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Review Article

Combating Urban Air Pollution in Indonesia: Recent Advances in Electrospun Nanofiber Membranes for High-Efficiency Particulate Matter Capture

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Abstract
Indonesia faces a severe air pollution crisis, with average PM2.5 concentrations exceeding WHO guidelines by more than sevenfold and contributing to an estimated 13% of annual deaths nationwide. Emerging evidence further links PM2.5 exposure to increased vulnerability to viral infections, including COVID-19 and influenza, compounding the country's public health burden. Conventional personal protective equipment, predominantly petroleum-based polypropylene masks, offers only short-lived electrostatic filtration and generates substantial non-biodegradable waste, undermining both protective efficacy and environmental sustainability. Electrospinning has emerged as a promising alternative, enabling the fabrication of nanofiber membranes with diameters from 10 nm to the submicron scale that achieve high particulate filtration efficiency at low pressure drop through mechanisms including interception, inertial impaction, Brownian diffusion, and electrostatic capture. This review synthesizes recent advances across single- and multi-spinneret fabrication techniques, bead-on-string architectures, and post-treatment strategies for optimizing filtration performance. It further examines the development of biodegradable polymer membranes, upcycled waste-derived nanofibers, and multifunctional designs incorporating antimicrobial, antiviral, and humidity-resistant properties tailored to tropical urban conditions. These innovations collectively achieve filtration efficiencies exceeding 99% while addressing plastic waste accumulation. This review proposes a practical roadmap toward sustainable, multifunctional electrospun membranes capable of mitigating both urban air pollution and airborne pathogen transmission in Indonesia's rapidly urbanizing tropical cities.

Keywords: Air Filtration, Electrospinning, Nanofiber, Particulate Filtration Efficiency, Pressure Drop

1 Introduction

Air pollution is a major public health concern in Southeast Asia, particularly in Indonesia. The country's average PM2.5 concentration is reported at 37.1 µg/m³, exceeding the WHO Air Quality Guideline, which is 5 µg/m³. PM2.5 exposure is also associated with adverse health effects and increased vulnerability to respiratory infections [1]-[8]. These conditions highlight the need for effective and sustainable air-filtration technologies.

Air pollution also presents a potential link to airborne pathogen exposure. Studies in Greater Jakarta have reported associations between long-term PM2.5 exposure and COVID-19 mortality and pediatric respiratory diseases [2]. Experimental studies further indicate that PM2.5 exposure can increase susceptibility to influenza infection [4]. Other research has explored the potential role of particulate matter in transporting airborne pathogens [6]–[8]. However, the interaction between air pollution and pathogen transmission remains an emerging research area.

Conventional masks commonly use petroleum-based polypropylene (PP). Their electrostatic filtration performance can decrease over time. In addition, single-use PP masks contribute to non-biodegradable plastic waste [9]-[11]. The non-woven membrane filter media can be manufactured through different methods such as electrospinning, template synthesis, interfacial polymerisation, and self-assembly. Electrospinning is a highly promising process for the production of nano-scale fibers with high porosity and surface area for several specialised fields [12], such as biomedical [13], [14] and the environment [15], [16].

Electrospinning offers a more promising path forward. The technique allows for the fabrication of non-woven membranes with fiber diameters reaching the true nanoscale, from 10 nanometers up to the submicron range by carefully tuning the polymer solution and processing parameters. At this scale, something useful happens: the fluid dynamics at the fiber-air interface change fundamentally, allowing these membranes to achieve high particle filtration efficiency at far lower pressure drops than conventional materials can manage. In practical terms, that means filtration that is both more effective and more comfortable to breathe through, an advantage simply unattainable with microscale fibers [4], [12], [15], [17], [18].

This review summarizes recent advances in electrospun nanofiber membranes for air filtration. It focuses on fabrication methods, particle-capture mechanisms, sustainable and waste-derived polymers, and multifunctional designs. Particular attention is given to antimicrobial, antiviral, and humidity-resistant membranes for tropical conditions. The review also discusses their potential to address particulate pollution, airborne pathogen exposure, and plastic-waste challenges in Indonesia.

2 Advanced Capture Physics at the Nanoscale

2.1 *Dominant filtration mechanisms*

There are two types of air filtering mechanisms: steady-state and unsteady-state. In a steady-state operation, both the pressure drop and the filtration efficiency remain constant throughout the filtration process. The features of the filter materials, the type of particulate matter, and the airflow all affect this process. However, because of the buildup of particulate matter on the filter, the unsteady-state process causes the filtering efficiency and pressure drop to fluctuate over time. The unsteady-state process, however, requires theories due to its complexity. Five mechanisms—interception, inertial impaction, Brownian diffusion, gravity effect, and electrostatic effect will be used in this section to describe the steady-state fiber filtration process, which can be seen in Figure 1a [4].

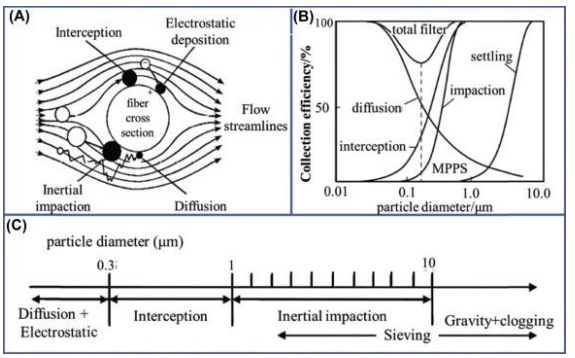


Figure 1: The schematic of (a) the air filtration mechanism of the single fiber, (b) the most penetrating particle size (MPPS) graph of particulate filtration efficiency effect for particles with different diameters, and (c) the filtration effect based on particle size [15], modified with permission from the author, © Copyright 2019, William Andrew Applied Science Publisher.

2.1.1 Interception mechanism

The aerosol or particulate matter has a simplified movement path. Unless there is an external push, the particles follow the streamline without touching the surface of the nanofiber filter materials. If the particles move near the filter fiber, they would come into contact with it. Van der Waals attraction would now pull them to the fiber. This technique can often capture particles with sizes ranging from 0.1 to 10 μm (Figure 1c). This filtration process is known as interception [17].

2.1.2 Inertial impaction mechanism

As the airflow passes through the nanofiber, the airflow streamlines shift direction close to the fiber boundaries. Particles larger than 0.3 to 1μm (Figure 1c) have trouble rapidly altering the direction of airflow along the streamline due to inertia. After separating from the streamline, the particles will be deposited onto the nanofiber along their original path. This mechanism has become the most popular way to achieve higher airflow velocities and capture larger particles. This technique will be more effective in capturing particulate matter if the airflow velocity, particle size, and fiber packing density are increased [15].

2.1.3 Brownian diffusion mechanism

When particulate matter is smaller than 0.1µm, Brownian diffusion takes place. Due to particle collisions while travelling along erratic paths, these particles display non-laminar flow. Brownian motion is the term used to describe the random movement that particles in a fluid show. Particle collisions with nanofibers and subsequent deposition on the fibers can also arise from this motion. When the airflow velocity is low and the particle size is tiny, the mechanism will be effective [4].

2.1.4 Electrostatic effect mechanism

When sub-micrometer particulate matter particles contain a charge that is opposite to the nanofiber, the electrostatic effect process takes place. The particles' trajectory is altered by the electrostatic force, which attracts them to the filter membrane's surface. Concurrently, the electrostatic effect increases the adherence of particles to the surface of the fibers. Without increasing the pressure drop, the electrostatic effect method can boost the filtering efficiency [15].

