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Advances In Nanomaterials For Air Filtration: A Comprehensive Review

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Abstract
Air quality management is a pressing global concern, necessitating innovative solutions for effective filtration and treatment. This study explores cutting-edge research on nanomaterials for air filtration, covering diverse techniques and applications. The studies investigate ambient air purification, emphasizing non-destructive adsorption processes and key sorbing materials. Electrospun nanofiber membranes, known for their versatility, are examined for their effectiveness in air-dust filtration. Catalysts, particularly cobalt-based oxide catalysts, are explored for transforming hazardous vapors. Electrospinning techniques for polymer membranes and nanofibers, especially polyacrylonitrile (PAN), are highlighted for their flexibility and cost-effectiveness. Specific nanofiber materials like PAN are discussed for their ability to catch PM2.5 particles. The potential of nanomaterial-based filtration membranes is showcased through studies on PAN-based electrospun carbon nanofibers (ECNFs) and PVDF/PUL composite air filtration membranes. The development of novel nanofiber membranes with additives like silver and polyimide is explored for enhanced filtration and antibacterial properties. Advancements in polyetherimide (PEI) nanofiber membranes, including those decorated by Cu-based metal-organic frameworks (CuMOF), are discussed for their multifunctionality in high-efficiency filtration and separation. Overall, this review provides a concise overview of the latest research in nanomaterials for air filtration, emphasizing their role in addressing the global challenge of air pollution.. The incorporation of nanomaterials enhances membrane performance, offering improved selectivity, antibacterial properties, and enhanced flux. Comparison tables highlight key findings and applications in each filtration technology. Additionally, the study discusses future prospects, challenges, and the environmental impact of nanomaterial production. The paper concludes by emphasizing the potential of nanomaterials-based membranes in revolutionizing air filtration technologies, ensuring cleaner and healthier air. This work contributes to the understanding of nanotechnology applications in air treatment and sets the stage for future advancements in the field.

Keywords: *Air Filtration, Nanomaterials, Membrane Technology, Ultrafiltration, Microfiltration, Membrane Distillation, Electrodialysis, Filtration Technologies, Air Quality, Environmental Impact, Nanomaterials Synthesis*

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I. Introduction

The world is currently grappling with significant challenges related to air, water, and a growing population. Because existence is impossible without air, global concerns about air pollution are escalating. The World Health Organization (WHO) estimates and declares that approximately seven million premature deaths occur annually due to air pollution [Gakidou et al., 2017]. The UNEP Pollution Action Note comprehensively outlines the current global levels of air pollution, its primary causes, effects on human health, and national initiatives to address this urgent issue. Every breath we take introduces small particles that can harm our hearts, brains, and lungs, creating various health issues. The hazard to human health, particularly the haze problem, is mainly caused by fine particulate matter [Gakidou et al., 2017]. The Eastern Mediterranean region and South-East Asia face the highest ambient air pollution levels, with annual mean levels frequently surpassing WHO guidelines [Faridi et al., 2023]. Reports indicate that air pollution contributes to more than 4.1 million fatalities, ranking as the sixth-highest risk factor for disability-adjusted life years (DALYs) worldwide [Zhao et al., 2017]. Therefore, it is crucial to gather sufficient information on the sources of air contaminants and develop cutting-edge technology for air treatment. Rapid industrialization in some developing countries, such as India and China, has led to a decline in air quality in major cities. The deterioration is attributed to uncontrolled traffic growth, urban population expansion, urban sprawl, industrial deforestation, increased industrial activity, and rising traffic emissions [Ghosh et al., 2021].

Air pollution comprises various particles such as dust and aerosols, hazardous gases (ozone, nitrogen dioxide, nitrous oxide, sulfur dioxide), volatile organic compounds (VOCs), and particulate matter (PM), which are microscale airborne pollutants [Schraufnagel, 2018]. The main sources of air pollution include fuel combustion from automobiles, power plants (e.g., coal power plants), industrial facilities (manufacturing factories, mines, and oil refineries), residential cooking, agricultural and municipal waste incineration/burning, heating and lighting with polluting fuel [Chow et al., 2006]. Additionally, natural sources of pollution like pollen, spores, fungi, bacteria, and virus-carrying aerosols contribute to health issues such as asthma, allergic reactions, and infectious diseases [Lee and Hieu, 2011].

To address the issue of air pollution, effective air treatment techniques are essential to preserve current air resources and ensure clean air [Kanaujia et al., 2022]. Scientists have employed various methods to decrease air pollution, including filtration techniques and emission source controls. Current methods, such as filtering or reducing particulate matter emissions, can ameliorate deteriorating air quality [Weiss et al., 2016]. Filtration is considered the best method for protecting against PM pollution. Technologies that can remove both natural and manmade pollutants from the air are necessary, and various air filtration materials have been researched [Han et al., 2021]. One notable method is membrane filtration, which, depending on pore size, can serve as a physical barrier to remove particles, compounds, contaminants, and microbes from the air [Rathna et al., Year]. The choice of membrane for air filtration applications should consider properties such as pore size, reactive functional groups, surface charge, long lifespan, low pressure drop, ease of handling and installation, and low production costs. Over the past two decades, various materials have been used for air filter design, with properties such as low air resistance, high filtration efficiency, non-toxicity, and no secondary pollution. Textile-based high particulate air filters (HEPA) and ultra-low particulate air filters (ULPA) have demonstrated filtration effectiveness of more than 99.90% [Roy et al., 2018]. Fibrous materials, including foams, carbon nanotubes, and fibers, have been investigated for high-performance air filtration [Norizana et al., 2020]. Electrostatic dust collecting filters and air filter filtration are two common types of filtering [Zhou et al., 2022]. Membrane filtration systems are currently under study due to their wide applications, non-secondary injury, and adjustable filtration performance [Zhou et al., 2022]. They offer cleaner air compared to chemical treatment, making them suitable for various filtration applications [Gul et al., 2021].

The increasing demands for air filters are driven by continuous innovation and advancements in science and technology. Nanotechnology has emerged as a favored tool for cleaning the air, incorporating nanomaterials into real-world settings to enhance, manage, and filter air contaminants [Han et al., 2021].

Nanomaterials with large specific surface areas (SSAs) and high surface-to-bulk ratios, along with unique chemical characteristics, are preferred for air filtration [Baig et al., 2021]. Researchers have extensively studied nanomaterials for air filtration, leveraging their high porosity, small pore size, and good connectivity to serve as nanocatalysts, nanoadsorbents, sensors, and membranes/nanofilters [Mekuye & Abera, 2023]. Nanostructured catalyst materials, including nanospheres, nanoplates/sheets, nanotubes/rods, and nanoaerogels, exhibit ideal properties for air pollution control. Functionalized and specifically designed nanomaterials have significant potential for treating particulate toxic pollutants and enhancing environmental pollution remediation technologies [Yetisgin et al., 2020]. Nanomaterial-based air filtering has become a focal point for researchers, leading to the continuous development of filtering membranes based on nanoparticles. Various techniques, such as photocatalysis, passive trapping, moisture capturing processes, and adsorption technology, are employed for pollutant removal or filtration. Technologies like centrifugal collectors, wet scrubbers, electrostatic precipitators, biofilters, cyclone collectors, and impacted or venture-scrubber physical filters have improved containment removal efficiency [Ahmad et al., 2020]. Wet electrostatic scrubbing techniques have enhanced contaminant removal efficiency, particularly for fine and ultrafine particles [Carotenuto et al., 2010]. Despite these advancements, inherent drawbacks such as high energy consumption, poor separation efficiency, and large equipment area limit the practical use of these technologies. Nanoscale fibers, researched in nanotechnology, are entering practical applications, and nanomembrane-based filters are gaining high approval among researchers [Singha & Mishra, 2020]. Research articles demonstrate the increasing interest in nanomaterial-based air filtration, as illustrated in Figure 1 [Singha & Mishra, 2020]. Scientists have improved filtering effectiveness and micro-particle collecting capability through the use of nanomaterials, with nanofibers being a unique material in nanotechnology research, applied in various industries, including air filtration [Attia et al., 2024].

In this study, we first concentrated on the pollutants, then on the origins of the pollutants, the problems that have arisen as a result of the increasing air pollution, and the work that researchers have done to address these issues using a variety of strategies. We focused on filtration methods, such as membrane filters, but nanomembrane air filtration is more appropriate for removing microscopic airborne contaminants. We also discussed about the effects of using nanomaterials in the design of nanomembranes on membrane materials, as well as how to increase the effectiveness of air filtration. The processes for creating nanomembranes were also covered, and extensive research had already been done on the subject. To the best of our knowledge, electrospining is highly suitable as a reason for us to concentrate more on producing nanomembrane air filters by electrospining and as far as we understand research has not done as much as it should be.

