the human coronavirus strain HCoV-229E.

The antimicrobial action and amphiphilicity of ionic liquids have also been investigated to develop antimicrobial fibers through electrospinning. Libel *et al.*[140] incorporated citric acid and an imidazolium-based ionic liquid with a 16-carbon long side chain into the PVA spinning solution to generate antimicrobial nanofibers. The resulting nanofibers exhibited resistance to bacterial adhesion and demonstrated bacterial degradation upon contact. Benzyl triethylammonium chloride was also used as an antimicrobial additive in the PVA spinning solution to develop nanofibrous membranes with improved bacterial filtration.[141] PVA–benzyl triethylammonium chloride nanofibers were found to be suitable for filtering bacteria and bacteriophages from contaminated water. In addition, sericin and Cloisite 30B clay were incorporated into the PVA spinning solution to generate antimicrobial air filtration masks via electrospinning.[142]

10. Other electrospun polymer nanofibers

In addition to the common polymers discussed in the previous sections, other polymeric systems and their combinations have also been investigated for the development of antimicrobial filters via electrospinning. Ju *et al.*[143] integrated AgNPs onto polyamide-6 electrospun nanofibers deposited on a PP nonwoven substrate through hydrogen bonding. Surface nanoroughening induced by AgNPs enhanced both the FE and antimicrobial and antiviral activities of the filters. Similarly, a mixture of soy protein isolate, polyamide-6, and silver nitrate was used as a spinning solution to generate nanofibers exhibiting antibacterial activity against *E. coli* and *Bacillus subtilis*. These filters, composed of natural and biodegradable soy protein isolate, exhibited excellent FE and bactericidal activity.[144]

In addition, AgNP-incorporated PAN nanofibrous membranes have also been reported as antimicrobial filters.[145,146] Lee *et al.*[147] developed transparent and visible-light-active antimicrobial air filters by embedding crystal violet dye onto PAN nanofibers obtained via electrospinning. Devi *et al.*[148] developed metal-doped electrospun PAN nanofibers with both antimicrobial and antioxidant activities for air purification (**Figure 6D**). ZnO and CuNPs were incorporated into the spinning solution to generate metal-doped PAN nanofibers, which were subsequently treated with chitosan solution containing pseudopeptide thiourea, an agent with combined antimicrobial and antioxidant properties, to generate air filters.

In a recent study, Choi *et al.*[149] developed spinning solutions containing an ethanolic extract of the herb *Sophora flavescens* with different concentrations of PVP to generate electrospun nanofibers. The resulting herbal extract-incorporated nanofibers exhibited excellent FE (99.99%) and antimicrobial activity (99.98%) against *S. epidermidis*. A spinning solution containing cellulose acetate and 1-vinyl-3-butylimidazole bromide polyionic liquids was also reported to generate antimicrobial nanofibers for air filters. These nanofibrous filters inhibited *S. aureus* and *E. coli* activity even at low polyionic liquid content.[150]

Electrospinning has been demonstrated to be an excellent method for controlling fiber dimensions, bacterial adhesion, bactericidal activity, wettability, FE, and surface properties of antimicrobial filters. The functional properties can be readily modified by adjusting the composition of the spinning solution. Strategic optimization of the solution components can yield nanofibrous filters with antimicrobial activity capable of filtering a wide range of bacteria and particulates from air and water streams. The characteristics of diverse polymeric electrospun nanofibers employed for air and water filtration are illustrated in **Table 5**.

11. Effect of antimicrobial fillers on filter properties

Electrospinning has emerged as one of the most effective methods for developing air and water purification filters. The incorporation of antimicrobial agents directly into the spinning solution enables the fabrication of filters with tailored fiber dimensions and scalable production. However, the addition of antimicrobial fillers can alter the viscoelastic properties of the polymer solution, thereby influencing the morphological and functional characteristics of the resulting membranes compared with unmodified filters. Studies have shown that antimicrobial fillers can affect the fiber diameter, wettability, porosity, and antimicrobial activity of the nanofibers. In general, bulky organic fillers tend to increase fiber diameter, whereas ionic inorganic fillers often produce finer nanofibers. Amphiphilic additives, such as ionic liquids and quaternary salts, improve the wettability of otherwise hydrophobic polymer filters. Furthermore, antimicrobial fillers significantly influence the mechanical properties of electrospun nanofibers, with their incorporation either enhancing or reducing mechanical strength relative to unmodified polymers.

PVDF exhibits excellent mechanical strength, and the tensile strength of PVDF nanofibers varies depending on the load of the antimicrobial agent incorporated into the spinning solution. Čech Barabaszová *et al.*[71] reported that the tensile

Table 5. Electrospun nanofilters manufactured using different base polymers and their characteristics.

Base polymer	Antimicrobial agent	Fiber diameter (nm)	Applications	References
PU	Si_3N_4	350	Window screen in the air filters (FE~79.36%)	120
PSU/PU	-	~585	Particulate air filter (FE~99.94%)	122
PS/FPU	GO–halamine	184.75	Antimicrobial air filter (FE~99.5%)	123
TPU	GO–montmorillonite	380–780	Microplastic filtration (FE>90%) and dye removal from water	124
PVA	AgNPs	~434	Antimicrobial air filter (FE>95%)	132
Cellulose acetate/ PVA/chitosan	AgNPs	301–357	Antimicrobial air filter (FE 99.78%)	133
PVA	Copper	~617	Antimicrobial air filter (FE 99.99%)	134
Chitosan, PVA	SiO_2, AgNPs	NA	Antimicrobial air filter (FE>97%)	135
PVA/chitosan	*N*-halamine	100–250	Antimicrobial air filter (FE~99.9%)	136
PVA	AuNPs	420	Antimicrobial membrane	137
PVA	AgNPs	559	Antimicrobial air filter	139
PVA	Aquacure	100–300	Antimicrobial water filters	140
PVA	Benzalkonium chloride	389–455	Antimicrobial and antiviral air filter (FE~99%)	141
PVA	Imidazolium ionic liquid	294	Antimicrobial membrane	142
Sericin/PVA	Cloisite clay	300–400	Antimicrobial air filtration mask	144
Polyamide-6	AgNPs	90	Air filter against infectious agents (FE~97.98%)	145
Soy protein isolate/ polyamide-6	AgNPs	~450	Antimicrobial air filter (FE~95%)	146
PAN	AgNPs	200–300	Antimicrobial air filters	147
PAN	AgNPs	250–400	Antimicrobial air filter (FE~100%)	148
PAN	Crystal violet	280	Antimicrobial air filter (FE>99.2%)	149
PAN	ZnO, CuNPs, pseudopeptide thiourea	350	Antimicrobial air filters (FE~30%)	150
PVP	Herbal extract	350–470	Antimicrobial air filter (FE~99.9%)	151
Cellulose acetate	Polyionic liquid	400–519	Antimicrobial air filter (FE>97.9%)	152