2.1.5 The gravity of settling effect

When particulate matter particles are larger than 0.5µm, gravity or settling takes place (Figure 1c). In the presence of an airstream, gravity may create a deviation from the initial route, and the nanofiber identifies the particles. For the majority of nanofiber filter membranes, the gravitational or sedimentation effect is negligible. For high-efficiency air filters, this effect has therefore had less bearing.

2.2 ***The transition regime and slip flow***

The nanoscale fiber diameter greatly enhances the material's specific surface area. As a result, the filtration efficiency is significantly increased for sub-micron particles with significant Brownian diffusion.

In nanofiber media, the slip characteristic allows it more straightforward to achieve less airflow resistance. The laminar flow around nanofibers has a Reynolds number (Re) that is much less than 1, which suggests that creeping flow is present in the flow. The Knudsen number can be used to assess the flow of a fiber ($Kn = \lambda/D$), where D is the fiber's radius and λ is the mean free path of air molecules. In Figure 2, the gas flow regime can be

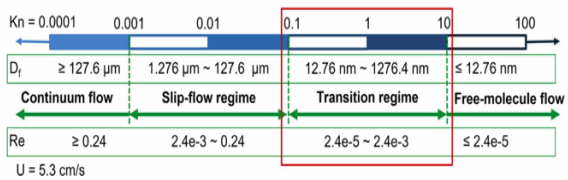


Figure 2: The Knudsen number of the nanofibers ranged from 0.1 to 10, indicating that they fall within the transition regime [19], [20].

divided into four types based on the Knudsen number: free molecular flow, transition flow, slip flow, and continuum flow. The nanofibers' Knudsen numbers ranged from 0.1 to 10, according to the data shown in Figure 2, suggesting that they are in the transition phase [19]-[21].

The MPPS (Most Penetrating Particle Size) of the nanofiber is less than that of the microfiber. Particles as small as 100 nm are captured by microfibers via diffusion. Nevertheless, the nanofiber will successfully confine the particle through interception because of its identical properties. In Figure 3, as the size of nanofibers decreases relative to microfibers, the importance of the interception effect increases. The low-velocity area on the fiber's surface decreases in proportion to the decrease in fiber diameter, while the flow field velocity surrounding the fiber becomes more homogeneous. As a result, there is less air resistance or pressure drop in the nanofiber [19], [20], [22].

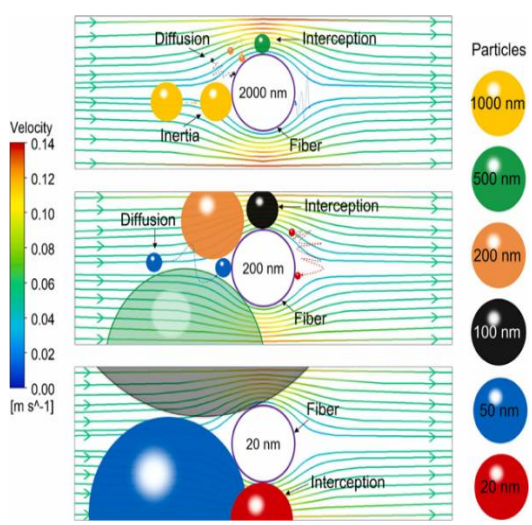


Figure 3: The schematic of the filtration performance of microfiber and nanofiber [20]. Adapted with permission by the authors, © Copyright 2023, Elsevier.

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Table 1: Summary of electrospinning process for several application areas.

Materials	Properties	Application Area	Ref.
PS/GO-APTES/Anti CD36	Immunosensing of CD36 as a marker for diabetes plasma	Biomedical: Biosensor	[13]
NiO/ZnO mesoporous nanofiber membrane	Urine metabolism analysis of smoker	Biomedical: Biosensor	[14]
PAN/PTA	Permeation Flux 7.66×10^4 L/m^2.h.bar	Water Filtration	[16]
Nylon-6	PFE= 98%; Pressure Drop= 69 Pa	Air Filtration	[24]
PP/Nylon-6	PFE= 99%; ressure Drop= 79 Pa	Air Filtration	[25]

3 High-Throughput and Specialized Fabrication Techniques

3.1 *Electrospinning*

3.1.1 Fundamentals of electrospinning

Nanofiber membranes with diameters ranging from 10 nm to submicron-scale can be fabricated by electrostatic spinning, also known as electrospinning, a highly advanced and efficient production technique. Due to the benefits of electrospinning, this technique can be applied in several applications, such as biomedical, water filtration, and air filtration (Table 1).

Four devices make up the basic electrospinning setup: (1) a polymer reservoir for pumping the polymer solution or melt; (2) a syringe pump attached to a spinneret or metal needle; and (3) a high-voltage power supply for creating the differential electric field between the metal needle and membrane collector, as shown in Figure 4. Following the revival of electrospinning in 1995, it was thought that the synthesis of nanofibers involved a continual process of splitting in the atomization zone. Ten years later. A high-frequency jet and a curved bending area were seen in the unstable atomization region [23]. This evidence indicates that the polymer nanofibers are rapidly stretched and dried during the electrospinning process, which can be divided into three distinct stages: the production of a Taylor cone, the formation of a linear jet, and the bending instability region.

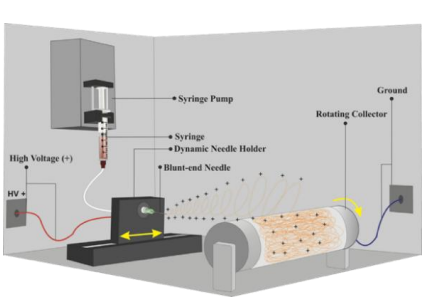


Figure 4: The schematic of the electrospinning process.

There are three separate processes in the electrospinning process. (1) The injection pump's spinneret makes it easier for the polymer solution to exit the syringe. Surface tension, thrust force, and gravity all produce spherical droplets. (2) Charges accumulate on the droplet's surface after the powerful generator is turned on. The electric field force causes the droplet to change from a spherical to a conical shape. The droplet's surface is impacted by the interaction between surface tension and the gravitational Coulomb force. When the Coulomb force exceeds the surface tension, a cone known as the Taylor cone forms, and a jet with a straight or linear trajectory is released. (3) The quick evaporation of the jet's menstruum causes instability in the linear jet during the third stage. The creation of unstable areas known as "bending instability," which results in the development of polymer fibers, is triggered by the interaction between the positive charge and the surface electric field [4], [12].

3.1.2 Influence of the electrospinning process parameters

System parameters of electrospinning

The concentration of the polymer solution, viscosity, molecular weight, surface tension, dielectric constant, and conductivity of the polymer are the system factors that have a major impact on the nanofiber. When the other parameters remain constant, the polymer solution's viscosity rises to a certain degree, which is beneficial for creating a nanofiber with the right morphology. Increased viscosity is also a result of increased polymer concentrations in a solution. Molecular weight also affects the solution's viscosity. If the viscosity of the polymer solution is too high or too low (bead-on-string), the probability of beaded fiber production increases. Furthermore, the viscosity of high molecular weight polymer solutions causes them to swiftly form linear nanofibers [18].

Other polymer solution factors include the solvent's volatility and solubility. The solvent can be changed by choosing a single solvent and altering the ratio of the combined solution. Furthermore, electrical conductivity has a greater impact on the synthesis of nanofibers. Excessive electrical conductivity causes severe discharge, reduces the uniformity of the fiber diameter distribution, and causes the electrospinning process to fail. The manufactured fiber beads are greatly diminished, and a rise in fiber diameter may have an impact on the increase in electrical conductivity. The dielectric constant is commonly used to discuss the composition of the solvent. Within a certain range, the diameter of the nanofibers decreases as the solvent dielectric constant increases. However, the stability of the jet is affected by an excessively high dielectric constant [17].