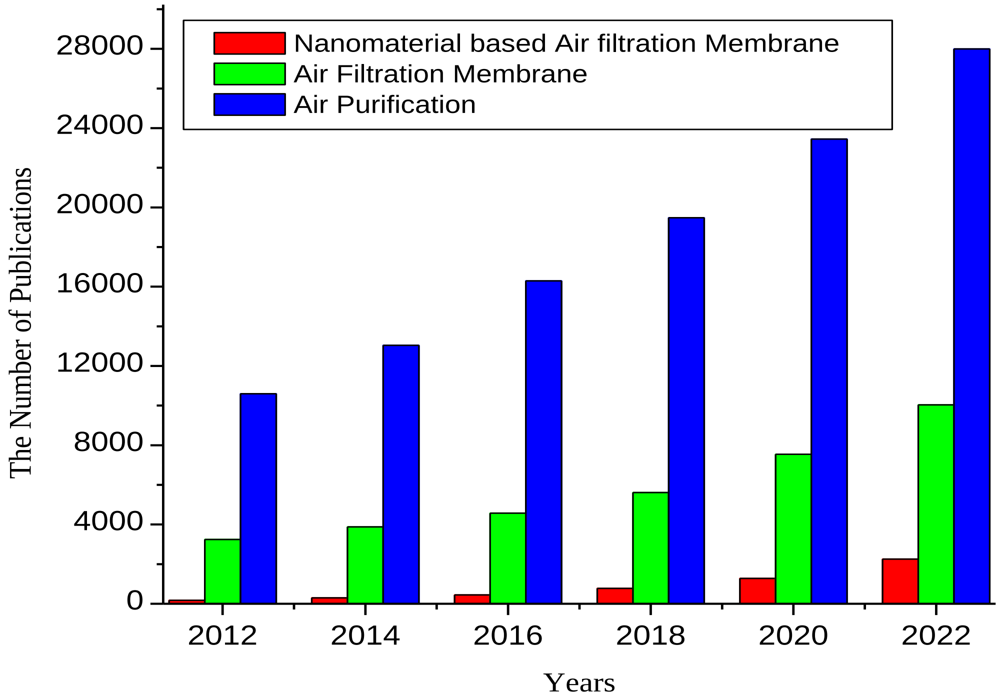


Figure1. Represents the Research has been done related to removing of air pollutant from Air

In today's era, we are all well aware of the rising issues caused due to pollution. Now, pollution can be of many types and each type has its own impact but the most hazardous form of pollution is the air pollution as it is directly affects the fundamental need of living beings and also as it is very difficult to prevent (1 of 1). People can survive without water for five days, but they cansurvive without air for not more than 2 minutes. People require roughly 15 m^3 of air per day to breathe, which is equal to a mass of 15 kg to 17 kg, which is nearly ten times that of water and food as people only require approximately 1 kilogram to 2 kg of food and water for normal survival every day.

Pollutants with the strongest evidence for public health concern include particulate matter (PM), carbon monoxide (CO), ozone (O3), nitrogen dioxide (NO2), and sulfur dioxide (SO2). The particulate matter is divided into two primary categories based on the average diameter size: the first type is the fine particle with a diameter less than 2.5 µm, and the second type is the aerodynamic with diameters of fewer than 10 µm (Manisalidis et al.). Particulate matter has a size threshold below which adverse effects do not occur. Generally, particulate matter with a diameter of fewer than 10 and 2.5 microns (PM10 and PM2.5) poses health hazards (Thangavel et al.). Fine particles, such as sulfate, nitrates, black carbon, and fine aerosols, are easily inhaled and can cause a number of respiratory and cardiovascular conditions, as well as an increased risk of death (Thangavel et al.).

II. Major Sources of PM2.5 and PM10

We studied information from China and India, specifically in regards to PM2.5 concentration and migration issues (Zhao et al., 2017). China has consumed large amounts of energy due to its recent rapid economic development and urbanization, primarily using coal and fossil fuels. As a result, China is one of the most polluted nations in the world in terms of PM2.5 levels. The ensuing nitrates and sulfates have caused significant air pollution, notably the haze associated with PM2.5. A variety of airborne pollutants, including PM, SOx, CO, unburned hydrocarbons, and NOx, are primarily produced by anthropogenically induced combustion-related emissions, including those from the burning of fossil fuels and biomass for energy and heat (Manisalidis et al., 2020). Sulfate, nitrates, black carbon (black carbon, a significant part of PM2.5 and a strong climatic warming agent, causes regional environmental disruption and hastens glacier melting and the effect on health due to the presence of black carbon in the air), and fine aerosols are examples of fine particles that are simple to breathe in."

Deep lung penetration by PM is capable of allowing it to reach the bloodstream, where it can have negative effects on the heart (ischaemic heart disease), brain (stroke), and lungs. The incidence and mortality of cardiovascular and respiratory disorders are linked to both exposures, including decreased exercise capacity in healthy people, shortened angina recovery times short-term and long-term exposure to particulate matter. Long-term exposure has also been connected to lung cancer, poor neonatal outcomes, and a higher chance of death. VOCs have a number of negative health effects, including a rise in the prevalence of asthma, eye, nose, and throat irritation, headaches, loss of coordination, nausea, and damage to the liver, kidneys, and central nervous system. Some VOCs are also known to cause cancer. The amount of oxyhaemoglobin in the blood decreases as carbon monoxide diffuses through the alveolar membrane, dissolves in the blood, and binds to haemoglobin with a stronger affinity than oxygen, leading to tissue hypoxia. Additionally, fine particle pollution in the air also contain a variety of bacteria, spores, fungi, pollen and allergens (Yang, 2012), which may cause allergies or respiratory infectious diseases. There are many health risks associated with carbon monoxide, increased rates of asthma in children, bronchiolitis, and increased rates of cardiovascular disease, cardiac disease, cardiac failure, and ischaemic heart disease in the elderly.

Scientific studies have shown that air pollution can cause a variety of illnesses, including cardiovascular disease, conjunctivitis, tumors, osteoporosis, dry eyes, fractures, infectious allergic disorders, and more (de Paula Santos et al., 2021). Other health impacts include glomerular filtration rate decline, inflammatory bowel disease, increased blood vessel clotting, and other physical illnesses (Waas et al., 2021). Air pollution control is a pressing issue that needs to be resolved due to the considerable harm it does to human health. Table 1 has briefly explained the types and sources of particulate matter.

Category of particulate Matte

Table: 1 Various category of particulate matter and Sources

Types	Composed of	Sources	References
Fine mode particles (PM2.5)	Sulfate (SO_4^{-2}), nitrate (NO_3), ammonium (NH_4^+), hydrogen ion (H^+), elemental carbon (C), organic compounds (PAH), metals (Pb, Cd, V, Ni, Cu, Zn), particle-bound water, and biogenic organics	High temperature operations; smelters and steel mills; combustion of coal, oil, and gasoline; transformation products of NOx, SO_2, and organics including biogenic organics, such as terpenes;	Srimuruganandam and Nagendra (2012) https://doi.org/10.1016/j.envint.2004.09.006
Coarse mode particles (PM10)	Pollen, mould spores, plant fragments, soil dust, street dust, coal and oil fly ash, metal oxides of silicon, aluminium, magnesium, titanium, and iron, calcium carbonate, sodium chloride, and sea salt	Suspension from disturbed soils, such as those in farming and mining; resuspension of industrial dusts; building; coal and oil burning; and ocean spray	Srimuruganandam and Nagendra (2012)

Air pollutants due to ambient pollutants such as particulate matter (PM2.5, PM10, and microorganisms) and poisonous gases have always been shared trouble faced by way of many nations within the world. PM2.5, being the maximum not unusual air pollutant, is posing an extraordinary threat to the global public health and economic system. The infamous PM2.5 is infamous for its risky nature of penetrating into the respiration machine of humans and delivering harmful chemical compositions through blood gadgets, for that reason chronically detrimental to human breathing and cardiovascular structures.

Air purification remedy is a great manner to lessen air pollution in the human frame. Filtration may be divided into electrostatic dust series filters and air filter out filtration. The former specifically makes use of corona discharge technology to ionize the dusty airflow, giving the particles inside the airflow a terrible price, after which captures and collects the particles on the Dirt collection substrates with a wonderful charge employ an energetic filtering method, while the latter uses precise materials to capture particles for gas-solid separation. Nanoparticles outperform ordinary materials due to unique characteristics like surface effects, size effects, quantum effects, and others. Nanoparticles can be utilized in surface-active adsorbent systems to capture hazardous gases and metals in the environment (Altammar, 2023). Novel biohybrid nanomaterials, created by combining natural and synthetic polymers with specific active elements, have the potential to be highly biocompatible and efficient antibacterial agents. The design of hybrid nanocomposites produces specific advanced materials with tailored properties, functions, and applications. The control and reduction of airborne particle pollution, leading to various chronic diseases and health risks, have been explored using nanomaterials specifically designed to treat particulate toxic pollutants (Saleem et al., 2022). These nanomaterials offer potential benefits and methodologies to enhance current environmental pollution remediation technologies, making them more effective.

III. Air Born Particulate matter removal techniques

Some very useful or commonly used techniques for the removal of airborne particulate matters include Mechanically aided wet Scrubber, Electrostatic precipitation method, Biofilter, Cyclone collectors, Impacted or venture-scrubber, and Physical filter (Zhang et al., 2023). The containment removal efficiency has been improved with the help of these technologies, specifically through the application of an Electrostatic Precipitation (ESP) index-driven bio-aerosol collection for high biological viability sampling (Zhang et al., 2023). Wet Electrostatic Scrubbing techniques have also contributed to improving contaminant removal efficiency, as evidenced by the work of Ramaswamy et al. (2022). These techniques play a vital role in reducing environmental chemicals, toxicity, and particulate matter in wet scrubber devices, aiming to achieve zero emissions**.**

Major post-combustion control methods for particulate matter, NOx and VOCs mitigation from sources

Various methods are employed for the treatment, control, or filtration of air pollution, focusing on particulate matter/dust control, nitrogen dioxide control, and volatile organic compounds. Electrostatic precipitation, wet scrubbers, cyclones, and baghouses (fabric filters) are notable methods for particulate matter control (Gakidou et al., 2017). Electrostatic precipitation relies on particle collection through electrostatic forces, while wet scrubbers involve filtration through porous textile fabrics. Nitrogen dioxide control utilizes methods like selective catalytic reduction, selective non-catalytic reduction, and three-way catalyst, each with distinct mechanisms (Gakidou et al., 2017). Volatile organic compounds control methods include adsorption, regenerative thermal oxidation, and regenerative catalytic oxidation, employing mechanisms such as gas adsorption, incineration at high temperatures, and catalytic oxidation.