Abbreviations: AgNP: Silver nanoparticles; CuNP: Copper nanoparticles; FE: Filtration efficiency; FPU: Fluorinated polyurethane; GO: Graphene oxide; NA: Not available; PAN: Polyacrylonitrile; PS: Polystyrene; PSU: Polysulfone; PU: Polyurethane; PVA: Polyvinyl alcohol; PVP: Polyvinylpyrrolidone; SiO_2: Silicon dioxide; Si_3N_4: Silicon nitride; TPU: Thermoplastic polyurethane; ZnO: Zinc oxide.

strength of PVDF nanofibers (55 MPa) decreased to 48 MPa and 44 MPa upon the addition of ZnO and ZnO–vermiculite, respectively. The tensile strength remained comparable to that of the unmodified polymer when chlorhexidine was included among the fillers. He *et al.*[74] reported a reduction in the tensile strength of electrospun PVDF nanofibers on the incorporation of an antimicrobial drug into the spinning solution. Similarly, Yao *et al.*[76] observed a decrease in the tensile strength of PVDF–HFP nanofibers from 7.27 MPa to 5.53 MPa when a quaternary ammonium salt was added as an antimicrobial filler.

In addition, PCL nanofibers showed variations in tensile strength with the addition of antimicrobial agents. Jaisankar *et al.*[90] reported an increase in the tensile strength of PCL nanofibers from 8.8 MPa to 9.4 MPa when AgNPs and 5-fluorouracil were added into the spinning solution. Similarly, the incorporation of the MOF zeolitic imidazolate framework-8 into the PLA spinning solution resulted in an increase in tensile strength from 15.5 MPa to 27.6 MPa.[115] Thus, the mechanical strength of electrospun fibers varies depending on the nature of the antimicrobial agents added. A similar enhancement in tensile strength was observed for PU-based systems when GO–halamine (4.48–9.37 MPa)[122] and GO–montmorillonite (2.6–6.6 MPa)[123] were used as additives. Libel *et al.*[140] reported an increase in the tensile strength of PVA nanofibers from 4 MPa to 7.6 MPa when an imidazolium-based ionic liquid was incorporated as the antimicrobial additive. Likewise, the tensile strength of polyamide-6 nanofibers increased when AgNPs were employed as antimicrobial additives.[143]

Ionic or inorganic fillers that can effectively interact with the polymer network typically enhance the mechanical strength of nanofibers, whereas bulky organic fillers tend to weaken it. These observations highlight that the type of antimicrobial additive employed during electrospinning plays a crucial role in determining the morphology, wettability, and mechanical strength of the resulting nanofibers. The homogenization method and solvent system used also influence the integration of additives into the polymer matrix.

12. Future outlook

Recently, the development of electrospun antimicrobial filters has attracted significant global attention, as evidenced by the growing number of publications in the post-COVID era. Electrospinning offers the flexibility to combine different base polymers and antimicrobial additives, enabling the development of a broad range of electrospun antimicrobial filters with diverse compositions. Most reports describe nearly 100% FE, demonstrating the ability of these filters to remove pathogens and particulates from both air and water streams. Although such efficiencies are achievable at the laboratory scale, several critical aspects require further consideration: the performance of these filters under real-world conditions, their long-term stability, and the cost-effectiveness of large-scale production. Interestingly, electrospun antimicrobial filters remain scarce in the global market. The selection of abundant raw materials and the development of economical fabrication routes are likely key factors for successful translation from research to commercialization. If cost-effective and highly efficient electrospun antimicrobial filters can be developed, they could have a significant impact on the global market.

The remarkable characteristics of electrospun antimicrobial fibers can be exploited for a wide range of biomedical applications beyond air and water filtration. As the fiber diameters are comparable to those of extracellular matrix collagen fibrils, these nanofibers can support cell migration and proliferation. Uniformly distributed nanofibers with excellent wettability, porosity, and mechanical strength could serve as promising candidates for the development of wound dressings, drug delivery systems, and tissue regeneration scaffolds.[151-153] The incorporation of photoactive antimicrobial additives, such as ZnO and TiO_2, could further enable their application in photocatalysis and related fields. Antimicrobial electrospun nanofibrous membranes have also been reported for use in wound healing, multimodal therapy, bone repair, nerve tissue repair, and periodontal regeneration.[154] Future exploration of these applications, with a focus on cost-effectiveness and translational feasibility, would help address the increasing global demand for advanced medical devices.

13. Conclusions

In recent years, the development of antimicrobial filters has gained significant importance, as the world continues to face challenges related to air and water pollution, as well as outbreaks of severe pathogens capable of causing pandemics. Unlike conventional filters that merely remove particulates and pathogens from air and water streams, antimicrobial filters not only eliminate pathogens but also inactivate them, thereby preventing formite formation and secondary pollution. Electrospinning is an excellent technique for fabricating micro- to nanoporous filters capable of capturing both pathogenic microorganisms and particulates from air and water streams. One of the most attractive features of this technique is its versatility in incorporating functional additives to enhance the performance of the resulting filter membranes. Electrospinning offers remarkable flexibility, allowing the use of a wide range of polymers as base materials together with diverse antimicrobial additives. Appropriate antimicrobial fillers can alter fiber dimensions, wettability, porosity, mechanical strength, and antimicrobial activity, leading to filters with FE approaching 100%. Such technologies hold strong potential for translation into cost-effective and sustainable filtration systems, particularly for low- and middle-income countries that are most affected by global pollution and climate change.

Acknowledgement
The authors would like to thank the Director of the Sree Chitra Tirunal Institute for Medical Sciences and Technology and the Head of the Biomedical Technology Wing, Sree Chitra Tirunal Institute for Medical Sciences and Technology, for providing the library facilities to carry out the literature survey for the study.

Financial support
The authors would like to thank the Department of Science and Technology-Technical Research Centre (DST-TRC) (Grant no: 8318) for the financial support.

Conflicts of interest statement
The authors declare they have no competing interests.

Author contributions

Conceptualization: RS; *Data curation:* AA and PVR; *Writing—original draft*: RS; *Writing—review & editing:* RJ. All authors have read and agreed to the published version of the manuscript.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data

Data are available from the corresponding author upon reasonable request.