Process parameters of electrospinning

Process variables include high voltage, polymer solution flow rate, spinneret-to-collector distance, metal needle diameter (single or multi-needle), and collector type. The electric field force, which is controlled by the voltage (V), drives solvent evaporation and the creation of polymer filaments. Every electrostatic spinning process requires a minimum starting voltage. The electric field force and thrust force of the syringe pump are greater than the surface tension and gravity of the droplet at the end of the spinneret. It has been proposed that when the electric field force equals the surface tension, a linear jet may occur even when the droplet's gravity and thrust are insignificant. When the voltage is above the minimum pressure, the solvent will evaporate very quickly, enabling the fiber to quickly transform into a filament. As a result, the fiber gets thinner. When a certain limit is surpassed, the average diameter does not decrease. It increased because the electric field did not expand, the voltage was too high, and the polymer dried too soon after forming a straight jet [26].

The flow rate of the polymer solution also influences the creation of nanofibers. A thin fiber may be produced with a low flow rate. However, at a high flow rate, the fiber's diameter may increase. On the other hand, when the flow rate is too high, a bead forms in the fiber structure. Another factor to take into account is the distance between the tip and the collector. The strength of the generated electric field and the advantage of polymer solvent evaporation both increase with distance from the collector in a particular range. As a result, the fibers have better surface shape and a smaller diameter. The increase in fiber diameter caused by the increase in spinneret diameter was mostly caused by an increase in viscosity [26].

Ambient parameters of electrospinning

Temperature and relative humidity are examples of ambient parameters that have an impact on the synthesis of nanofiber membranes. Increasing the temperature can boost the volatilisation rate, lead to quick solidification of the polymer solution, and result in a finer fiber with a tiny diameter. Conversely, an increase in relative humidity influences the decrease in volatilisation and results in the formation of a beaded fiber. Integrating the solvent and polymer characteristics is necessary to modify the environmental factors [17].

3.2 *Electrospinning for air filtration application*

It explains the latest advancements in nanofiber, including single polymer, multi-polymer, integrated nanoparticle, and multi-process nanofiber, to enhance air filtering efficacy. Some of these procedures provide an additional purpose in addition to increasing the particulate matter's capture efficiency. For example, it may be used at high temperatures and humidity levels [3], [27], is breathable [28], has good antibacterial qualities [29]-[32], and is biodegradable [33]-[37].

Generally, electrospinning is used to fabricate nanofibers, which consist of a single polymer solution in a single spinneret (Figure 5). This process is relatively simple. The polymer solution that is prepared for the single process has spinnable properties. Furthermore, the preparation of polymer solution for single-process electrospinning can be blended with other polymer solutions [38] or added to nanoparticle solution [39]. For instance, the fabrication of polyamide nanofiber using a single spinneret with a concentration of 20 wt% of polymer solution; the variation of flow rate from 0.4 to 1.2 mL/h and needle diameter 23 to 29 G as well; the voltage 28 kV; and the gap distance between needle-tip and collector of 10 cm resulted in uniform nanofibers with fiber diameter 293 to 442 nm [40]. In addition, the mixture of PVDF/PAN using a single spinneret with a concentration of 15 wt% resulted in ultrathin nanofibers with a diameter of 172 to 198 nm and high air filtration efficiency (99.93%) as well [38].

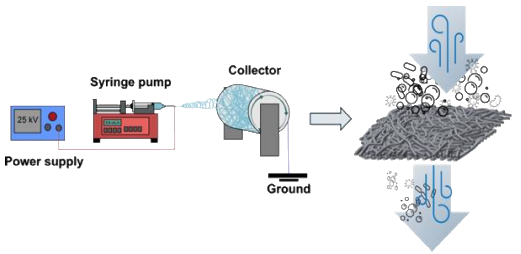


Figure 5: The schematic of single spinneret electrospinning.

The nanofiber membrane was created by Bui *et al.,* using DMAc and 2-butanone as solvents in a PVDF polymer solution. Because of the β-phase's piezoelectric characteristics, the PVDF's β-phase production enhances the electrostatic attraction between the nanofiber and particulate matter. Consequently, the PVDF nanofiber has a low pressure drop of 51 Pa and a high filtration efficiency of 97.4% [41]. On the other hand, introducing nanoparticles such as SiO_2 NPs also improves electrostatic attraction. The PEI/SiO2 NPs composite nanofiber, created by Li *et al.,* has a homogeneous structure and a fiber diameter of about 600 nm. This nanofiber membrane has an air resistance of 59.4 Pa, a high filtering efficiency of roughly 99.92%, and a degradation rate of less than 10% for 200 minutes [42].

Recently, the problematic issue of airborne viruses has led to the excessive utilisation of membrane filters for personal protective equipment fabricated from a non-degradable polymer, such as polypropylene, which poses a massive challenge for environmental issues, especially causing secondary pollution to the environment [43]-[46]. An environmental problem can be resolved by using a biodegradable polymer that breaks down over time. Wang *et al.,* produced the multiscale nanofiber membrane filter from polylactic acid (PLA) as a derivative of starch and tetrabutylammonium chloride (TBAC) as a salt. It resulted in true-nanoscale PLA with a fiber diameter of about 151–253 nm, a high filtration efficiency of 99.99%, and the ability of the membrane to break down through soil burial and enzymatic breakdown [33].

The other option to handle the secondary environmental concern is to create a reusable or washable nanofiber membrane. The reusable nanofiber membrane filter was created by Ding *et al.,* using a composite nanofiber made of polystyrene (PS) and spiropyran (SP). A homogeneous nanofiber with a diameter of about 500 nm was the end product. In addition, the filtration effectiveness of its membrane is greater than 95%, and it may be cleaned and reused without diminishing the filtering performance [47]. A full summary of the utilisation of the electrospinning technique for air filtration can be seen in Table 1.

3.3 *Multi-Spinneret systems*

Implementing the multi-spinneret electrospinning technique enhances the nanofiber's characteristics and speeds up the process of creating electrospun nanofibers for air filtration. As shown in Figure 6b, Robert *et al.,* created coaxial nanofibers using the PMIA PAN polymer solutions. The concentrations of PAN and PMIA range from 8 to 12 weight percent and 6 to 10 weight percent, respectively. The tensile strength of PAN (2.14 MPa) is increased to 13.8 MPa by using PMIA as a core-shell. Additionally, the filtration efficiency increases from 96.09 to 99.56% [48].

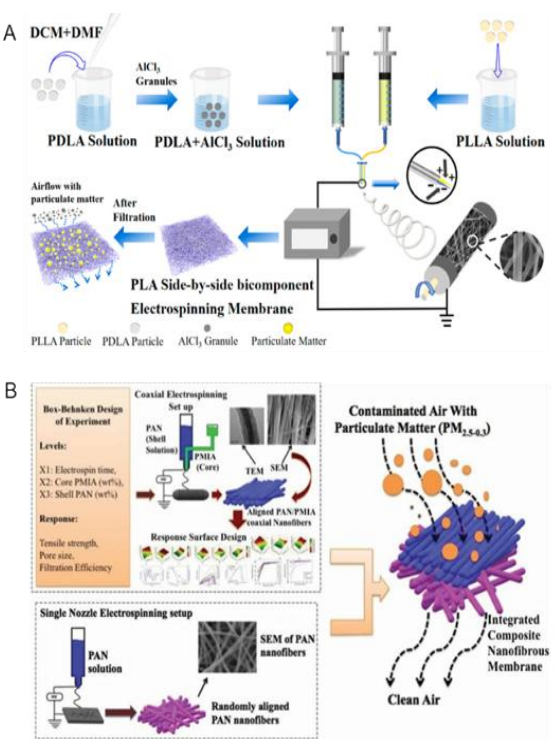


Figure 6: The schematic and the properties of (a) side-by-side nanofibers [49]. Adapted with Permission from the Authors, © Copyright 2021, MDPI. (b) electrospun nanofiber with coaxial nanofiber [48]. Adapted with Permission from the Authors, © Copyright 2022, Taylor & Francis.