The advantages of these technologies are significant. Physical filtration technologies, particularly high-efficiency particulate air (HEPA) filters and ultra-low penetration air filters (ULPA), are ideal for air pollutant removal due to their ease of operation and low energy requirements (Gorji et al., 2017). HEPA filters are widely used to remove particles smaller than 10 µm with an efficiency of over 99%, while ULPA filters achieve a removal efficiency of at least 99.999% for 0.1-0.2 µm particles (Gorji et al., 2017).

Table 2; Technologies used for the Removal of Air born Particulate Matter

Techniques	**Particulate Matter**	**Removing efficiency**	**Reference**
Collecting Chamber	Aerosol to 45 µm.	90%	8-9
Mechanically Aidedwet Scrubber	Black Carbon , Fine Aerosol >3.5 µm	97%	11
Cyclone Collector	Sulfate, Nitrate >2.5 µm	92%	12
Impacted and Venturi Scrubber	Sulfate (SO24), nitrate (NO3), ammonium (NH+4),	94%	12-14
Biofilter	organics including biogenic organics, such as terpenes;	98%	15-17
Physical Filter	metals (Pb, Cd, V, Ni, Cu, Zn),	92%	18-20

Yang jiand and his group has Design a nanofiber membranes using electrospinning technology have been hailed as a top candidate for air filters. Electrospinning can offer a quick and effective one-step method to create intricate functional nanofiber structures such core-sheath structures, Janus structures, and other multilayered structures in order to meet the needs of material functionalization.

To improve the physiochemical and performance capabilities of the membrane, the nanomaterials can be coated, grafted, or implanted in various layers of the membrane. However, some nanomaterials have reportedly been linked to environmental toxicity and health risks for humans.

Numerous studies have been conducted on the removal of airborne particulate matter and the development of membrane filtration technology that is enough to regulate the release of micro to submicron particles into the environment. Figure 1 depicts the published paper relating to air purification, air filter membranes, and nanomaterial-based membranes.

Pollution from particulate matter and a comparison of several air filters

Recently, there have been serious PM pollution problems in developing countries with a large manufacturing industry such as China. Figure 1a,b shows images of a location in Beijing during clear and hazy days, respectively. During hazy days, the visibility decreased greatly and the air quality was poor because of extremely high levels of $PM_{2.5}$.

Public safety measures during cloudy days tend to concentrate on individual protection outside, such as the use of mask filters, which are frequently clumsy and restrict airflow15. residential homes hardly ever provides filtration protection from PM in indoor areas; protection is only offered in contemporary commercial buildings through filtering in ventilation systems or central air conditioning. Additionally, due to the extensive usage of pumping systems, all of these active air exchanges by mechanical ventilation need tremendous quantities of energy.

Indoor air quality is a major issue when individuals are confined indoors for long periods of time17. It would be ideal if indoor air filtering could be accomplished through passive air exchange, or natural ventilation, through windows. Because most windows have a big surface area, air exchange is quite effective In order to protect windows, air filters must not only have a high ability to absorb particulates (PM), but also a high optical transparency that allows for simultaneous use of natural sunlight illumination and sight-viewing. Here, we first offer the idea of a transparent air filter that protects indoor air quality at the window.

Interception and impaction on a filter surface are the two main techniques for removing some stiff inorganic PM particles from the air. Some soft PM would deform on filter surfaces, such as those from combustion exhaust, and necessitate greater binding during the attachment process. These PM deform on the filter surface because they contain a lot of carbon compounds or water. It is essential to look into the air filter's surface properties to increase PM particle capture.

However, there hasn't been a lot of investigation into the properties of filter materials in air filter technology. There are typically two types of air filters utilised 15. One has a membrane that is porous and resembles a air filtration filter (shown in Fig. 1c). Making pores on a solid substrate is how this type of air filter is created. It typically has low porosity (30%) and relatively small pores to filter out bigger particulate debris. As a result, the filtering efficiency is excellent despite the substantial pressure decrease.

A fibrous air filter is an additional type of air filter that may capture PM particles by utilising a combination of robust physical barriers and adhesion (shown in Fig. 1d). This type of filter is often made of numerous layers of thick fibres with sizes ranging from a few microns to tens of microns, and it typically has porosities above 70%. In order to achieve a high efficiency, this sort of filter is often thick. The drawbacks of the second type of filter are bulkiness, opaqueness, and a trade-off between air circulation and filter efficacy.

A transparent, high-efficiency PM2.5 filter would not be possible with current technology. Here, we provide an unique polymer nanofibre filter technology that, as shown in Fig. 1e, has the appealing properties of high filtering effectiveness, good optical transparency, low air flow resistance, and light weight. We discovered that when the air filter's surface chemistry is adjusted to match that of PM particles, the single fiber's ability to catch particles increases significantly more than that of the current fibrous filters. As a result, the amount of material used in the air filter can be greatly decreased to a level of transparency to enable both transparency to sunlight and enough air flow.

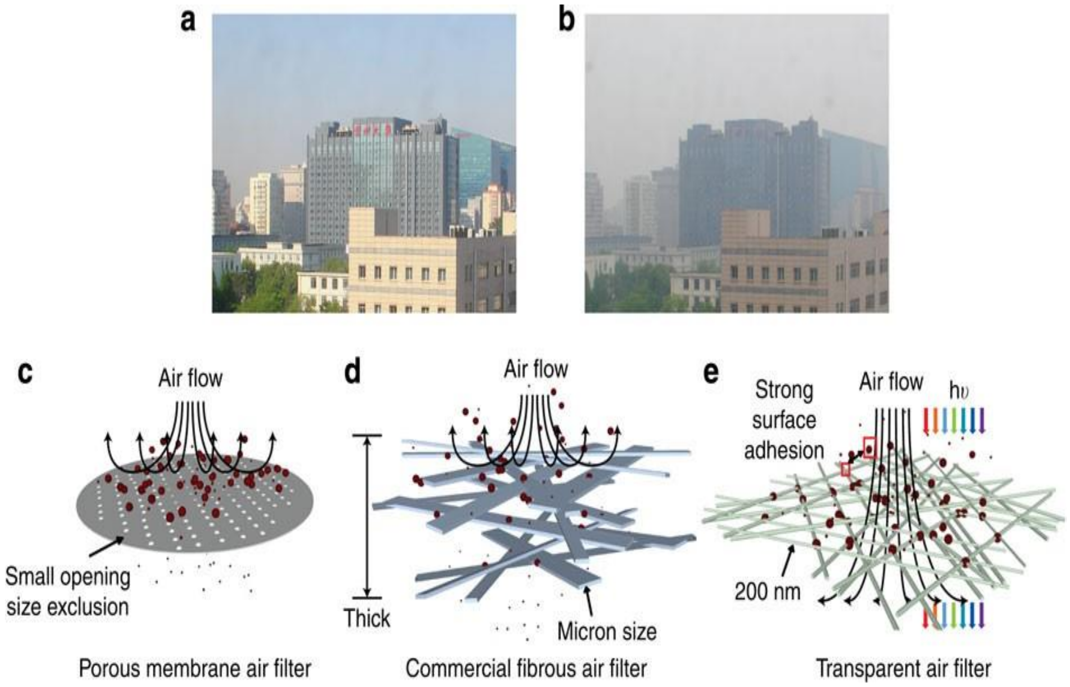


Figure 7 Pollution from particulate matter and a comparison of several air filters. (A) A picture taken on a sunny day in Beijing of an arbitrary location. (b) A photo taken at the same location in Beijing on a day when the PM2.5 concentration was dangerous. (c) A porous air filter schematic for trapping PM particles via size exclusion. diagram of a large, fibrous air filter that captures PM particles by a strong physical barrier and stickiness. (e) Air transparency schematics filters that trap PM particles by providing for maximum light and air penetration and strong surface adherence

Another Purification/filtration Techniques

Passive trapping is another technique for removing airborne particulates, and the majority of modern commercial purification products use dense fibre networks to block off contaminants. This technique is referred to as passive trapping in this article. By obstructing the particle-transport path and filtering impurities through collision, attachment, and trapping, the substance serves as a "obstacle" in this process. Materials adopting such a mechanism have been widely employed and commercialized due to their wide variety of applications, low cost, and high purifying efficiency. As demonstrated in **Figure 2**, a number of processes, including inertial impaction, interception, Brownian motion, and gravitational settling, work together to capture PM

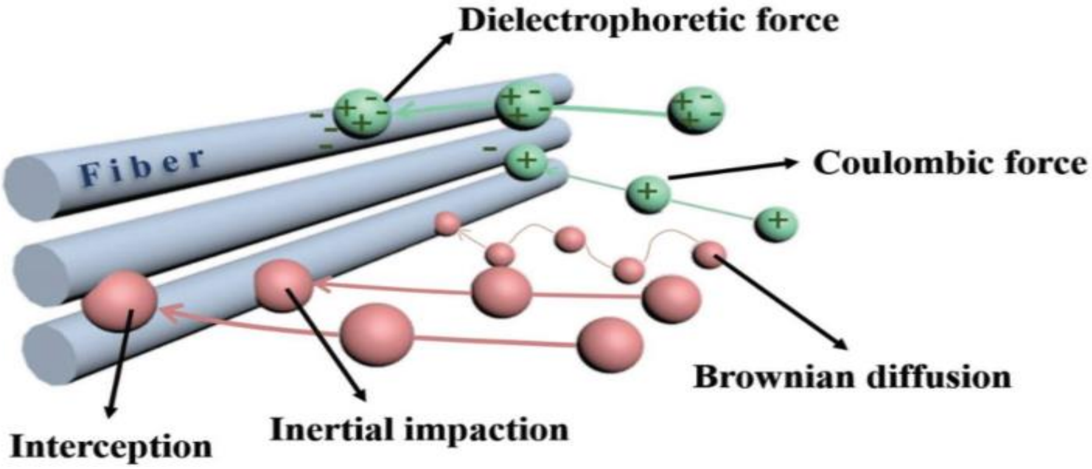


Figure. 2 The method for catching PM. The green particle represents a proactive capture method, whereas the red particle represents a passive trapping strategy.