Open-access statement

References

1. Ashraf MA, Mohd Hanafiah M. Sustaining life on earth system through clean air, pure water, and fertile soil. *Environ Sci Pollut Res*. 2019;26(14):13679-13680. doi: 10.1007/s11356-018-3528-3
2. Edo GI, Itoje-akpokiniovo LO, Obasohan P, *et al*. Impact of environmental pollution from human activities on water, air quality and climate change. *Ecol Front*. 2024;44(5):874-889. doi: 10.1016/j.ecofro.2024.02.014
3. Kelly FJ, Fussell JC. Air pollution and public health: Emerging hazards and improved understanding of risk. *Environ Geochem Health*. 2015;37(4):631-649. doi: 10.1007/s10653-015-9720-1
4. Lin L, Yang H, Xu X. Effects of water pollution on human health and disease heterogeneity: A review. *Front Environ Sci*. 2022;10:880246. doi: 10.3389/fenvs.2022.880246
5. Azimi MN, Rahman MM. Unveiling the health consequences of air pollution in the world's most polluted nations. *Sci Rep*. 2024;14(1):9856. doi: 10.1038/s41598-024-60786-0
6. McNeely JA. The sinking ark: Pollution and the worldwide loss of biodiversity. *Biodivers Conserv*. 1992;1(1):2-18. doi: 10.1007/bf00700247
7. Alvarenga MOP, Dias JMM, Lima BJLA, Gomes ASL, Monteiro GQM. The implementation of portable air-cleaning technologies in healthcare settings - a scoping review. *J Hosp Infect*. 2023;132:93-103. doi: 10.1016/j.jhin.2022.12.004
8. Brainard J, Jones NR, Swindells IC, *et al*. Effectiveness of filtering or decontaminating air to reduce or prevent respiratory infections: A systematic review. *Prev Med*. 2023;177:107774. doi: 10.1016/j.ypmed.2023.107774
9. Nourozi B, Wierzbicka A, Yao R, Sadrizadeh S. A systematic review of ventilation solutions for hospital wards: Addressing cross-infection and patient safety. *Build Environ*. 2024;247:110954. doi: 10.1016/j.buildenv.2023.110954
10. Gustavsson J. New developments in air filter test methods and classification. *Filtr Sep*. 1996;33(2):155-154. doi: 10.1016/S0015-1882(97)84207-3
11. First, Melvin W. HEPA filters. *J Am Biol Saf Assoc*. 1998;3.1:33-42.
12. Sankurantripati S, Duchaine F. Indoor air quality control for airborne diseases: A review on portable UV air purifiers. *Fluids*. 2024;9(12):281. doi: 10.3390/fluids9120281
13. Dudziak M, Kudlek E. Removal of hardness in wastewater effluent using membrane filtration. *Archit Civ Eng Environ*. 2019;12(2):141-147. doi: 10.21307/acee-2019-030
14. Abdulraheem FS, Al-Khafaji ZS, Hashim KS, Muradov M, Kot P, Shubbar AA. Natural filtration unit for removal of heavy metals from water. *IOP Conf Ser Mater Sci Eng*. 2020;888(1):012034. doi: 10.1088/1757-899X/888/1/012034
15. Ayach J, El Malti W, Duma L, *et al*. Comparing conventional and advanced approaches for heavy metal removal in wastewater treatment: An in-depth review emphasizing filter-based strategies. *Polymers (Basel)*. 2024;16(14):1959. doi: 10.3390/polym16141959
16. Venis RA, Basu OD. Mechanisms and efficacy of disinfection in ceramic water filters: A critical review. *Crit Rev Environ Sci Technol*. 2021;51(24):2934-2974. doi: 10.1080/10643389.2020.1806685
17. Ahmedna M, Marshall WE, Husseiny AA, Rao RM, Goktepe I. The use of nutshell carbons in drinking water filters for removal of trace metals. *Water Res*. 2004;38(4):1062-1068. doi: 10.1016/j.watres.2003.10.047
18. Kim KH, Kabir E, Jahan SA. Airborne bioaerosols and their impact on human health. *J Environ Sci (China)*. 2018;67:23-35. doi: 10.1016/j.jes.2017.08.027
19. Bing-Yuan, Zhang YH, Leung NHL, Cowling BJ, Yang ZF. Role of viral bioaerosols in nosocomial infections and measures for prevention and control. *J Aerosol Sci*. 2018;117:200-211. doi: 10.1016/j.jaerosci.2017.11.011
20. Ahmed O, Oproescu M, Iana GV. Necessity of emergent materials development for air filtration to increase air quality. In: *2024 16th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*. United States: IEEE; 2024. p. 1-5. doi: 10.1109/ECAI61503.2024.10607478
21. Guardabassi L, Courvalin P. Modes of antimicrobial action and mechanisms of bacterial resistance. In: Aarestrup FM, editor. *Antimicrobial Resistance in Bacteria of Animal Origin*. Columbia: ASM Press; 2019. p. 1-18. doi: 10.1128/9781555817534.ch1
22. Komaladewi AAIAS, Khoiruddin K, Surata IW, Subagia IDGA, Wenten IG. Recent advances in antimicrobial air filter. In: Kusrini E, Juwono FH, Yatim A, Setiawan EA, eds. *E3S Web of Confernces*. Vol. 67. 2018. p. 03016. doi: 10.1051/e3sconf/20186703016
23. Yong LX, Calautit JK. A comprehensive review on the integration of antimicrobial technologies onto various surfaces of the built environment. *Sustainability*. 2023;15(4):3394. doi: 10.3390/su15043394
24. Liu Q, Deng J, Yan W, *et al*. Burden and trends of infectious disease mortality attributed to air pollution, unsafe water, sanitation, and hygiene, and non-optimal temperature globally and in different socio-demographic index regions. *Glob Health Res Policy*. 2024;9(1):23. doi: 10.1186/s41256-024-00366-x
25. Daels N, De Vrieze S, Sampers I, *et al*. Potential of a functionalised nanofibre microfiltration membrane as an antibacterial water filter. *Desalination*. 2011;275(1-3):285-290. doi: 10.1016/j.desal.2011.03.012
26. Zhou Y, Liu Y, Zhang M, Feng Z, Yu DG, Wang K. Electrospun nanofiber membranes for air filtration: A review. *Nanomaterials*. 2022;12(7):1077. doi: 10.3390/nano12071077
27. Beyth N, Houri-Haddad Y, Domb A, Khan W, Hazan R. Alternative antimicrobial approach: Nano-antimicrobial materials. *Evid Based Complement Alternat Med*. 2015;2015:246012. doi: 10.1155/2015/246012
28. Pullangott G, Kannan U, Gayathri S, Kiran DV, Maliyekkal SM. A comprehensive review on antimicrobial face masks: An emerging weapon in fighting pandemics. *RSC Adv*. 2021;11(12):6544-6576. doi: 10.1039/D0RA10009A
29. Madalosso HB, Machado R, Hotza D, Marangoni C. Membrane surface modification by electrospinning, coating, and plasma for membrane distillation applications: A State-of-the-art review. *Adv Eng Mater*. 2021;23(6):2001456. doi: 10.1002/adem.202001456
30. Miller DJ, Dreyer DR, Bielawski CW, Paul DR, Freeman BD. Surface modification of water purification membranes. *Angew Chem Int Ed*. 2017;56(17):4662-4711. doi: 10.1002/anie.201601509
31. Bhardwaj N, Kundu SC. Electrospinning: A fascinating fiber fabrication technique. *Biotechnol Adv*. 2010;28(3):325-347. doi: 10.1016/j.biotechadv.2010.01.004
32. Teo WE, Ramakrishna S. A review on electrospinning design and

nanofibre assemblies. *Nanotechnology*. 2006;17(14):R89-R106. doi: 10.1088/0957-4484/17/14/R01