The other type of multi-spinneret is side-by-side electrospinning, as in Figure 6a. Gao. *et al.,* used 6 wt% PLLA and 8 wt% PDLA polymer solutions and incorporated them with Aluminum Chloride Hexahydrate to fabricate side-by-side nanofiber with two sizes of needle diameters 0.39- and 0.63-mm. The process parameters, such as voltage, flow rate, the distance between the needle tip and the roller drum collector, and the rotating speed of the receiver, are 25 kV, 1 mL/h, 17 cm, and 400 rpm, respectively. PLLA/PDLA-$AlCl_3$ nanofibers from this electrospinning process resulted in a uniform and smooth structure that improved the filtration performance from 94-98% with a pressure drop of less than 30 Pa [49]. Table 2 provides a comprehensive overview of the electrospinning process's spinneret modification.

3.4 *Needle-Less and bipolar electrode techniques*

Munir *et al.,* produced multilayer expanded polystyrene (EPS) nanofiber for air filtration applications utilising the needle-less or nozzle-less electrospinning technology in place of the needle as a spinneret. In Figure 7, 20 weight percent of EPS was dissolved in a 1:1 DMF: DL-limonene solvent. The roller drum serves as a collector during the spinning process, which uses high voltage, flow rate, gap distance, and spinning duration of 15 kV, 0.3 mL/h, 20 cm, and 6 to 18 minutes, respectively. Compared to single-needle electrospinning, this method produces 10 times as much fiber. The needleless electrospinning method produces polystyrene nanofibers with a fiber diameter of about 1040 nm, regular porosity fiber, and a filtration efficiency of 90–94%. [57].

3.5 *Post-Treatment and surface roughness*

To enhance the function of the nanofiber filter membrane, the researchers additionally executed a further post-electrospinning treatment for the multi-processor. For example, Gobi *et al.,* work on PAN nanofiber coated with polyamide: PEG and alkali-treated to produce a web structure, with a filtering efficiency of 36.54-78.56% [64], that can be seen in Figure 8.

Table 2: Summary table of the application of electrospinning for air filtration application.

Materials	Electrospinning Methods	Fiber Diameter (nm)	Fiber Shape	Filtration Performance		Ref.
				PFE (%)	Pressure Drop (Pa)	
6 PLLA/ 8 PDLA	Side-by-side	336-559	Smooth without beads	94 - 98	<30	[49]
PVA/CNCs	Single spinneret	210-128	Uniform regular	99.99	110-230	[50]
1.6-2.2 wt% PLLA	Single Spinneret	NA	Porous fiber	99.7	91	[51]
8, 10 wt% PAN	Single Spinneret	100-550	Uniform regular	99.41	423.5	[52]
8 to 16 wt% PAN/MgO	Single Spinneret	52-314	Regular with accumulated nanoparticle	99.97	132-602	[53]
15 wt% PVDF/PAN	Single Spinneret	172-198	Ultrathin fiber grain-like structure	99.93	105.2	[38]
20 wt% Ethyl cellulose/ PTFE	Single Spinneret	NA	Uniform regular	~99.99	NA	[54]
22 wt% TPU	Single Spinneret	NA	Uniform regular	99	28	[55]
10 wt% PAN/CNs	Single Spinneret	471-760	Uniform with broad diameter	90-98.2	94.14-599.8	[56]
20 wt% expanded polystyrene	Needle-less	1,040-8,940	Regular porous fiber	90-99.4	48.41-58.36	[57]
5 to 10 wt% PMIA/PAN	Coaxial nanofiber	206-373	Uniform	99.5	49.03	[58]
12 PAN / 12 TPU/ 11 PVA/ 12 PS	Electrode-free - bipolar	NA	uniform	97.8-99.1	48.4- 58.4	[59]
PLA	Single Spinneret	137-274	Bead-on-string nanofiber	98	29.3	[60]
Zein	Single Spinneret	350	Ribbon-like structure	97.6-99.8	NA	[34]
Gelatin/ β-cyclodextrin	Single needle	130- 247	Web structure	99	125	[61]
PASS/Ag/ZnO	Single spinneret	168-321	Uniform structure	99.41-99.89	42-79	[62]
PS/CNC	Multi-spinneret	1100-2500	uniform	96.6-98.8	237-338	[63]

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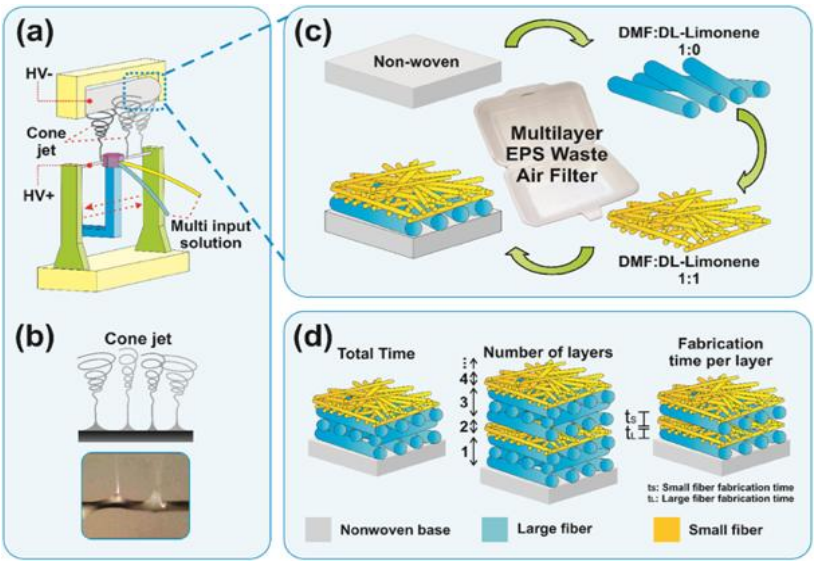


Figure 7: The schematic of (a) the needleless electrospinning process of EPS nanofiber, (b) the structure of a single-layer EPS membrane filter, and (c) the structure of a multilayer EPS membrane filter [57]. Adapted with permission from the author, © Copyright 2022, Elsevier.

In a different study, Wong *et al.,* used the multi-spinneret electrospinning approach to create the PS/CNC composite nanofiber, which was deposited on an aluminum roller drum collector at a voltage, flow rate, and gap distance of 2 kV, 10 mL/h, and 0.5 cm, respectively (Figure 9). A 10-nozzle splitter with a syringe needle as the spinneret was used in the procedure. The fiber's diameter is reduced from 2.52 to 1.1 µm when Intense Pulse Light Treatment is added after spinning.

The evaporation of remaining DMF solvent causes the surface roughness of the nanofiber to increase. Furthermore, filtering efficiency increases from 96.6 to >99% after treatment with Intense Pulse Light (IPL) [63]. Table 2 provides an overview of the electrospinning process used to fabricate the as-spun nanofiber.