In mechanical purification methods, the key elements vary based on filtering conditions, and the process involves inertial impaction and Brownian motion effects. In the initial stage, particles deviate from the original gas streamline and collide with the purification material, leading to inertial impaction. Subsequently, Brownian motion induces erratic movements in sub-micrometer particles, causing them to diverge from the initial airflow pattern (Zhang et al., 2022).

Cleanable Air Filter That Transfers Moisture and Captures PM2.5 Effortlessly

Xinglei and his group (Zhao et al., 2017) have explored a technique for removing PM2.5 using a cleanable air filter that transfers moisture and effectively captures PM2.5. Development of the gradient he developed fibrous membranes with a gradient structure using PAN-SiO2 fibres as the outer layer, PVDF/PAN-SiO2 fibres as the interlayer, and PVDF fibres as the inner layer. He was inspired by the moisture absorption capabilities of a desiccant. A gradient structure with PVDF fibres acting as the outer layer, PVDF/PAN-SiO2 fibres acting as the interlayer, and PAN-SiO2 fibres acting as the inner layer with a low thickness of 2.1 µm was also created for comparison. **Figure 2a** illustrates the materials' synthesis process. The PAN-SiO2 fibres' super-hydrophilicity and the composite PVDF/PAN-ability SiO2's to efficiently accelerate the MVTR worked in tandem with the PVDF layer's hydrophobic properties to prevent capillary water from forming.

Although the PAN-SiO2-2/PVDF/PAN-SiO2-2/PVDF fibrous membranes (M2) needed 47 min to obtain a steady value of water vapour delivery, in the **Figure 2b** the gradient M1 fibrous membranes took just 30 min. These findings showed that the water vapour may be successfully transmitted across fibrous membranes with a gradient structure.

Furthermore, the gradient M1's greater ability to transmit moisture-vapor was supported by a steady value of humidity that reached 90%, which was higher than the values seen for gradient M2 and PVDF fibrous membranes (82%) and the gradient M1 itself (80%). (**Figure 2c**). These findings suggested that the M1 structure might move moisture vapour more quickly from the area of high concentration to the area of low concentration.

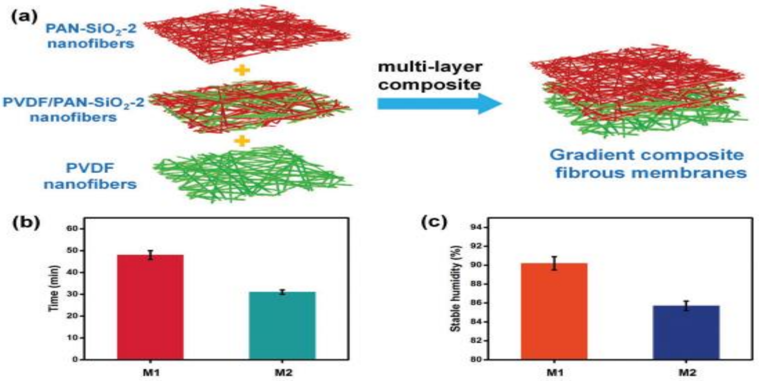


Figure. 2 The process used to make gradient fibre membranes and its effectiveness at transferring moisture. a) Diagram outlining the steps involved in creating gradient composite fibrous membranes. b) The period of time during which fibrous membranes with various structures were installed in the test cabin and the humidity increased from 40% to a steady amount.

Miaomiao Zhu and his group (Zhu et al., 2019) have designed and fabricated a bio-based air filtration membrane using electrospinning techniques and UV-curing.

this environmentally friendly technique, toxic organic solvents that can leave behind residual chemicals that cause human health harm are avoided. To boost the efficacy of filtration, superhydrophobic silica nanoparticles are specifically added to the nanofibers to create a rough surface. multipurpose, and bio-based chitosan/poly (vinyl alcohol) air filtering membrane. We also added hydrophobic silica nanoparticles (SiO2 NPs) to the CS-PVA composite electrospun nanofibrous membranes to improve filtering performance and create a hierarchical structure on the surfaces of the CS-PVA composite nanofibers. Finally, Ag nanoparticles (Ag NPs, reduction of Ag+ to Ag nanoparticles using UV light) were added to the CS-PVA@SiO2 NPs filtration membranes to accomplish the antibacterial activity of these bio-based electrospun air filtration nanofibrous membranes. It proved that the filtration membranes perform air filtration and antibacterial activities effectively. We considered the CS-PVA@SiO2-Ag NPs nanofibrous membranes (Fig. 1(a) and (b)) to be an effective, antibacterial, green, eco-friendly air filtration material with a lot of potential use in the area of personal safety.

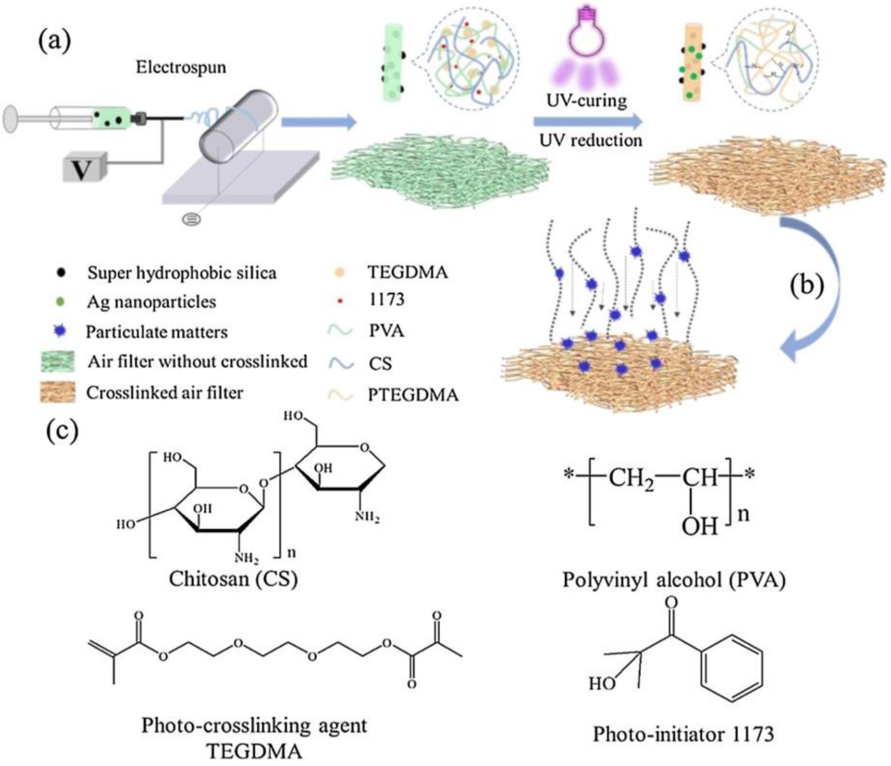


Figure 3 (a) electrospinning, one step UV reduction and cured. (b) Filtration process of the PVA@SiO2 NPs-Ag NPs air filtration membranes. (c) The chemical structure of CS/ PVA/TEGDMA/1173

IV. Nanomaterial based Air Purification method

The use of nanomaterials for environmental remediation now has outstanding prospects thanks to recent advancements in nanotechnology. Catalysts 2021, 11, 1276 6 of 41 nanomaterials have remarkably distinct electrical, magnetic, and catalytic characteristics for PM 100 nm in comparison to bulk materials, making them preferable for filtering, adsorption, and photocatalysis. The fundamentals of ambient air purification with nanoparticles (APN) are covered here, with special emphasis on air pollutants with low concentrations (sub-ppb to ppm range), low emission intensities, and sources that are distributed. These uses benefit from the unique characteristics of nanomaterials, such as quantum confinement and surface/interface phenomena.

Nanomaterials have been employed in many types of purification devices to reduce particulate matter (PM), gaseous precursors (i.e., NOx, VOCs, etc.), and toxic pollutants. They can be Utilised for particle filtration, gas adsorption, bacteria disinfection, and catalytic processes. Modest working circumstances, a lack of cumbersome instrument setup, and minimal operating costs are benefits of nanomaterials. APN technology is in fact frequently a good option for enhancing the quality of the air in residential and urban locations, and it is especially well suited for applications in restricted spaces. A significant budget was granted by the Chinese government for research on nanomaterials and APN technology for pollution abatement as a result of these benefits, and APN will definitely get more attention globally in the future.

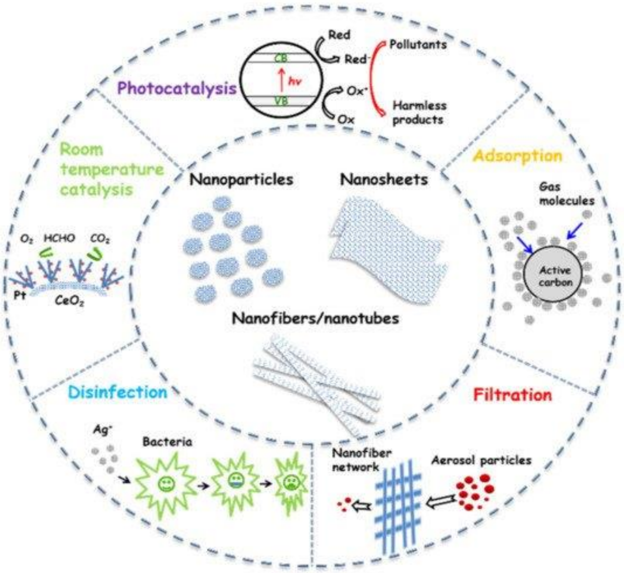


Figure. 4 Technologies used for ambient air purification by nanomaterials

Technique for Nanomaterial based Air Filtration membrane and its preparation

Nowadays, air filter films are presently the investigated hotspot, as air channel films don't cause auxiliary hurt, their filtration execution is controllable, and they have a wide application run. An idealized air filter ought to have the taking after properties: (Gakidou E, Afshin A, Abajobir A A, Abate K H, Abbafati C, Abbas K M, Abd-Allah F, Abdulle A M, Abera S F, and Aboyans V 2017 *The Lancet* **390** (10100) 1345) high filtration proficiency, low air resistance, and (3nontoxic secondary contamination. The center of filter-screen filtration is the determination and arrangement of filter-screen materials. At the show, the core functional layer of the channel screen mindful of expelling PM is made of nonwoven filaments. Miaomiao Zhu et al. have designed or fabricated a bio-based Air Filtration membrane using electrospinning techniques and UV-Cured (Zhu, M., Xiong, R., & Huang, C., 2019).