33. Henning LM, Abdullayev A, Vakifahmetoglu C, *et al*. Review on polymeric, inorganic, and composite materials for air filters: From processing to properties. *Adv Energy Sustain Res*. 2021;2(5):2100005. doi: 10.1002/aesr.202100005
34. Souzandeh H, Wang Y, Netravali AN, Zhong WH. Towards sustainable and multifunctional air-filters: A review on biopolymer-based filtration materials. *Polym Rev*. 2019;59(4):651-686. doi: 10.1080/15583724.2019.1599391
35. Hossain MT, Shahid MA, Mahmud N, *et al*. Research and application of polypropylene: A review. *Discov Nano*. 2024;19(1):2. doi: 10.1186/s11671-023-03952-z
36. Demir B, Cerkez I, Worley SD, Broughton RM, Huang TS. N-halamine-modified antimicrobial polypropylene nonwoven fabrics for use against airborne bacteria. *ACS Appl Mater Interfaces*. 2015;7(3):1752-1757. doi: 10.1021/am507329m
37. Medvedev AZ, Bokhonov BB, Kiselev OS, *et al*. Silver nanoparticle-modified melt-blown polypropylene: Antibacterial and antifungal properties and antiviral activity against SARS-CoV-2. *Mater Lett*. 2023;346:134557. doi: 10.1016/j.matlet.2023.134557
38. Kim S, Chung J, Lee SH, Yoon JH, Kweon DH, Chung WJ. Tannic acid-functionalized HEPA filter materials for influenza virus capture. *Sci Rep*. 2021;11(1):979. doi: 10.1038/s41598-020-78929-4
39. Kasbe PS, Gade H, Liu S, Chase GG, Xu W. Ultrathin polydopamine-graphene oxide hybrid coatings on polymer filters with improved filtration performance and functionalities. *ACS Appl Bio Mater*. 2021;4(6):5180-5188. doi: 10.1021/acsabm.1c00367
40. Abd Ali SAZ, Joubert A, Andrès Y. Evaluation of antimicrobial effect of zinc pyrithione against airborne fungi and bacteria growth collected onto new and loaded HVAC fibrous filters. *Processes*. 2021;9(9):1528. doi: 10.3390/pr9091528
41. Sasi R, Sreejith SL, Ramesh G, *et al*. Ionic liquid based antimicrobial coating on polymeric surface: A green chemistry approach. *Results Surf Interfaces*. 2021;5:100026. doi: 10.1016/j.rsurfi.2021.100026
42. Kumaran S, Oh E, Han S, Choi HJ. Photopolymerizable, universal antimicrobial coating to produce high-performing, multifunctional face masks. *Nano Lett*. 2021;21(12):5422-5429. doi: 10.1021/acs.nanolett.1c00525
43. Ren Y, Guo J, Lu Q, Xu D, Qin J, Yan F. Polypropylene nonwoven fabric@ poly(ionic liquid)s for switchable oil/water separation, dye absorption, and antibacterial applications. *ChemSusChem*. 2018;11(6):1092-1098. doi: 10.1002/cssc.201702320
44. Jeong SB, Heo KJ, Lee BU. Antimicrobial air filters using natural sea salt particles for deactivating airborne bacterial particles. *Int J Environ Res Public Health*. 2019;17(1):190. doi: 10.3390/ijerph17010190
45. Watson R, Oldfield M, Bryant JA, *et al*. Efficacy of antimicrobial and anti-viral coated air filters to prevent the spread of airborne pathogens. *Sci Rep*. 2022;12(1):2803. doi: 10.1038/s41598-022-06579-9
46. Rak MJ, Friščić T, Moores A. One-step, solvent-free mechanosynthesis of silver nanoparticle-infused lignin composites for use as highly active multidrug resistant antibacterial filters. *RSC Adv*. 2016;6(63):58365-58370. doi: 10.1039/C6RA03711A
47. Hwang GB, Heo KJ, Yun JH, *et al*. Antimicrobial air filters using natural *Euscaphis japonica* nanoparticles. *PLoS One*. 2015;10(5):e0126481. doi: 10.1371/journal.pone.0126481
48. Ko YS, Joe YH, Seo M, Lim K, Hwang J, Woo K. Prompt and synergistic antibacterial activity of silver nanoparticle-decorated silica hybrid particles on air filtration. *J Mater Chem B*. 2014;2(39):6714-6722. doi: 10.1039/C4TB01068J
49. Jung JH, Hwang GB, Lee JE, Bae GN. Preparation of airborne Ag/CNT hybrid nanoparticles using an aerosol process and their application to antimicrobial air filtration. *Langmuir*. 2011;27(16):10256-10264. doi: 10.1021/la201851r
50. Le VCT, Yoon S, Kang E, *et al*. A capture and inactivation system against pathogens in indoor air using copper nanoparticle decorated melamine sponge hybrid air filters. *Environ Sci Adv*. 2022;1(3):356-364. doi: 10.1039/D2VA00041E
51. Heo KJ, Jeong SB, Shin J, *et al*. Water-repellent TiO_2 -organic dye-based air filters for efficient visible-light-activated photochemical inactivation against bioaerosols. *Nano Lett*. 2021;21(4):1576-1583. doi: 10.1021/acs.nanolett.0c03173
52. Dong X, Al Awak M, Wang P, Sun YP, Yang L. Carbon dot incorporated multi-walled carbon nanotube coated filters for bacterial removal and inactivation. *RSC Adv*. 2018;8(15):8292-8301. doi: 10.1039/C8RA00333E
53. Musico YLF, Santos CM, Dalida MLP, Rodrigues DF. Surface modification of membrane filters using graphene and graphene oxide-based nanomaterials for bacterial inactivation and removal. *ACS Sustain Chem Eng*. 2014;2(7):1559-1565. doi: 10.1021/sc500044p
54. Woo MH, Lee JH, Rho SG, *et al*. Evaluation of the performance of dialdehyde cellulose filters against airborne and waterborne bacteria and viruses. *Ind Eng Chem Res*. 2011;50(20):11636-11643. doi: 10.1021/ie201502p
55. Ji D, Lin Y, Guo X, *et al*. Electrospinning of nanofibres. *Nat Rev Methods Primer*. 2024;4(1):1. doi: 10.1038/s43586-023-00278-z
56. Wendorff JH, Agarwal S, Greiner A. *Electrospinning: Materials, Processing, and Applications*. United States: Wiley-VCH; 2012.
57. Park JS. Electrospinning and its applications. *Adv Nat Sci Nanosci Nanotechnol*. 2010;1(4):043002. doi: 10.1088/2043-6262/1/4/043002
58. Subbiah T, Bhat GS, Tock RW, Parameswaran S, Ramkumar SS. Electrospinning of nanofibers. *J Appl Polym Sci*. 2005;96(2):557-569. doi: 10.1002/app.21481
59. Han W, Wang L, Li Q, *et al*. A review: Current status and emerging developments on natural polymer-based electrospun fibers. *Macromol Rapid Commun*. 2022;43(21):2200456. doi: 10.1002/marc.202200456
60. Li D, Xia Y. Electrospinning of nanofibers: Reinventing the wheel? *Adv Mater*. 2004;16(14):1151-1170. doi: 10.1002/adma.200400719
61. Folgado E, Ladmiral V, Semsarilar M. Towards permanent hydrophilic PVDF membranes. Amphiphilic PVDF-b-PEG-b-PVDF triblock copolymer as membrane additive. *Eur Polym J*. 2020;131:109708. doi: 10.1016/j.eurpolymj.2020.109708
62. Dallaev R, Pisarenko T, Sobola D, Orudzhev F, Ramazanov S, Trčka T. Brief review of PVDF properties and applications potential. *Polymers (Basel)*. 2022;14(22):4793. doi: 10.3390/polym14224793
63. Tang Y, Lin Y, Ma W, Wang X. A review on microporous polyvinylidene fluoride membranes fabricated via thermally induced phase separation for MF/UF application. *J Membr Sci*. 2021;639:119759. doi: 10.1016/j.memsci.2021.119759
64. Xiao Y, Wen E, Sakib N, *et al*. Performance of electrospun polyvinylidene fluoride nanofibrous membrane in air filtration. *Autex Res J*. 2020;20(4):552-559. doi: 10.2478/aut-2019-0043
65. Wang X, Xiao C, Liu H, Chen M, Hao J, Wu Y. A study on fabrication of PVDF-HFP/PTFE blend membranes with controllable and bicontinuous structure for highly effective water-in-oil emulsion separation. *RSC Adv*. 2018;8(49):27754-27762. doi: 10.1039/C8RA04547J
66. Ganesh VA, Ranganath AS, Baji A, *et al*. Electrospun differential wetting membranes for efficient oil-water separation. *Macromol Mater Eng*. 2016;301(7):812-817. doi: 10.1002/mame.201600074
67. Wang Y, Lai C, Wang X, *et al*. Beads-on-string structured nanofibers for smart and reversible oil/water separation with outstanding antifouling property. *ACS Appl Mater Interfaces*. 2016;8(38):25612-25620. doi: 10.1021/acsami.6b08747
68. Bakhsh N, Ahmed Z, Mahar RB, Khatri Z. Development and application