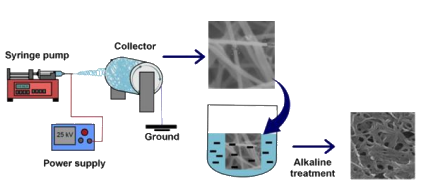


Figure 8: The schematic of multi-process electrospinning with polyamide coating and alkali treatment [64]. Modified with permission from the author, © Copyright 2022, RAPRA Technology Ltd.

3.6 *Comparison of electrospinning strategies for air filtration applications*

Different electrospinning strategies offer distinct advantages and limitations for air filtration. Single-spinneret electrospinning offers a relatively simple and flexible configuration, while polymer blending and nanoparticle incorporation can be performed within the same spinning solution to tailor filtration and functional properties. Multi-spinneret approaches, including coaxial and side-by-side electrospinning, provide greater control over fiber architecture and enable the combination of different materials; reported examples show filtration efficiencies of 99.5% for coaxial nanofibers and 94-98% for side-by-side nanofibers, with the latter maintaining a pressure drop below 30 Pa [52], [53], [60]. These systems, however, require more complex control of multiple polymer streams or spinnerets than single-spinneret configurations.

Needleless electrospinning provides a major productivity advantage, producing approximately ten times more fiber than single-needle electrospinning, but the reported EPS fibers were comparatively coarse (about 1,040-8,940 nm) and showed filtration efficiencies of 90-99.4% [54]. Bipolar-electrode approaches can achieve high filtration efficiency of 97.8-99.1% with a pressure

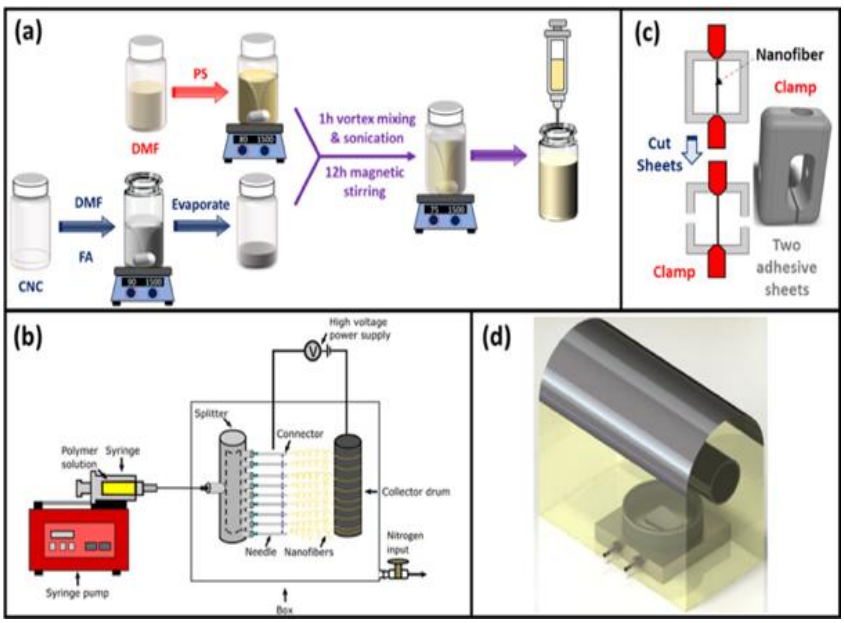


Figure 9: The schematic of (a) synthesis of PS/CNC polymer solution, (b) the multi-needle electrospinning of PS/CNC nanofiber, (c) the Fabrication of multi-process electrospinning with IPL treatment [63]. Adapted with permission from the author, © Copyright 2021, American Chemical Society Publications.

drop of 48.4-58.4 Pa [61], while post-treatment can further modify fiber diameter and surface characteristics; for example, intense pulsed light treatment reduced fiber diameter from 2.52 to 1.1 µm and increased filtration efficiency from 96.6 to above 99% [56]. Thus, selection of the electrospinning strategy should consider the balance among production rate, fiber architecture, filtration efficiency, pressure drop, material functionality, and process complexity, rather than filtration efficiency alone.

4 Material Sustainability and The Mask Waste Crisis

4.1 *Biodegradable polymers*

The development of sustainable air filtration media has increasingly focused on polylactic acid (PLA) derivatives due to their inherent biodegradability and versatile functionalization potential. Pure PLLA membranes fabricated via single-needle electrospinning achieve a Particulate Filtration Efficiency (PFE) of 99.21% while maintaining biocidal activity, moisture resistance, and reusability. The performance is further enhanced in PLA/PCL-Ag/Zn composites, which utilize multi-process electrospinning to create uniform, bead-free fibers that demonstrate a bactericidal ratio of over 99% against *E. coli* and *S. aureus*, coupled with a complete decomposition profile in soil burial within 90 days [45], [65].

Natural biopolymers like PHB and Zein offer tailored morphological characteristics that influence both air permeability and environmental degradation rates. PHB biopolymer fibers form interconnected networks without bead formation, yielding a PFE of 95.85% at a relatively low pressure drop of approximately 50 Pa. In contrast, Zein produces unique ribbon-like flat and twisted structures that significantly enhance capture efficiency to 99.76%, while exhibiting one of the most rapid environmental degradation profiles with a 90% decomposition rate after only 42 hours [34], [66].

Finally, protein and polysaccharide-based composites, specifically PVA/Konjac glucomannan and Soy protein isolate/PVA, emphasize maximum biological safety alongside high mechanical efficiency. Membranes incorporating Konjac glucomannan deliver a 99.99% PFE and distinct bacterial inhibition zones against common pathogens. Similarly, Soy protein isolate/PVA nanofibers achieve peak efficiencies up to 99.99% and complete decomposition within 40 days, ensuring that the filter media itself does not contribute to long-term environmental accumulation [37], [46]. The detailed summary can be seen in Table 3.

Taken together, these advances in biodegradable electrospun nanofibrous membranes highlight a viable

pathway for improving urban air quality in Indonesia, as summarized in Table 3. Their capacity to achieve efficient particulate matter removal while reducing the environmental footprint of filtration systems aligns well with the sustainability goals of densely populated tropical cities facing persistent air pollution and waste management challenges

4.2 *Upcycling Indonesia's plastic waste*

Indonesia's systemic plastic waste crisis, characterized by the annual generation of approximately 9.21 ± 1.52 million tonnes, is exacerbated by a 59% mismanagement rate where open burning (45%) and direct environmental leakage predominate. The persistence of these long carbon chains induces severe ecological degradation and microplastic contamination, posing significant threats to marine biodiversity and public health [68], [69]. Strategically upcycling prevalent post-consumer polymers, specifically polyethylene terephthalate (PET), polystyrene (PS), and polypropylene (PP), into electrospun nanofibers offers a transformative circular economy pathway to mitigate this surplus. These waste-derived architectures, characterized by ultra-fine fiber diameters and high surface areas, enable the fabrication of high-performance air filtration media, providing a sustainable technological solution for combating urban air pollution in Indonesia while simultaneously addressing the nation's critical plastic waste surplus [70]-[72].

Among these polymers, waste polystyrene has demonstrated considerable potential as a precursor for electrospun nanofiber filtration membranes. For instance, waste polystyrene from household industries, such as food packaging, can be processed via needleless electrospinning to fabricate hydrophobic nanofiber membranes with a uniform structure and a fiber diameter of approximately 500 nm, offering a filtration efficiency of around 94% and preventing bacterial attachment [50].