Xinglei et al. work on another technique for the removal of PM2.5 via the cleanable air filter transferring moisture and effectively capturing PM2.5 (Zhao, X., Li, Y., ..., & Ding, B., 2017).With the nonstop advancement and advance of science and innovation, the necessities for air filters are getting to be higher and higher. In conventional filter materials, the fiber diameter is more often than not on a micrometer scale, and the filter layer is ordinarily composed of numerous layers

There are numerous methods for removing airborne particulate matter, but one of the most common is the passive trap. According to the classical single-fibre filtration method, Xunzheng and his team used the passive trap method, which involves interception, inertial impaction, diffusion, and gravity.

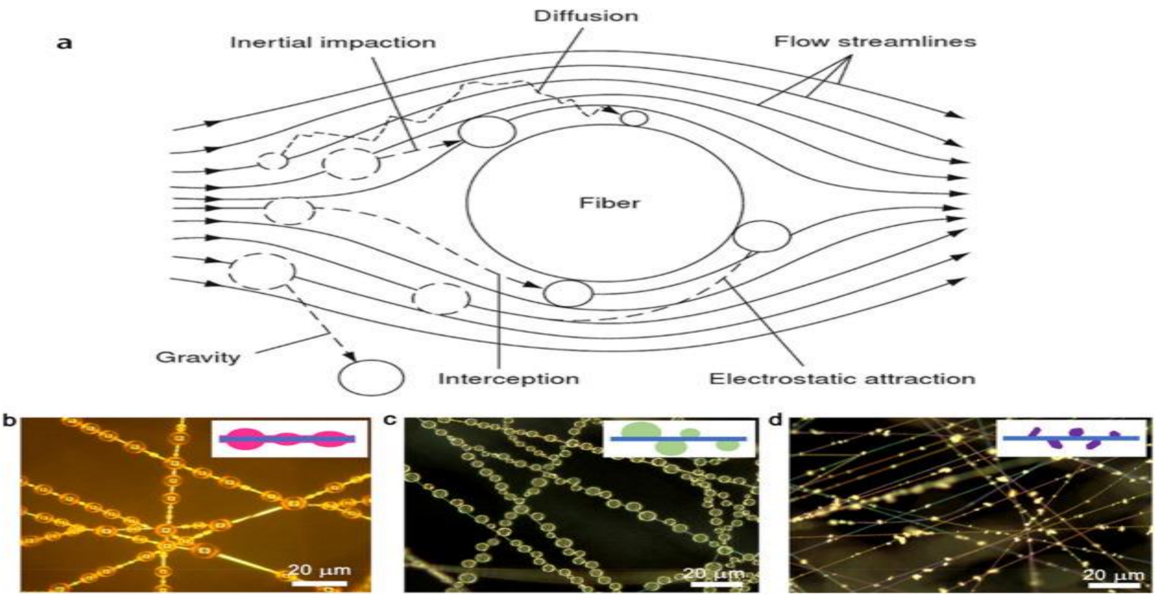


Figure 5

Filtration Method

It may take a decade or longer for particle filtration to be decreased to an acceptable level, according to new data collected by the Institute of Earth Environment in Xi'an, China and historical experiences in American cities (Ji et al.) have contributed to advances in particulate matter filtration, covering materials, performance, and application (Ji, X., Huang, J., Teng, L., Li, S., Li, X., Cai, W., Chen, Z., & Lai, Y., 2022).Although world or Specially China has lately tightened limits on PM2.5 emissions from vehicles and industry, negative health effects are still a major worry. Due to their better filtration effectiveness and minimal pressure drop, membranes/filters, particularly those constructed from electrospun nanofibers, have become widely accepted for applications in PM2.5 collection.

Large pollution particles can be captured by conventional filtering, but in fact this method has some serious drawbacks, such as frequent clogging, high energy consumption, and high operating expenses. Electrospun nanofiber mats exhibit low airflow resistance and little pressure drops due to their high porosity and micrometer-sized void spaces, in contrast to traditional multilayer air filters Zhou et al. have conducted a comprehensive review on electrospun nanofiber membranes for air filtration (Zhou, Y., Liu, Y., Zhang, M., Feng, Z., Yu, D.-G., & Wang, K., 2022).For these materials, high-power pumps are not necessary.

Pressure drop and filtration efficiency both have an impact on filtration performance. The most popular methods for enhancing the filtering effectiveness of nanofibers are to increase the polarity and surface electrostatic charges of the polymers used to create them. Incorporating active ingredients into the polymers used to create nanofibers is another way to give them additional unique functions. For instance, magnetic metal oxide nanoparticles (Fe3O4) can be added to electrospun nanofibers to attract dust through magnetic attraction as iron oxide makes up a significant portion of airborne dust (Figure 2a,b)

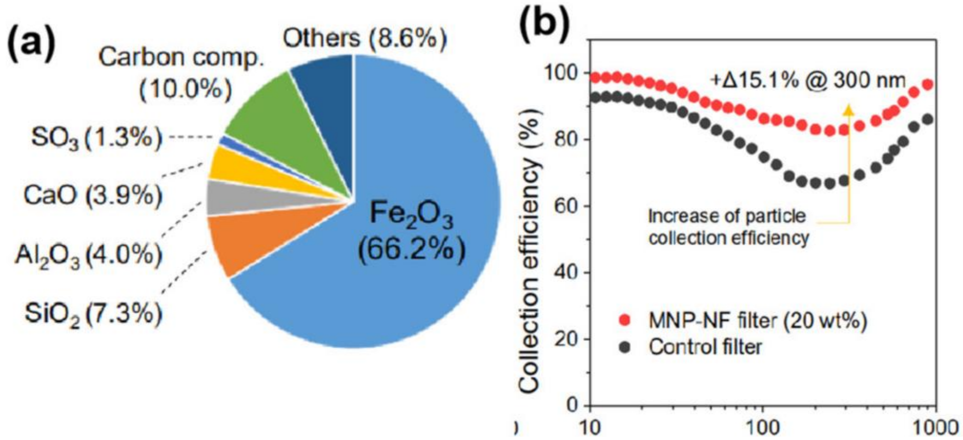


Figure 6. (a) Chemical composition of dust from a subway station in Seoul, South Korea. (b) Comparison of subway dust collection efficiency for a control filter versus a 20 wt % Fe3O4 nanoparticle-NF filter.

Photocatalysis Method

An environmentally friendly method for eliminating air pollutants from the atmosphere is nanomaterial-driven photocatalysis. Takeuchi and Ibusuki discovered that metal oxides in atmospheric PM were essential for the photochemical catalytic conversion of hydrocarbons and NOx at the beginning of 1986. Several photoactive metal oxides, such as TiO_2, ZnO, and Fe2O3, can be relatively abundant in the atmosphere. Heterogeneous reactions catalysed by these photoactive materials have been considered for removing pollutants from the air. These reactions strongly enhance the formation of CO_2 and HNO_3 and weakly reduce O_3 (de Almeida et al.) have discussed the use of nanofiber filters for air pollution control in indoor environments, including the application of nanomaterial-driven photocatalysis (de Almeida, D. S., Martins, L. D., & Aguiar, M. L., 2022).

Principles of Photocatalysis and Major Nanomaterial

With the help of irradiation semiconductors, the advanced oxidation process (AOP) known as photocatalysis modifies both the pace and the direction of a chemical reaction. A positive hole (h+) is simultaneously left in the valence band as one electron (e) is excited from the valence band maximum (VBM) to the conduction band minimum (CBM) according to the Fujishima-Honda energy band theory (Equation 1). By diffusion or migration, photogenerated e-h+ couples are spatially separated from the sites of the surface reactions.

Excited charge carriers can react with the pre-adsorbed H_2O and O_2 at the photocatalyst surface to create reactive oxygen species (ROS), such as hydroxyl (Equation 2) and superoxide radicals (Equation 3). The entire transformation of the gaseous pollutants into innocuous chemicals is made possible by the radicals' Catalysts 2021, 11, 1276 10 of 41 incredibly strong oxidation potentials, which hardly exhibit any selectivity towards pollutants.