of electrospun modified polyvinylidene fluoride (PVDF) nanofibers membrane for biofouling control in membrane bioreactor. *Desalination Water Treat.* 2021;217:74-82. doi: 10.5004/dwt.2021.26734

69. Ince Yardimci A, Kayhan M, Durmus A, Aksoy M, Tarhan O. Synthesis and air permeability of electrospun PAN/PVDF nanofibrous membranes. *Res Eng Struct Mater.* 2022;8:223-231. doi: 10.17515/resm2022.357na1027
70. Felix Swamidoss V, Bangaru M, Nalathambi G, Sangeetha D, Selvam AK. Silver-incorporated poly vinylidene fluoride nanofibers for bacterial filtration. *Aerosol Sci Technol.* 2019;53(2):196-206. doi: 10.1080/02786826.2018.1554892
71. Čech Barabaszová K, Holešová S, Hundáková M, *et al.* Antimicrobial PVDF nanofiber composites with the ZnO - vermiculite - chlorhexidine based nanoparticles and their tensile properties. *Polym Test.* 2021;103:107367. doi: 10.1016/j.polymertesting.2021.107367
72. Spasova M, Manolova N, Markova N, Rashkov I. Superhydrophobic PVDF and PVDF-HFP nanofibrous mats with antibacterial and anti-biofouling properties. *Appl Surf Sci.* 2016;363:363-371. doi: 10.1016/j.apsusc.2015.12.049
73. Ali Hussein A, Sabr OH. Preparation and facilitation of antibacterial activity, hydrophilicity of piezo–pvdf/n-mgo film by electro-spinning and spin coated for wound dressing: A comparative study. *J Mech Eng Res Dev.* 2019;42(4):23-31. doi: 10.26480/jmerd.04.2019.23.31
74. He T, Wang J, Huang P, *et al.* Electrospinning polyvinylidene fluoride fibrous membranes containing anti-bacterial drugs used as wound dressing. *Colloids Surf B Biointerfaces.* 2015;130:278-286. doi: 10.1016/j.colsurfb.2015.04.026
75. Capkova P, Kormunda M, Kolska Z, Trögl J, Munzarova M, Rysanek P. Electrospun antimicrobial PVDF-DTAB nanofibrous membrane for air filtration: Effect of DTAB on structure, morphology, adhesion, and antibacterial properties. *Macromol Mater Eng.* 2018;303(3):1700415. doi: 10.1002/mame.201700415
76. Yao C, Li X, Neoh KG, Shi Z, Kang ET. Antibacterial activities of surface modified electrospun poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP) fibrous membranes. *Appl Surf Sci.* 2009;255(6):3854-3858. doi: 10.1016/j.apsusc.2008.10.063
77. Khalil AM, Hassanin AH, El-kaliuoby MI, *et al.* Innovative antibacterial electrospun nanofibers mats depending on piezoelectric generation. *Sci Rep.* 2022;12(1):21788. doi: 10.1038/s41598-022-25212-3
78. Woodruff MA, Hutmacher DW. The return of a forgotten polymer-polycaprolactone in the 21st century. *Prog Polym Sci.* 2010;35(10):1217-1256. doi: 10.1016/j.progpolymsci.2010.04.002
79. Tan PS, Teoh SH. Effect of stiffness of polycaprolactone (PCL) membrane on cell proliferation. *Mater Sci Eng C.* 2007;27(2):304-308. doi: 10.1016/j.msec.2006.03.010
80. Azari A, Golchin A, Mahmoodinia Maymand M, Mansouri F, Ardeshirylajimi A. Electrospun polycaprolactone nanofibers: Current research and applications in biomedical application. *Adv Pharm Bull.* 2022;12(4):658-672. doi: 10.34172/apb.2022.070
81. Kodali D, Syed F, Jeelani S, Rangari VK. Fabrication and characterization of forcespun polycaprolactone microfiber scaffolds. *Mater Res Express.* 2020;7(12):125402. doi:10.1088/2053-1591/abcac1
82. Ekram B, Abdel-Hady BM, El-kady AM, Amr SM, Waley AI, Guirguis OW. Optimum parameters for the production of nano-scale electrospun polycaprolactone to be used as a biomedical material. *Adv Nat Sci Nanosci Nanotechnol.* 2017;8(4):045018. doi: 10.1088/2043-6254/aa92b4
83. Kao HH, Kuo CY, Tagadur Govindaraju D, Chen KS, Chen JP. Polycaprolactone/chitosan composite nanofiber membrane as a preferred scaffold for the culture of mesothelial cells and the repair of damaged mesothelium. *Int J Mol Sci.* 2022;23(17):9517. doi: 10.3390/ijms23179517
84. Borges-Vilches J, Unalan I, Fernández K, Boccaccini AR. Fabrication of biocompatible electrospun poly(ε-caprolactone)/gelatin nanofibers loaded with pinus radiata bark extracts for wound healing applications. *Polymers (Basel).* 2022;14(12):2331. doi: 10.3390/polym14122331