Furthermore, the use of expanded polystyrene at a 15 wt% concentration resulted in exceptional PM2.5 removal performance, achieving a filtration efficiency of 99.99% and a quality factor of 0.15 Pa^{-1}, demonstrating the strong potential of waste-derived PS nanofibers for high-performance air filtration applications. The surface morphology of these rPET fibers was successfully controlled to create hierarchically porous structures. These rPET fibrous membranes demonstrate high capture capabilities for both PM2.5 air pollutants and proteins, underscoring their potential as an integrated high-efficiency aerosol and virus filtering solution. Processing rPET into these functional materials further enhances the high specific surface area of the electrospun membranes, providing more possibilities for advanced engineered applications [73].

Table 3: The summary of biodegradable electrospun nanofiber for air filtration application.

Materials	Fiber Diameter (nm)	Filtration Performance		Biodegradable Characteristics	Ref.
		PFE (%)	ΔP (Pa)		
PLLA	NA	99.21	≈91	Kill the bacteria, Good moisture resistance, reusable, and sterilizability. Biodegradable	[65]
PLA/PCL-Ag/Zn coated on cotton	475-160	95-98.51	62-80	Favorable cell ability, Bactericidal ratio against *E. coli* and *S. aureus* are 99.33 and 99.19%. Long-lasting durability (>12h) 99.411%, Decomposed soil burial for 90 days.	[45]
Zein	~200	99.76	109	Degradation rate 90% after 42h	[34]
CA/TPU-LiCl	220-390	99.8	52	Reusable	[33]
PLA/TBAC	151-253	99.97-99.99	104	Completely decomposed in the soil after 150 days Completely degrade with enzyme proteinase K after 16h	[67]
Shellac/PVP	439	95-98.1	133	Biodegradable	[36]
Silk protein/PEO	300	~97	~12	Degradation rate 40% for 4h Can detect NH_3 gas and MeOH vapor	[36]
Zn encapsulated PVA/Konjac glucomannan	>100	99.99	130	Degradation efficiency 98% after 20 min Inhibition zone against *E. coli* and *S. aureus* are 1.58 and 1.4 cm	[46]
Soy protein isolate/PVA	152 - 88	99.76-99.99	99	Completely decomposed after 40 days, No bacteria found	[37]

4.3 *Electrostatic effects*

Nanofiber filter media have emerged as a superior alternative to traditional air filtration materials due to their high surface area and the slip-flow effect at the nanoscale [74]. However, a significant challenge in nanofibrous membranes is the inherent trade-off between particle capture efficiency and airflow resistance; as efficiency increases, the resulting high packing density often leads to a substantial pressure drop [74]-[76]. To address this, current research focuses on nanoscale architecture, specifically the bead-on-string (BoS) morphology, and the enhancement of electrostatic effects [74], [75], [77]. These BoS structures are characterized by nanobeads distributed along the fiber axis, which strategically redistribute solid volume to lower air resistance while maintaining high removal performance through various mechanisms, including physical interception and electrostatic attraction [74], [75].

Beyond these structural advantages, the integration of electrostatic effects transforms passive sieving into active particle capture. During electrospinning, high voltages *in situ* inject substantial charges into the nanofibers, including surface, volume, dipole, and interfacial charges, which generate strong local electrostatic fields. These fields attract charged particles via Coulombic forces and polarize neutral particles for capture through dielectrophoretic interaction. This active capture mechanism is particularly effective for ultrafine particles, as it can dramatically improve filtration efficiency without increasing physical obstruction to airflow. However, these electrostatic benefits are often sensitive to environmental conditions, as high relative humidity can lead to charge dissipation through water vapor uptake, as summarized in Table 4 [75], [77].

5 Enhanced Functionalities for Urban Environments

5.1 *Antimicrobial and antiviral properties*

The growing demand for advanced air purification has driven the development of multifunctional electrospun nanofiber membranes that combine high-efficiency particulate capture with biocidal activity. Using polymer matrices with antimicrobial agents such as silver nanoparticles, metal oxides, and bio-based proteins, these membranes can achieve high Bacterial Filtration Efficiency (BFE) while maintaining relatively low pressure drop [87], [91], [92]. The five capture mechanisms described in Section 2.1 diffusion, interception, inertial impaction, gravitational settling, and electrostatic attraction—operate differently depending on particle size. Bare virions, typically 20–300 nm, lie near the

Table 4: Summarize electret nanofiber for air filtration application.

Polymer System	Fiber Diameter (nm)	Fiber Shape	PFE (%)	ΔP (Pa)	Surface Potential (V)	% Decay	Decay Time (hour)	Ref.
PU/ Si_3N_4	350	Uniform	99	108	1800	56	168	[78]
PES/ $BaTiO_3$	280	Uniform	99.99	67	NA	<10	5	[79]
PA-6/ Boehmite	73-90	Protuding structure	96.8	48	109	NA	NA	[80]
PEI/ SiO_2	604	Uniform	99.992	61	NA	<10	3.5	[42]
PVB/ Si_3N_4	400- 600	Uniform	99.95	55	2080-2140	3.8	5	[81]
P(VDF-TrFE)/ $BaTiO_3$	280- 460	Uniform	96	182	-2000 to -8000	NA	NA	[82]
PLA/ Zn-TIO	264	Uniform with protuding structure	$PM_{0.3}$ 96.5 $PM_{2.5}$ 99.8	133.7	5700	NA	NA	[83]
PU foams coated MnO_2	NA	NA	90.5	~13	NA	NA	NA	[84]
MnO_2/PE/PP	NA	NA	71.73	6.02	14000	<5	720	[85]
PP/$BaTiO_3$	1000-3000	uniform	99.97	95	NA	NA	NA	[86]
PP/boehmite/ZnO	1500	uniform	~95	~22	2500	~12.5	168	[87]
PP/MgSt	NA	NA	99.2	13.93	4500	NA	NA	[88]
PI/PVP/ $BaTiO_3$	380-525	Protuding	~99.1	<70	1900	~12	120	[89]
PVDF-TrFE/Li-doped ZnO	430	Uniform porous with wurtzite crystal	73.3	~91	20	NA	NA	[90]

transition between Brownian diffusion and interception, overlapping the most penetrating particle size (MPPS) range. However, airborne viruses are more commonly associated with respiratory droplets or droplet nuclei of approximately 0.3–5 μm, where interception and inertial impaction become more important. Nanofibers can enhance interception because of their small diameter and associated airflow effects, but physical capture alone does not inactivate viable pathogens [93].

Biocidal functionality is therefore essential for dual-purpose filtration. Silver, ZnO, and CuO can disrupt microbial membranes through ion release and oxidative stress, while photocatalytic materials such as TiO_2 and ZnO generate Reactive Oxygen Species (ROS). Bio-based agents, including lysozyme and chitosan derivatives, can damage microbial structures, whereas quaternary ammonium compounds (QACs) disrupt microbial membranes through electrostatic interactions. Combining physical retention with biocidal activity increases the likelihood that captured pathogens are neutralized rather than merely retained on the filter surface. This is particularly important for virus-containing bioaerosols, where prolonged retention under humid conditions may increase the risk of pathogen persistence or secondary release [30], [32], [92].