It is significant to note that the respective VB and CB positions of a particular photocatalyst play a major role in determining the capacity to produce ROS as well as their oxidation and reduction capacities. The band locations of certain semiconductors are shown in Figure 3 along with their relation to the production of $\bullet OH$ and $\bullet O_2$ at various redox levels.

$$\text{Photocatalyst} + h\nu \rightarrow h^{+} + e^{-}, \qquad (1)$$

$$h^{+} + H_2O \rightarrow \bullet OH + H^{+}, \qquad (2)$$

$$e^{-} + O_2 \rightarrow \bullet O^{-2}, \qquad (3)$$

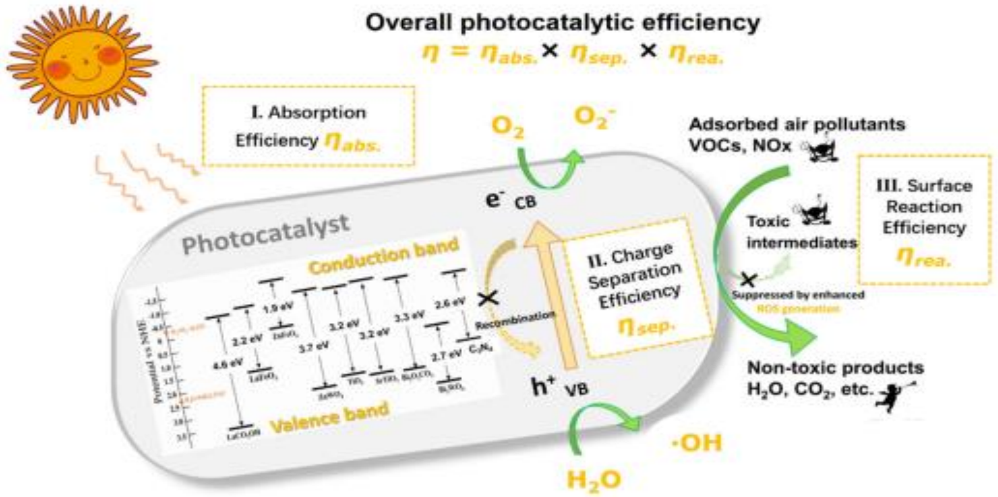


Figure 9. Scheme of environmental remediation principle by semiconductor photocatalysis

Figure 9 also depicts the semiconductor photocatalysis principles relevant to the removal of environmental pollutants. As demonstrated, the efficiency of charge separation and light absorption play a role in the functional nanomaterials' overall photocatalytic performance.

Adsorption Method

Under ambient conditions, the removal of gaseous pollutants from the air can be achieved through the non-destructive adsorption process, involving non-covalent physisorption and covalent chemisorption processes. Various factors significantly impact sorption capacity, including the molecular structure, polarity, acidity, and wettability of the target pollutants; pore size/distribution and surface functional groups of the sorption materials; the physical structure and chemical composition of the sorption materials, including their specific surface area; and adsorption conditions, primarily temperature and humidity (Cao et al., 2021).

Metal oxides, spinels, perovskites, zeolites, carbonaceous material, and heteropolyacids have been identified as key sorbing materials with high absorption capabilities for NOx removal, as indicated in the research conducted by Gomez-Garca et al. (Gómez-García, M. A., Pitchon, V., & Kiennemann, A., 2005). Because of the covalent connections that formed between the metal ions and NO, transitional metal oxides (Co, Cu, Ni, Fe, and Mn) were shown to have the best NO absorption [40–42]. Alkaline earth and rare earth metals, such as Ce, La, Ba, and Na, had relatively little NO adsorption, in contrast .Excellent NO uptake performance was also demonstrated via zeolite exchange with transitional metal ions and carbonaceous materials treated with iron or copper oxides.

Classification of Air Filtration Material

Filter materials come in a variety of types because different settings have varied demands of them. For instance, high-temperature environments call for materials that can withstand the heat, while high humidity calls for hydrophobic air-filter materials. The following two categories generally correspond to how air-filter materials have evolved over time

Traditional Filter Material; Particulate and micron air filters, such as bamboo charcoal bags and masks, make up the majority of conventional air filter materials. The major reasons why particle-filter materials are employed are their low cost, high temperature resistance, and corrosion resistance. The efficiency of materials in the field of air and water purification is crucial, especially for masks and filters. Roche et al. (2019) developed novel electrospun polyacrylonitrile (PAN) nanofibrous membranes for point-of-use water and air cleaning. These membranes were created using heat-press lamination under various conditions. Air permeability and burst-pressure testing were employed to select membranes for point-of-use air and water cleaning. The electrospun PAN nanofibrous membranes exhibited exceptional air-dust filtration effectiveness, surpassing 99.99% in the PM0.3 to PM2.5 range. Additionally, cross-flow filtration tests revealed outstanding water permeability exceeding 600 L/(m2hbar) after 6 hours of operation [Roche, R., & Yalcinkaya, F. (2019). Electrospun Polyacrylonitrile Nanofibrous Membranes for Point-of-Use Water and Air Cleaning. ChemistryOpen]. **Modern Filter** The modern Filter nowadays uses such Electro spun Air filter materials due to their high selectivity, porosity, low-pressure drop, and pore connectivity. Cui et al. [55] produced air-filtration fibre membranes in 2021 by electrospinning TA and PVA-124. The air passage resistance is 35 Pa when the filtration efficiency of PVA-TA nanofiber membranes is set to 99.5%. In terms of overall performance, the membranes also did well. Modern filter materials, including fibre filter membranes utilised in high-temperature environments, are also relatively developed in terms of performance optimization. A PI-POSS@ZIF hybrid filter, utilizing electrospinning technology, was developed with a high PM0.3 filter effectiveness of 99.28% and an air passage resistance of 49.21 Pa at elevated temperatures of 280 °C (Zhou et al., 2022). In order to increase the high-temperature resilience, some ZIF was added during the hybridization process

Table 3

Category	Example	Advantages	Disadvantages
Porous Membrane filter Material	CS/PVA PVDE/PEG PES PVDF/SiO2 PAN/F127	1.High filtration efficiency 2. Small aperture	1. Low porosity 2. Poor hole connectivity 3. High air resistance 4. High energy consumption
Granular Filter Material	Coal ash, Diatomite, activated carbon, volcanic rock	1 High temperature resistance 2 Chemical corrosion resistance 3. Low cost	1. Low filtration efficiency 2. High air resistances 3. serious deficiencies in the filtration of the particules with particle sites
Micron Grad Filter Material	Ultrafine glass fiber air-filter materials	1. Hightemperature resistance 2. Corrosion resistance 3. Mechanical Operatio	1. Smooth and brittle surface 2. Difficult process 3. low bonding strength with base material.
	Melt-blown electrets mcron-fiber air-filter materials (PP,PLA,PE	1. Charge storage capacity 2. High filtration efficiency	1. Limited and easily decayed charge storage capacity 2. Filtration efficiency greatly affected by the charge storage
Electrospinning Nanofiber Filter Material	PP, PCL, PAN, PVDF Modern Filter Material	1. Small aperture 2. Uniform fiber diameter 3. Good tunnel connectivity 4. High Porosity	1. Low production capacity 2. Industrial production has not been fully achieved

Functional Filter Materials	AgNPs PP/ PVDF/PVA/ZIF-8 PI/ZIF-8	1. High filtration efficiency 2. Strong addition ability	1. Industrial production is difficult 2. High cost

V. Recent Advances of Nanomaterial for Air Filtration

The utilization of nanomaterials for air filtration has been a subject of extensive research, offering promising solutions to combat air pollution. One approach involves employing nano-catalysts with enhanced surface areas to act as catalysts in gaseous processes. These catalysts facilitate the conversion of hazardous vapors into safer gases, addressing pollutants emitted from sources like automobiles and industrial plants (Chen et al., 2022). Another strategy involves the use of nanostructured membranes with minute pores for the removal of specific gases like carbon dioxide or methane from exhaust emissions.

Nanoparticles exhibit unique characteristics and a large surface area, making them valuable for pollution control methods. Nanotechnology leverages these features, utilizing nanomaterials as catalysts, adsorbents, sensors, and membranes/nanofilters. This advanced treatment strategy is pivotal in reducing and remediating air pollution. Given the current scenario, maintaining air quality has become crucial for public health and the sustainable growth of humanity. Various control and treatment strategies are being developed to mitigate the threats posed by harmful gases to the environment and human health.

Among these strategies, air filtration stands out as a key method to protect individuals from particulate matter (PM) pollution. The increasing demand for air filters is driven by constant innovations in science and technology (Vijayan et al., 2015). Over the past three decades, extensive research has been conducted on air filtration, a highly promising and efficient approach for PM removal and reducing air pollution. The significance of air filter membranes cannot be overstated, as they play a crucial role in determining filtration efficiency and results. This field has witnessed vigorous development over the last two decades, reflecting the ongoing efforts to enhance air quality and mitigate the impact of air pollution. Additionally, the development of filtration technology along with the filter membrane has been promoted by the emergence of new materials which exhibit excellent physical and chemical properties. In light of this, numerous PM filtration systems and materials have been investigated. The nanomaterial based air filtration membrane is quite acceptable in the modern day among the different air filtration strategies that have been considered. So, we looked into these here.

Nanofiber /Nanofiber membrane

In the air filtration sector, activated carbon and fibreglass are frequently employed. The science of nanotechnology is expanding in a very amazing way. One of the rare materials that is an order of magnitude smaller than typical fibres is nanofibers. Nanofibers are a desirable material for various applications, including filtration of air, energy, and healthcare because to their high surface-to-volume ratio, low resistance, and improved filtration efficacy. Recent developments in the elimination of airborne bacterial contaminants, Particulate matter PM10 and PM2.5, nanoparticles, and volatile organic compounds (VOC) are discussed. Additionally shown are nanofibers' aerosol filtration capabilities. The use of nanofibers in protective gear and their enhanced activity as a result of their small size are highlighted.

Recent research has looked on the air filtration properties of PAN nanofibers. During field experiments, PAN nanofillers were found to be more than 95% effective at removing PM2.5 pollutants from hazardous air (PM2.5 index > 300). PAN's chemical structure, which has a large dipole moment, allowed it to remove more single fibres and nearly five times as much particle pollution.