85. Karuppuswamy P, Reddy Venugopal J, Navaneethan B, Luwang Laiva A, Ramakrishna S. Polycaprolactone nanofibers for the controlled release of tetracycline hydrochloride. *Mater Lett.* 2015;141:180-186. doi: 10.1016/j.matlet.2014.11.044
86. Madhaiyan K, Sridhar R, Sundarrajan S, Venugopal JR, Ramakrishna S. Vitamin B12 loaded polycaprolactone nanofibers: A novel transdermal route for the water soluble energy supplement delivery. *Int J Pharm.* 2013;444(1-2):70-76. doi: 10.1016/j.ijpharm.2013.01.040
87. Palacios Hinestroza H, Urena-Saborio H, Zurita F, Guerrero De León AA, Sundaram G, Sulbarán-Rangel B. Nanocellulose and polycaprolactone nanospun composite membranes and their potential for the removal of pollutants from water. *Molecules.* 2020;25(3):683. doi: 10.3390/molecules25030683
88. López-Esparza J, Espinosa-Cristóbal LF, Donohue-Cornejo A, Reyes-López SY. Antimicrobial activity of silver nanoparticles in polycaprolactone nanofibers against gram-positive and gram-negative bacteria. *Ind Eng Chem Res.* 2016;55(49):12532-12538. doi: 10.1021/acs.iecr.6b02300
89. Pazos-Ortiz E, Roque-Ruiz JH, Hinojos-Márquez EA, *et al.* Dose-dependent antimicrobial activity of silver nanoparticles on polycaprolactone fibers against gram-positive and gram-negative bacteria. *J Nanomater.* 2017;2017:1-9. doi: 10.1155/2017/4752314
90. Jaisankar E, Azarudeen RS, Thirumarimurugan M. Nanoparticle-mediated polycaprolactone based nanofiber mats for enhanced apoptosis of breast cancer cell line with improved cell viability of fibroblast cell line: Controlled drug release and antimicrobial assay. *J Drug Deliv Sci Technol.* 2023;84:104451. doi: 10.1016/j.jddst.2023.104451
91. Permyakova ES, Manakhov A, Kiryukhantsev-Korneev PV, *et al.* Self-sanitizing polycaprolactone electrospun nanofiber membrane with ag nanoparticles. *J Funct Biomater.* 2023;14(7):336. doi: 10.3390/jfb14070336
92. El-Naggar ME, Shalaby ES, Abd-Al-Aleem AH, Abu-Saied MA, Youssef AM. Synthesis of environmentally benign antimicrobial dressing nanofibers based on polycaprolactone blended with gold nanoparticles and spearmint oil nanoemulsion. *J Mater Res Technol.* 2021;15:3447-3460. doi: 10.1016/j.jmrt.2021.09.136
93. Dias AM, Da Silva FG, Monteiro APDF, Pinzón-García AD, Sinisterra RD, Cortés ME. Polycaprolactone nanofibers loaded oxytetracycline hydrochloride and zinc oxide for treatment of periodontal disease. *Mater Sci Eng C.* 2019;103:109798. doi: 10.1016/j.msec.2019.109798
94. Wang Y, Wang X, Zhou D, *et al.* Preparation and characterization of polycaprolactone (PCL) antimicrobial wound dressing loaded with pomegranate peel extract. *ACS Omega.* 2023;8(23):20323-20331. doi: 10.1021/acsomega.2c08180
95. Sahal G, Nasseri B, Ebrahimi A, Bilkay IS. Electrospun essential oil-polycaprolactone nanofibers as antibiofilm surfaces against clinical *Candida tropicalis* isolates. *Biotechnol Lett.* 2019;41(4-5):511-522. doi: 10.1007/s10529-019-02660-y
96. Permyakova ES, Solovieva AO, Sitnikova N, *et al.* Polycaprolactone nanofibers functionalized by fibronectin/gentamicin and implanted silver for enhanced antibacterial properties, cell adhesion, and proliferation. *Polymers.* 2024;16(2):261. doi: 10.3390/polym16020261
97. Khandaker M, Progri H, Arasu DT, Nikfarjam S, Shamim N. Use of polycaprolactone electrospun nanofiber mesh in a face mask. *Materials.* 2021;14(15):4272. doi: 10.3390/ma14154272
98. Permyakova ES, Manakhov AM, Kiryukhantsev-Korneev PV, *et al.* Electrospun polycaprolactone/ZnO nanocomposite membranes with high antipathogen activity. *Polymers.* 2022;14(24):5364. doi: 10.3390/polym14245364
99. Qasim M, Duong DD, Lee JY, Lee NY. Fabrication of polycaprolactone nanofibrous membrane-embedded microfluidic device for water