Table 5 summarizes representative electrospun nanofiber membranes and demonstrates the relationship between fiber morphology, filtration performance, and antimicrobial activity. Ultra-fine PA6@Ag nanofibers with an average diameter of 90 nm achieved 99.99% PFE with a pressure drop of only 31 Pa [35], whereas PVA/AgHEC fibers with a diameter of 434 nm showed >95% PFE with a higher pressure drop of 59–230 Pa [90]. Beaded or knotted structures, such as PCL/HNTs-ZnO and PASS/Ag/ZnO, can reduce packing density while maintaining high PFE (>99%) and relatively low pressure drops of 46–79 Pa [36], [62]. The PVDF/Dye Photosensitizer membrane further demonstrated 98.2–99.9% PFE at only 0.47–0.8 Pa, whereas PCL/Zein/AgNPs showed comparable PFE (97.2–99.2%) but a substantially higher pressure drop of 72–510 Pa [91], [93]. These results illustrate the importance of controlling fiber morphology and membrane structure to balance filtration efficiency and airflow resistance.

Antimicrobial performance also varies with the active agent and membrane architecture. Silver-containing membranes, including PVA/AgHEC, PA6@Ag, PASS/Ag/ZnO, and PCL/Zein/AgNPs, achieved BFE values of approximately 95.4–100% [35], [62], [90], [93]. PCL/HNTs-ZnO achieved 95.9–97.9% BFE, with halloysite nanotubes helping to reduce ZnO agglomeration [36]. Meanwhile, the PMIA/PAN coaxial membrane demonstrated inhibition zones of 15 and 18 mm, highlighting the diversity of antimicrobial evaluation methods [58]. These variations, from filtration efficiency and inhibition zones to adsorption capacity, reinforce the need for standardized testing under realistic urban and tropical conditions.

Table 5: Summary of electrospun nanofibers for biological performance.

Materials	Fiber Size (nm)	Filtration Performance		BFE(%)	Ref.
		PFE (%)	ΔP (Pa)		
PVA/AgHEC	434	>95	59-230	~100	[91]
PCL/HNTs-ZnO	169-200	99.06	46	96-98	[32]
PMIA/PAN	184-346	99	24.5	NA	[60]
PVDF/Dye Photosensitizer	~200	98-100	0.47-0.8	99	[94]
PASS/Ag/ZnO	140-334	99.9	79	95-7	[64]
PA6@Ag	90	99.99	31	97.4-99	[31]
Sericin/PVA/Clay	300-400	NA	NA	97-99	[95]
PCL/Zein/Ag	275	97-99	72-510	97-98	[92]

5.2 *Optimization for tropical climates*

The optimization of nanofiber membranes for tropical climates requires a specialized focus on high-humidity stability and multi-gas filtration capabilities to combat the unique environmental challenges of these regions. Membranes utilizing PVA/citric acid/sodium acetate demonstrate exceptional performance in extreme humidity, maintaining high filtration efficiency (99.93%) during humidification at 85±5%, a condition typical of tropical monsoons. Furthermore, the integration of Metal-Organic Frameworks (MOFs) into PVA matrices (PVA/MOF basolite F300) addresses the prevalence of malodorous urban gases by effectively removing and, providing a dual-functional approach that pairs high particulate matter removal (40–97% PFE) with chemical gas neutralization [27], [96]. Therefore, the development of multifunctional nanofiber

membranes, as summarized in Table 6, represents a highly relevant technological pathway by integrating high-efficiency PM2.5 filtration, VOC adsorption, moisture management, and gas-removal functionalities; these advanced membranes hold significant potential to support sustainable air quality improvement and reduce pollution-related health risks in major Indonesian urban centers.

6 Industrial Applications and Commercialization Challenges of Electrospun Nanofiber for Air Filtration in Indonesia

In Indonesian urban settings, air filtration is applied at several levels, including personal respiratory protection, indoor air cleaning, building ventilation and air-conditioning filtration, and industrial air-pollution control devices. Recent national guidance on indoor air quality identifies air purifiers, sterilization systems, and other appropriate technologies as practical options for indoor environments, while Jakarta continues to expand air-quality monitoring and emission-control measures. These applications indicate that electrospun nanofiber filters are more likely to be introduced as high-performance filter media integrated into existing systems rather than as a stand-alone replacement for source-control measures [101].

Indonesia also has an established nonwoven manufacturing base that can support the substrate side of advanced filter production. The Ministry of Industry's 2024 National Work Competency Standard for the nonwoven industry explicitly includes operation and setup of spunbond and meltblown web lines, together with product-quality testing such as thickness, basis weight, tensile strength, and porosity. In parallel, a 2026 Indonesian study demonstrated modification of commercial PP melt-blown media with electrospun Nylon-6 nanofibers and reported particulate filtration efficiency above 95% for PM0.3, showing a locally relevant pathway for hybrid filter development. However, laboratory-scale electrospinning capability should not be equated with industrial-scale production; process uniformity, solvent handling, high-voltage safety, equipment productivity, and quality assurance remain important implementation requirements [24], [102].

From an economic perspective, a practical route is to deposit a relatively thin electrospun active layer onto an existing commercial nonwoven substrate, which can reduce the amount of nanofiber material required while retaining mechanical support. Nevertheless, commercialization in Indonesia may be constrained by the capital cost of scalable electrospinning equipment, energy and solvent consumption, occupational safety controls, the need for stable fiber deposition over large areas, and the cost of filtration-performance testing and certification. Additional barriers include maintenance requirements, replacement intervals, and the need to demonstrate that improvements in filtration efficiency justify the associated pressure-drop and manufacturing costs under local operating conditions. These factors should be evaluated using life-cycle cost and performance data rather than filtration efficiency alone [102].

The policy environment in Indonesia primarily emphasizes prevention and control of air pollution at the source, air-quality monitoring, and environmental management. PP No. 22/2021 establishes provisions for air-quality protection and management, including pollution prevention and response. At the regional level, Jakarta's air-pollution strategy includes monitoring, control of mobile and stationary sources, vehicle-emission testing, industrial emission control, and development of low-emission areas; the 2026 roadmap further expands the low-emission-area approach across transport, buildings, waste, energy, industry, and land-use

Table 6: Summary of nanofiber membrane filters with optimization for tropical climates.

Materials	Fiber Size (nm)	Filtration Performance		Tropical Climates Function	Ref.
		PFE (%)	ΔP (Pa)		
PVA/citric acid/ sodium acetate	190-240	99.9	128	Humidity 85±5%	[27]
PVA/MOF	166-451	40-97	10-120	Toxic gas removal	[96]
PAN/Mt	207	98.7	46.8	Cu Adsorption capacity 227.27	[97]
Polyimide/MOF	470-860	NA	NA	Good adsorption of m-xylene	[98]
Cellulose/ Zeolitic imidazolate	393	98-100	30.7	Low charge decay	[99]
Zein	350	98-99.8	NA	Breathable	[28]
PA-6/Clay/TiO_2	76-136	NA	NA	Good air and water vapor permeability	[100]
Gelatin/β-cyclodextrin	130-247	99	125	Excellent adsorption of volatile pollutant	[63]

sectors. Relevant product-performance standards also exist, including SNI EN 1822-1:2019 for EPA/HEPA/ULPA filters and SNI IEC 63086-1:2023 for household and similar electrical air-cleaning appliances. Therefore, future Indonesian electrospun-filter deployment should be aligned with existing environmental policy and tested against applicable product-performance standards [5].

7 Commercialization and Scale-Up

The transition from laboratory electrospinning to commercial air-filter production requires a shift from single-point material optimization toward continuous, reproducible manufacturing. Multi-needle, needleless, bipolar-electrode, and roll-to-roll or rotating-collector configurations can increase production rate and improve the feasibility of coating larger substrates, but scale-up introduces additional requirements for fiber-uniformity control, solvent evaporation, collector management, electrical safety, web handling, and process monitoring. Recent reviews identify industrialized electrospinning and scalable nanofiber architectures as important directions for air-filtration technology [50].