Micro/Nanosize particle capturing mechanism

Chau-sen and his group has Fibrous filters are easy-to-use, reasonably priced, and effective tools for eliminating submicrometer particles from gas streams. Fibrous filters have been used in a variety of applications, including disposable respirators, industrial gas cleaning equipment, cleanroom air purification systems, automotive cabin air filters, and indoor air purifiers. This is because fibres can be made of a wide range of materials, including cellulose, glass, plastics, ceramics, or metals. Additionally, they have been used to gather aerosol particle samples for chemical investigation.

A pad of loosely coiled fibres that is often perpendicular to the direction of aerosol movement makes up a fibrous filter. The metrics used to evaluate a filter's performance are collection efficiency and pressure drop. High collection efficiency and minimal pressure drop are desirable characteristics in a filter.

The percentage of entering particles that are collected by the filter called the collection efficiency

$$E = \frac{N_0 - N}{N_0}$$

where N_0 and N are the input and exit particle number concentrations, respectively. As an alternative, the efficiency can be determined by the mass concentration of the particles. Because it is a smaller value and hence exhibits a greater relative change than the collection efficiency, the penetration P (= 1 E) is a clearer indicator for a high-efficiency filter. For instance, P decreases from 10 to 1% when E rises from 90 to 99%.

Capture Mechanism

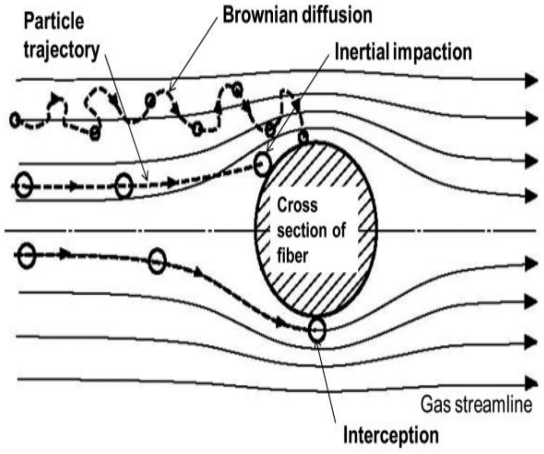
Several mechanisms, including inertial impaction, Brownian motion, interception, gravitational settling, and electrostatic forces, may work simultaneously as an aerosol stream approaches a fibre to cause particles to deposit on the fibre. (Figures 8 and 9).

VI. Manufacturing Of Nano Filters

In most cases, the investigations use a polyester filter. It is commonly 4.5 mm thick. photos taken of a filter cross-section were examined using a scanning electron microscope. Porosity measurements are typically 0.882 0.003 on average. The average filter diameter was used as a reference for all of the filter in most cases, the investigations use a polyester filter. It is commonly 4.5 mm thick. photos taken of a filter cross-section were examined using a scanning electron microscope. Porosity measurements are typically 0.882 0.003 on average. The average filter diameter was used as a reference for all of the filter bed. The particle-laden gas (urea solution) can be produced using the TSI Electro spray Aerosol Generator use This device is capable of producing monodisperse nanometric particles, at107 particles per cubic centimeter at a flow rate of 0.2 to 2.5 liters per minute. By counting, the filters' efficiencies may be determinedutilizing a TSI Condensation Particle Counter, comparing the particle counts before and after the filter. The tests should be conducted at ambient temperatures of 25 °C and gas velocities ranging from 0.03 to 0.25 m/s.

Even in a stationary gas with a fixed particle concentration, this movement occurs. Therefore, the underlying physical idea here is distinct from the diffusion mechanism, which depends on a concentration gradient. When a particle truly occupies a volume larger than its own [see Fig.1], the chaotic movement can be described as having an "effective" diameter. Therefore, if this "effective" diameter—rather than the particle's actual diameter—is taken into consideration in the interception parameter, the particle will be caught when it gets close to the fiber surface. The average dislocation of the particle during the period it spends close to the fiber surface, which is a function of the fiber diameter and of the gas, can be used to estimate this "effective" diameter.

These urea particles will create a coating on the walls of the nano filter, which will be ready for use in controlling NO & NO2 emissions for industrial purposes after cooling at a certain temperature. The figure's brown and blue area represents the abrupt drop in NOX particle concentration in the contaminated air.



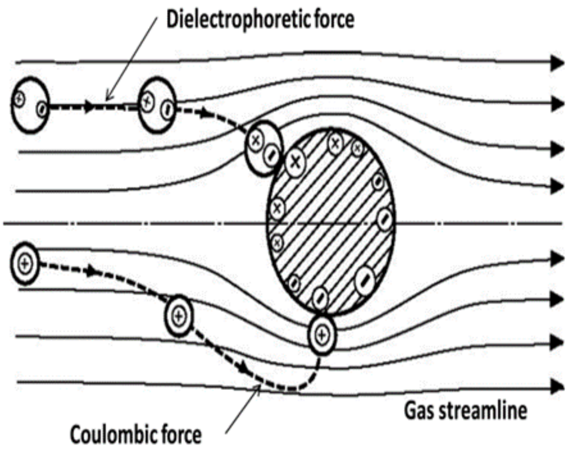


Figure. 8 Convective Brownian diffusion, interception, and inertial impaction particle collection.
Figure. 9 Particle collection by Coulombic and dielectrophoretic forces.

The first four methods are mechanical capture mechanisms because they don't rely on electrostatic forces.When a particle strikes a fiber, inertia causes it to break off from the original gas streamline. A particle's finite size causes it to be intercepted, which causes deposition when it approaches the fibre surface by just one particle radius even though it remains on the initial streamline. The Brownian motion can be powerful enough to propel particles smaller than a few tenths of a micrometre from their originating streamlines to a fibre. If the aerosol stream falls downward, gravitational settling can aid in particle collection, but the effect is minimal for nanoparticles.

Controle of Air Pollution via membrane technology

Various membrane types have been employed to reduce indoor and outdoor air pollution. Polymeric materials, including polyacrylonitrile (PAN), polyimide (PI), polyurethane (PU), polysulfone (PSf), and polypropylene, are used to make the majority of membranes (PP). The use of various membrane technologies, such as nanofibrous membrane, microporous membrane, and other membrane kinds, will be covered in this subchapter.

Nanofibrous Membrane for Air Filtration techniques

Various processes can be employed to create nanofibers, including drawing, self-assembly, melt-blowing, conjugate spinning (sea-island technique), chemical vapor deposition, phase separation (sol-gel process), multi-component fiber spinning, and electrospinning [18]. Electrospinning, in particular, is a versatile and popular method for producing air filter media [19]. While some research explores biopolymers [Anusiya & Jaiganesh, 2022], electrospun materials made from synthetic polymers remain favored for air filter media preparation [Kadam et al., 2016].

Recent developments involve functionalizing electrospun nanofibers with additives to simultaneously filter out particulate matter (PM) and collect gaseous pollutants [Al-Abduljabbar & Farooq, 2023]. The scientific community is leveraging compiled data on electrospun nanomembranes to guide the creation of improved electrospun filters capable of capturing various air contaminants. This approach holds promise for advancing air filtration technologies and addressing the complex challenges posed by air pollution. Vinod and his group revied and focuses on the many polymeric materials that can be electrospun to create nanofibre membranes for the filtration of particulate matter and gaseous pollutants, as well as the additives that can be added to enhance those membranes' performance. The information in this paper will be helpful in evaluating the effectiveness of electrospun filter material against particulate matter and gaseous pollutants using the proper characterization methods. Also addressed are the difficulties in the research and the potential of electrospun materials to filter various air contaminants in the future

VII. Electrospinning Techniques

Electrospinning is a rapid and efficient method for producing nanomaterials within the dimensional range of tens of nanometers to twenty micrometers. Initially developed in 1934 for synthesizing one-dimensional materials, electrospinning has demonstrated its applicability to a wide array of materials, including polymers, hybrid composites (organic/inorganic), and inorganic materials, to generate uniform one-dimensional structures [Baig et al., 2021].

The technique involves the production of ceramic nanofibers (NFs) from electrospun organometallic NFs by heating in an oxidizing environment. Similarly, metal NFs or nanowires are created by heating NFs containing metal atoms in a reducing environment. Hydrocarbon NFs, like polyacrylonitrile, can be transformed into carbon NFs through low-temperature oxidation followed by heating in an inert atmosphere.

Polymer membranes exhibit significant potential for air purification, and electrospinning stands out as a straightforward, versatile, and cost-effective method for creating continuous nonwoven nanofibers from various polymer solutions [Xue et al., 2019]. The structure and size of these nanofibers can be tailored using electrospinning, a "top-down" preparation method, by adjusting electrospinning conditions and polymer formulations. Electrospinning has gained popularity for its ability to produce high-quality continuous fibers with diameters ranging from sub-micrometer to nanoscale.

Consequently, polymer membranes manufactured by electrospinning are highly recommended for air-filter media due to their effectiveness [Henning et al., 2021]. However, further detailed research on electrospinning technology is warranted for a comprehensive understanding of its capabilities and limitations. Electrospinning produces ultrathin fibres from a wide range of materials, including metal oxide/ceramics like CuO, Fe_2O_3, TiO_2, and NiO, mixed metal oxides (37–39)62-63 like $NiFe_2O_4$, $TiNb_2O_7$, and $LiMn_2O_4$, composites 64-66 like PVA/TiO_2, Carbon/SnO_2, 35 Graphene/TiO_2, Nylon-6/gelatin Collagen/hydroxyapatite, polymers [43,44] such polyvinyl alcohol (PVA), polyacrylonitrile (PAN), polyvinylidene fluoride (PVDF), polyvinylpyrrolidone (PVP), polyethylene glycol (PEG), polystyrene (PS), and materials based on carbon are examples. It may be easy to create hierarchical nanostructures using electrospinning and controlled calcinations, which are challenging to create using other techniques.