filtration. *J Appl Polym Sci*. 2020;137(40):49207. doi: 10.1002/app.49207

100. Gupta B, Revagade N, Hilborn J. Poly(lactic acid) fiber: An overview. *Prog Polym Sci*. 2007;32(4):455-482. doi: 10.1016/j.progpolymsci.2007.01.005
101. Casasola R, Thomas NL, Trybala A, Georgiadou S. Electrospun poly lactic acid (PLA) fibres: Effect of different solvent systems on fibre morphology and diameter. *Polymer*. 2014;55(18):4728-4737. doi: 10.1016/j.polymer.2014.06.032
102. Maleki H, Azimi B, Ismaeilimoghadam S, Danti S. Poly(lactic acid)-based electrospun fibrous structures for biomedical applications. *Appl Sci*. 2022;12(6):3192. doi: 10.3390/app12063192
103. Yang J, Li F, Lu G, *et al*. Electrospun biodegradable poly(L-lactic acid) nanofiber membranes as highly porous oil sorbent nanomaterials. *Nanomaterials (Basel)*. 2022;12(15):2670. doi: 10.3390/nano12152670
104. Soo XYD, Jia L, Lim QF, *et al*. Hydrolytic degradation and biodegradation of polylactic acid electrospun fibers. *Chemosphere*. 2024;350:141186. doi: 10.1016/j.chemosphere.2024.141186
105. Ge J, Lv X, Zhou J, *et al*. Multi-level structured polylactic acid electrospun fiber membrane based on green solvents for high-performance air filtration. *Sep Purif Technol*. 2024;331:125659. doi: 10.1016/j.seppur.2023.125659
106. Karabulut FNH, Fomra D, Höfler G, Chand NA, Beckermann GW. Virucidal and bactericidal filtration media from electrospun polylactic acid nanofibres capable of protecting against COVID-19. *Membranes (Basel)*. 2022;12(6):571. doi: 10.3390/membranes12060571
107. Chiloeches A, Cuervo-Rodríguez R, Gil-Romero Y, Fernández-García M, Echeverría C, Muñoz-Bonilla A. Electrospun polylactic acid-based fibers loaded with multifunctional antibacterial biobased polymers. *ACS Appl Polym Mater*. 2022;4(9):6543-6552. doi: 10.1021/acsapm.2c00928
108. Palmieri S, Pierpaoli M, Riderelli L, Qi S, Ruello ML. Preparation and characterization of an electrospun PLA-cyclodextrins composite for simultaneous high-efficiency PM and VOC removal. *J Compos Sci*. 2020;4(2):79. doi: 10.3390/jcs4020079
109. Wang Z, Pan Z, Wang J, Zhao R. A novel hierarchical structured poly(lactic acid)/titania fibrous membrane with excellent antibacterial activity and air filtration performance. *J Nanomater*. 2016;2016:1-17. doi: 10.1155/2016/6272983
110. Lin M, Shen J, Qian Q, Li T, Zhang C, Qi H. Fabrication of poly(lactic acid)@TiO2 electrospun membrane decorated with metal-organic frameworks for efficient air filtration and bacteriostasis. *Polymers (Basel)*. 2024;16(7):889. doi: 10.3390/polym16070889
111. Subash A, Naebe M, Wang X, Sahoo SK, Kandasubramanian B. Electrospinning of polylactic acid fibers reinforced with Ti3C2 for the removal of nickel ions from wastewater. *Hybrid Adv*. 2023;4:100109. doi: 10.1016/j.hybadv.2023.100109
112. Ke L, Yang T, Liang C, *et al*. Electroactive, antibacterial, and biodegradable poly(lactic acid) nanofibrous air filters for healthcare. *ACS Appl Mater Interfaces*. 2023;15(27):32463-32474. doi: 10.1021/acsami.3c05834
113. Shao W, Niu J, Han R, *et al*. Electrospun multiscale poly(lactic acid) nanofiber membranes with a synergistic antibacterial effect for air-filtration applications. *ACS Appl Polym Mater*. 2023;5(11):9632-9641. doi: 10.1021/acsapm.3c02109
114. Chen Q, Zhao K, Li G, *et al*. Highly permeable polylactic acid membrane grafted with quaternary ammonium salt for effective and durable water disinfection. *ACS Appl Mater Interfaces*. 2022;14(38):43741-43748. doi: 10.1021/acsami.2c11551
115. Zhu G, Li X, Li XP, *et al*. Nanopatterned electroactive polylactic acid nanofibrous MOFilters for efficient $PM_{0.3}$ filtration and bacterial inhibition. *ACS Appl Mater Interfaces*. 2023;15(40):47145-47157. doi: 10.1021/acsami.3c11941
116. Facchi DP, Facchi SP, Souza PR, *et al*. Composite filter with antimicrobial and anti-adhesive properties based on electrospun poly(butylene adipate-co-terephthalate)/poly(acid lactic)/Tween 20 fibers associated with silver nanoparticles. *J Membr Sci*. 2022;650:120426. doi: 10.1016/j.memsci.2022.120426
117. Akindoyo JO, Beg MDH, Ghazali S, Islam MR, Jeyaratnam N, Yuvaraj AR. Polyurethane types, synthesis and applications - a review. *RSC Adv*. 2016;6(115):114453-114482. doi: 10.1039/C6RA14525F
118. Akduman C, Kumbasar EPA. Electrospun polyurethane nanofibers. In: Yilmaz F, editor. *Aspects of Polyurethanes*. London: InTech; 2017. doi: 10.5772/intechopen.69937
119. Liu F, Li M, Shao W, *et al*. Preparation of a polyurethane electret nanofiber membrane and its air-filtration performance. *J Colloid Interface Sci*. 2019;557:318-327. doi: 10.1016/j.jcis.2019.08.099
120. Beycan B, Kalkan Erdoğan M, Sancak E, Karakışla M, Saçak M. Creating safe, biodegradable nanofibers for food protection: A look into waterborne polyurethane electrospinning. *Ind Eng Chem Res*. 2024;63(33):14495-14507. doi: 10.1021/acs.iecr.4c00759
121. Chen X, Xu Y, Liang M, *et al*. Honeycomb-like polysulphone/polyurethane nanofiber filter for the removal of organic/inorganic species from air streams. *J Hazard Mater*. 2018;347:325-333. doi: 10.1016/j.jhazmat.2018.01.012
122. Shao W, Zhang Y, Sun N, Li J, Liu F, He J. Polystyrene/fluorinated polyurethane electrospinning nanofiber membranes incorporated with graphene oxide-halamine as mask filter materials for reusable antibacterial applications. *ACS Appl Nano Mater*. 2022;5(9):13573-13582. doi: 10.1021/acsanm.2c03269
123. Juraij K, Ammed SP, Chingakham C, *et al*. Electrospun polyurethane nanofiber membranes for microplastic and nanoplastic separation. *ACS Appl Nano Mater*. 2023;6(6):4636-4650. doi: 10.1021/acsanm.3c00112
124. Ding W, Wei S, Zhu J, Chen X, Rutman D, Guo Z. Manipulated electrospun PVA nanofibers with inexpensive salts. *Macromol Mater Eng*. 2010;295(10):958-965. doi: 10.1002/mame.201000188
125. Kusumaatmaja A, Sukandaru B, Chotimah, Triyana K. Application of Polyvinyl Alcohol Nanofiber Membrane for Smoke Filtration. In: *AIP Conference Proceedings*; 2016. p. 150006. doi: 10.1063/1.4958579
126. Kim G, Doh SJ, Kim Y, Oh HJ, Lee GD, Im JN. Electrospun polyvinyl alcohol composite nonwovens for air filtration materials in the humidity environment. *Fibers Polym*. 2022;23(3):690-698. doi: 10.1007/s12221-022-3418-7
127. Li J, Gao F, Liu LQ, Zhang Z. Needleless electro-spun nanofibers used for filtration of small particles. *Express Polym Lett*. 2013;7(8):683-689. doi: 10.3144/expresspolymlett.2013.65
128. Kim HJ, Choi DI, Sung SK, *et al*. Eco-friendly poly(vinyl alcohol) nanofiber-based air filter for effectively capturing particulate matter. *Appl Sci*. 2021;11(9):3831. doi: 10.3390/app11093831
129. Rochardjo HS, Fatkhurrohman F, Kusumaatmaja A, Yudhanto F. Fabrication of nanofiltration membrane based on polyvinyl alcohol nanofibers reinforced with cellulose nanocrystal using electrospinning techniques. *Int J Technol*. 2021;12(2):329. doi: 10.14716/ijtech.v12i2.4173
130. Zhang Q, Li Q, Zhang L, *et al*. Preparation of electrospun nanofibrous poly(vinyl alcohol)/cellulose nanocrystals air filter for efficient particulate matter removal with repetitive usage capability via facile heat treatment. *Chem Eng J*. 2020;399:125768. doi: 10.1016/j.cej.2020.125768
131. Blosi M, Costa AL, Ortelli S, *et al*. Polyvinyl alcohol/silver electrospun nanofibers: Biocidal filter media capturing virus-size particles. *J Appl Polym Sci*. 2021;138(46):51380. doi: 10.1002/app.51380
132. Chueachot R, Promarak V, Saengsuwan S. Enhancing antibacterial activity and air filtration performance in electrospun hybrid air filters of chitosan (CS)/AgNPs/PVA/cellulose acetate: Effect of CS/AgNPs ratio. *Sep Purif Technol*. 2024;338:126515. doi: 10.1016/j.seppur.2024.126515