For commercialization, performance should be specified at the product level rather than only at the material level. Key qualification parameters include particulate filtration efficiency, pressure drop, quality factor, mechanical adhesion of the nanofiber layer to its substrate, electrostatic-charge stability, resistance to humidity, loading-induced performance decay, and service life. These properties should be evaluated under standardized test conditions and, where appropriate, field conditions representative of Indonesian urban environments. Product formats such as replacement HVAC media, portable-air-cleaner filters, industrial prefilters or final filters, and respiratory-protection layers may provide different routes to market, each requiring different mechanical, airflow, safety, and certification requirements. [36], [70], [72]

A staged scale-up strategy is therefore recommended: laboratory validation, pilot-scale continuous production, long-duration testing, prototype integration, third-party performance certification, and finally industrial production with statistical process control. Hybrid designs that use commercial melt-blown or other nonwoven substrates as structural support and electrospun nanofibers as the high-efficiency active layer are particularly suitable for this pathway because they can leverage existing converting and nonwoven infrastructure while limiting the electrospinning step to the functional surface. The economic assessment should include equipment depreciation, energy, solvent recovery, substrate cost, labor, quality control, certification, filter lifetime, and end-of-life management. [65], [70], [71]

8 Research Gaps and Future Technological Challenges

Despite rapid progress, several research gaps remain before electrospun nanofiber filters can be broadly deployed in real air-filtration systems. Published studies frequently use different face velocities, relative humidity, particle-size distributions, loading histories, and testing protocols, making direct comparison difficult. Long-term retention of electrostatic charge, humidity-induced performance loss, mechanical durability, adhesion to substrates, and behavior during particle loading are also insufficiently standardized. Recent reviews specifically identify persistent under-reporting of relative humidity, face velocity, and durability protocols as limitations in the literature. [70], [72]

Future research should therefore move toward integrated performance and sustainability targets: high submicron filtration with low pressure drop, durable charge retention, humidity tolerance, mechanical robustness, scalable deposition, low-toxicity or solvent-efficient processing, and controlled end-of-life pathways. Greater attention is also needed to multifunctional filtration for bioaerosols and gas-phase pollutants, while verifying long-term safety and minimizing nanoparticle or additive release. For Indonesia, field validation using urban aerosol conditions, comparative life-cycle cost and environmental assessment, local supply-chain analysis, and conformity with Indonesian standards would help bridge the gap between laboratory demonstrations and deployable products. The combination of advanced materials such as dielectric or piezoelectric nanoparticles with locally available PP melt-blown substrates represents a promising research direction, but its benefit should be demonstrated through reproducible long-term testing and techno-economic evaluation rather than filtration efficiency alone. [65], [66], [36], [70], [72]

AI-assisted membrane design and machine learning optimization represent promising directions for accelerating this development. Machine learning models could be used to relate polymer type, solvent composition, solution properties, applied voltage, flow rate, collector conditions, fiber diameter,

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porosity, and surface charge to filtration performance. Such models could support rapid identification of promising material combinations and processing conditions. AI-assisted optimization could also help balance filtration efficiency, pressure drop, mechanical stability, humidity resistance, and production cost. However, reliable models will require standardized and sufficiently large experimental datasets. Data quality and validation under independent experimental conditions will therefore remain essential.

Another important direction is green electrospinning. Conventional electrospinning may involve volatile organic solvents, high energy consumption, and solvent-recovery requirements. Future studies should prioritize safer solvents, aqueous or bio-based solvent systems, lower-energy processing, solvent recovery, and efficient material utilization. The use of biodegradable polymers and waste-derived feedstocks should be evaluated together with processing impacts rather than considered solely on the basis of material origin. Recent studies emphasize that solvent selection and membrane fabrication can substantially influence the overall environmental profile of electrospun materials [70], [71].

Life-cycle assessment (LCA) should consequently become an integral part of membrane development. Environmental performance should be evaluated from raw-material production and electrospinning through use, replacement, regeneration, recycling, and final disposal. Important indicators include energy demand, greenhouse-gas emissions, solvent consumption, material recovery, waste generation, and filter service life. Recent LCA research on waste-derived electrospun air filters demonstrates that process scale-up and regeneration can substantially influence the overall environmental impact [73]. For Indonesia, LCA should also consider local energy sources, transportation, waste-management systems, and the availability of recycled or bio-based feedstocks.

Future filtration systems may also evolve from passive filters toward smart and self-cleaning membranes. Smart membranes could incorporate sensing or responsive functions to monitor particle loading, humidity, pressure drop, or filter condition. Self-cleaning or regenerative systems could reduce the accumulation of particles and extend service life. Possible approaches include electrostatic regeneration, triboelectric or piezoelectric effects, photocatalytic surfaces, and responsive surface structures. These technologies should be assessed not only for their cleaning efficiency but also for energy demand, durability, particle-release risks, and long-term stability. Recent research has highlighted the potential of self-powered and intelligent electrospun filtration systems as an emerging direction for next-generation air filtration [74].

Finally, industrial commercialization remains a major research challenge. Laboratory-scale electrospinning must be translated into reproducible, continuous, and economically viable manufacturing. Multi-needle, needleless, and roll-to-roll systems can increase production capacity, but scale-up requires control of fiber uniformity, solvent evaporation, web handling, electrical safety, and process monitoring [70], [72]. A practical commercialization pathway should include laboratory validation, pilot-scale production, long-duration testing, prototype integration, third-party performance certification, and industrial production with statistical process control. Hybrid structures that deposit a thin electrospun active layer onto established nonwoven substrates may provide a practical route because they can utilize existing manufacturing infrastructure.

For Indonesia, commercialization should also consider local raw materials, waste-derived polymers, energy and solvent requirements, production costs, product certification, supply-chain availability, and end-of-life management. Performance should be assessed under realistic tropical conditions rather than based only on short laboratory tests. Key indicators should include filtration efficiency, pressure drop, quality factor, charge stability, humidity resistance, service life, cost per unit area, energy consumption, and environmental impact. Addressing these research gaps will help transform electrospun nanofiber membranes from high-performance laboratory materials into sustainable, intelligent, scalable, and locally manufacturable air-filtration products.

9 Conclusion

Electrospun nanofiber membranes demonstrate strong potential for sustainable air filtration in Indonesia, combining high filtration efficiency, low pressure drop, antimicrobial functionality, and the use of biodegradable or waste-derived materials. To translate these advances into practical applications, three priorities should be pursued: (1) validate long-term performance under realistic tropical conditions, including humidity, particle loading, durability, and pathogen filtration; (2) scale up sustainable manufacturing, particularly using biodegradable

polymers and post-consumer plastics with optimized electrospinning processes and life-cycle assessment; and (3) advance multifunctional and self-regenerating membranes toward commercialization through humidity-resistant, antimicrobial, and self-powered electrostatic designs, supported by pilot-scale production and industry collaboration.

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Author Contributions

Januar Nur Rohmah Suprihartini: conceptualization, literature search, data curation, writing an original draft, reviewing and editing, validation. Candra Irawan: conceptualization, literature search, writing. Bima Yatna Anugerah Ramadhani: writing, writing and editing, data curation, validation. All authors have read and agreed to the published version of the manuscript.

Conflicts Of Interest

The authors declare no conflict of interest.

Declaration of Generative AI And AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors did not use any AI or AI-assisted technologies.

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