133. Zhu M, Xiong R, Huang C. Bio-based and photocrosslinked electrospun antibacterial nanofibrous membranes for air filtration. *Carbohydr Polym*. 2019;205:55-62. doi: 10.1016/j.carbpol.2018.09.075
134. Zhang L, Li L, Wang L, Nie J, Ma G. Multilayer electrospun nanofibrous membranes with antibacterial property for air filtration. *Appl Surf Sci*. 2020;515:145962. doi: 10.1016/j.apsusc.2020.145962
135. Bai J, Li Y, Yang S, *et al*. A simple and effective route for the preparation of poly(vinylalcohol) (PVA) nanofibers containing gold nanoparticles by electrospinning method. *Solid State Commun*. 2007;141(5):292-295. doi: 10.1016/j.ssc.2006.10.024
136. Sobolčiak P, Ali A, Hassan MK, *et al*. 2D Ti3C2Tx (MXene)-reinforced polyvinyl alcohol (PVA) nanofibers with enhanced mechanical and electrical properties. *PLoS One*. 2017;12(8):e0183705. doi: 10.1371/journal.pone.0183705
137. Yoon SK, Pahn LO, Kyun JJ, Cho SH. Fabrication of air conditioning antimicrobial filter for electrically powered port tractors via electrospinning coating. *Coatings*. 2024;14(2):180. doi: 10.3390/coatings14020180
138. Gule NP, De Kwaadsteniet M, Cloete TE, Klumperman B. Electrospun poly(vinyl alcohol) nanofibres with biocidal additives for application in filter media, 2-antimicrobial activity, regeneration, leaching and water stability. *Macromol Mater Eng*. 2012;297(7):618-626. doi: 10.1002/mame.201100276
139. Muniz NO, Gabut S, Maton M, *et al*. Electrospun filtering membrane designed as component of self-decontaminating protective masks. *Nanomaterials (Basel)*. 2022;13(1):9. doi: 10.3390/nano13010009
140. P Libel G, Facchi SP, De Almeida DA, *et al*. Cross-linked poly(vinyl alcohol)/citric acid electrospun fibers containing imidazolium ionic liquid with enhanced antiadhesive and antimicrobial properties. *Mater Chem Phys*. 2024;316:129087. doi: 10.1016/j.matchemphys.2024.129087
141. Park JA, Kim SB. Antimicrobial filtration with electrospun poly(vinyl alcohol) nanofibers containing benzyl triethylammonium chloride: Immersion, leaching, toxicity, and filtration tests. *Chemosphere*. 2017;167:469-477. doi: 10.1016/j.chemosphere.2016.10.030
142. Purwar R, Sai Goutham K, Srivastava CM. Electrospun Sericin/PVA/Clay nanofibrous mats for antimicrobial air filtration mask. *Fibers Polym*. 2016;17(8):1206-1216. doi: 10.1007/s12221-016-6345-7
143. Ju Y, Han T, Yin J, *et al*. Bumpy structured nanofibrous membrane as a highly efficient air filter with antibacterial and antiviral property. *Sci Total Environ*. 2021;777:145768. doi: 10.1016/j.scitotenv.2021.145768
144. Jiang Z, Zhang H, Zhu M, *et al*. Electrospun soy-protein-based nanofibrous membranes for effective antimicrobial air filtration. *J Appl Polym Sci*. 2018;135(8):45766. doi: 10.1002/app.45766
145. Chaudhary A, Gupta A, Mathur RB, Dhakate S. Effective antimicrobial filter from electrospun polyacrylonitrile-silver composite nanofibers membrane for conductive environments. *Adv Mater Lett*. 2014;5(10):562-568. doi: 10.5185/amlett.2014.572
146. Bortolassi ACC, Nagarajan S, De Araújo Lima B, *et al*. Efficient nanoparticles removal and bactericidal action of electrospun nanofibers membranes for air filtration. *Mater Sci Eng C*. 2019;102:718-729. doi: 10.1016/j.msec.2019.04.094
147. Lee SY, Shin JH, Kim IH, *et al*. Transparent and visible light-activated antimicrobial air filters from electrospun crystal violet-embedded polyacrylonitrile nanofibers. *Environ Res*. 2025;266:120490. doi: 10.1016/j.envres.2024.120490
148. Devi R, Kumar M, Singh J, Randhawa JK, Kaur N, Singh N. Electrospun nanofibers with antibacterial and antioxidant activities for air purification. *ACS Appl Nano Mater*. 2025;8(11):5513-5526. doi: 10.1021/acsanm.4c07222
149. Choi J, Yang BJ, Bae GN, Jung JH. Herbal extract incorporated nanofiber fabricated by an electrospinning technique and its application to antimicrobial air filtration. *ACS Appl Mater Interfaces*. 2015;7(45):25313-25320. doi: 10.1021/acsami.5b07441
150. Zhu M, Cao Q, Liu B, *et al*. A novel cellulose acetate/poly (ionic liquid) composite air filter. *Cellulose*. 2020;27(7):3889-3902. doi: 10.1007/s10570-020-03034-8
151. Surendranath M, Ramesan RM, Nair P, Parameswaran R. Zein and 3-aminophenyl boronic acid conjugated polyvinylpyrrolidone polymer blend: Electrospinning, characterization, and mucoadhesive drug delivery. *ACS Appl Bio Mater*. 2024;7(11):7429-7443. doi: 10.1021/acsabm.4c01052
152. Sumam P, Parameswaran R. Neuronal cell response on aligned fibroporous electrospun mat generated from silver ion complexed ethylene vinyl alcohol copolymer. *J Biomed Mater Res B Appl Biomater*. 2023;111(4):782-794. doi: 10.1002/jbm.b.35189
153. Velutheril Thomas L, Nair PD. An electrospun citric acid modified polyvinyl alcohol scaffold for vascular tissue engineering. *J Bioact Compat Polym*. 2019;34(3):263-279. doi: 10.1177/0883911519841390
154. Chen S, Xie Y, Ma K, *et al*. Electrospun nanofibrous membranes meet antibacterial nanomaterials: From preparation strategies to biomedical applications. *Bioact Mater*. 2024;42:478-518. doi: 10.1016/j.bioactmat.2024.09.003

Received: June 13, 2025
Revised: September 15, 2025
Accepted: September 26, 2025