Principal and equipment of Electrospinning

Electrospinning is a cutting-edge technique used to produce fine fibers from polymer solutions or melts by harnessing electrostatic forces [Bhardwaj & Kundu, 2010]. This method generates fibers with a reduced diameter (ranging from nanometers to micrometers) and an increased surface area compared to conventional spinning processes. Similar to electrostatic precipitators and pesticide sprayers, electrospinning relies on the dominance of strong mutual electrical repulsive forces over weaker surface tension forces in a charged polymer liquid. The process employs an electric field to stretch a polymer, creating fibers [Bhardwaj & Kundu, 2010].

The electrospinning process operates based on the interaction between the medium and the electric field, following a "top-down" method that is straightforward, effective, affordable, and versatile for producing nanofibers. Four essential tools are required for this process: a high-voltage generator, an infusion pump for precise control of solution or melt distribution, a metal needle or spinneret, and a collector [Ning et al., 2021].

The electrospinning procedure involves three key steps. First, the injection pump causes the polymer solution to flow out of the spinneret, forming spherical droplets shaped by gravity, thrust force, and surface tension. Second, as the high-voltage generator is connected, the droplet's surface accumulates charges, and under the influence of the electric field force, the droplet transforms from a sphere to a cone. The Taylor cone, formed when the Coulomb force surpasses surface tension, produces a straight jet [Rosell-Llompart et al., 2018]. The process enables the rapid stretching and drying of the working liquid and is divided into three parts: Taylor cone, linear jet, and unstable region [He et al., 2022].

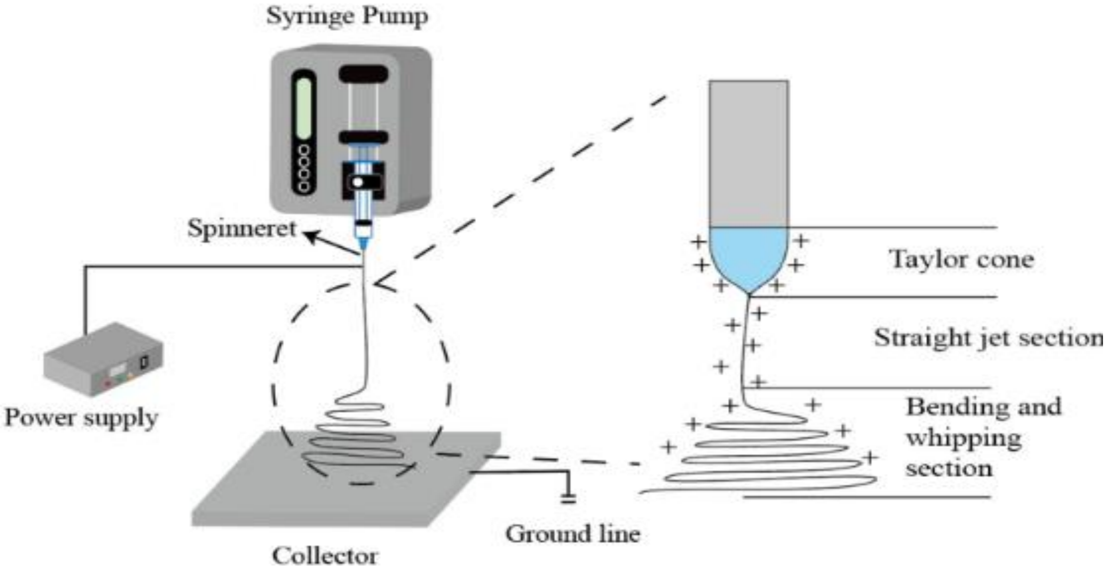


Figure Electrospinning equipment and process schematic.[Gakidou et al., 2017]

In the third stage of the electrospinning process, the linear jet experiences instability due to the rapid evaporation of the jet's menstruum. The interaction between the positive charge and the electric field on the surface leads to whipping and bending, ultimately resulting in the formation of polymer fibers. Electrospinning is a fiber processing method known for its straightforward procedure and high potential. It is widely employed due to its ability to create various fiber architectures, adaptable preparation designs, simple experimental conditions, minimal experimental cost, high fiber yield, and the broad applicability of materials [Wen et al., 2020].

Nanofiber Structure, properties and filtration membrane

Polyacrylonitrile (PAN) nanofibers have been extensively studied for their remarkable mechanical strength, flexibility, and the ability to be functionalized and integrated [Ali et al., 2021]. Achieving efficient PM2.5 capture requires the fibrous membrane to have the appropriate pore structure. The pore structure of the fibrous membrane is crucial for efficiently collecting PM2.5 particles while simultaneously reducing airflow resistance. Resolving the trade-off between the filtration membrane's pressure drop and filtration efficiency underscores the importance of the pore structure [Wang et al., 2022].

Nanomaterial based Filtration membrane for Air Purification

Nanomaterial-based filtration membranes, particularly those produced by electrospinning techniques, have proven effective in removing particulate matter due to their small pore sizes and high specific surface areas [Ali et al., 2021]. These membranes enhance filtration efficiency by trapping dust particles on their surfaces [Wang et al., 2022]. The effectiveness of air purification membranes lies in their ability to retain pollutant particles while allowing air transport. Additionally, these membranes should meet criteria such as long lifespan, minimal pressure drop, ease of handling and installation, and cost-effectiveness. Electrospun membranes, with their interconnected pore structure, tunable porosity, controlled morphology, and high surface area to volume ratio, are gaining attention as a key solution to meet these criteria for efficient air filtration performance [12,13]. Figure 1 illustrates a typical electrospun membrane with a membrane support.

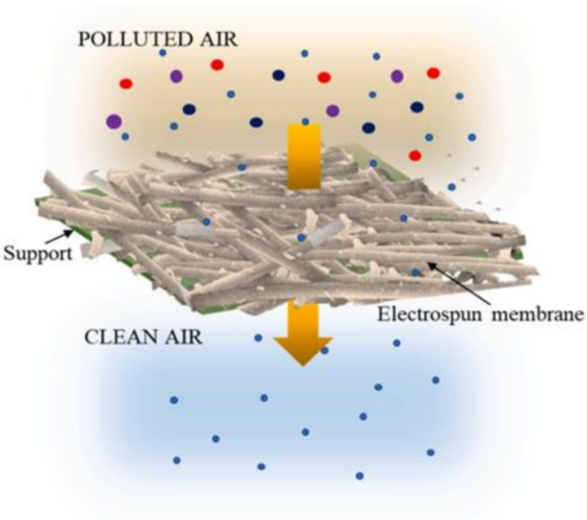


Figure A typical electrospun membrane for air filtration is graphically shown.

Various research groups have contributed significantly to the development of nano-based membranes for air filtration. Bortolassi et al. (2019) aimed to produce and evaluate novel silver/polyacrylonitrile (Ag/PAN) electrospun fibers deposited on a nonwoven substrate for air filters, demonstrating efficient nanoparticles removal and antibacterial activity [Bortolassi et al., 2019]. Ji et al. (2022) fabricated polyetherimide (PEI)/zeolitic imidazolate framework-67 (PEI/ZIF-67) nanofibrous membranes, exhibiting consistent, high-efficiency PM filtration capability under challenging conditions [Ji et al., 2022]. Another contribution comes from Zhong et al. (2012), who developed a polyurethane/silicon nitride (PU/Si3N4) electret nanofiber membrane with a minimum diameter of 350 nm, showing improved performance compared to other membrane compositions [Zhong et al., 2012]. Wu et al. (2022) prepared a multifunctional polyetherimide (PEI) nanofiber membrane decorated by Cu-based metal-organic framework (CuMOF) for high-efficient filtration/separation in complex environments [Wu et al., 2022]. Daniela and her group (2021) developed novel PET electrospun micro and nanofibers with varying diameters, achieving a high collection efficiency of up to 99% for nanoparticles with low-pressure drops, suggesting a high-quality filter medium for gas filtration [Daniela et al., 2021]. Additionally, Gao et al. (2020) contributed to enhanced air filtration performance under high-humidity conditions through electrospun membranes with an optimized structure [Gao et al., 2020]. Each of these studies has played a crucial role in advancing the field of air filtration using nano-based membranes. bead-on-string hydrophobic polyvinyl chloride (PVC) nanofiber filters are used to gradually remove particulate matter from a high relative humidity environment of 90%–95%. The newly developed hydrophobic filters have much improved stability and equivalent separation performance to the hydrophilic ones. Due to the vast voids and hydrophobicity created by the beadon-string structure, the filtration performance can be further enhanced. Such hydrophobic PVC filters may offer promising options for practical air purification, particularly during rainy seasons. Wenxiu at.el create an electrospun nanofiber membrane with high performance filtration and antibacterial properties. The antibacterial properties of the Ag nanoparticles (AgNPs) obtained by reducing AgNO3.

We have applied a number of different techniques for air purification, including adsorption, disinfection, photocatalysis, filtration, room-temperature catalysis, and passive trapping. Other than adsorption, filtering is the most effective method for removing airborne particles from the atmosphere. 99.9% efficiency is achieved by using filtration techniques and constructing an air filter membrane based on nanomaterials. Although we have utilised a variety of methods to create membranes, electrospuning is the most acceptable. Table 1 provides an overview of some recent developments in nanofibrous membrane technologies and their performance.

Table Air Filtration Application of Nanofibrous Membranes

Fabrication Method	**Fiber Materials**	**Application**	**Characteristics of Nanofibrous**	**Performance of Nanofibrous Membrane**	**Ref**
Melt-blown method	Polypropylene	Removal of Aerosol	Fiber Diameter: 260 nm Avrg pore sizes = 6--10 m Thickness: 0.5mm	- Air Permeabilty:15-17cm3/cm2/sec - Presssure drop: □55 Pascale - Filtration efficiency: 80 %	38
Melt-blown via [Die: L/D 50]	Unspecified Polymer	Dioctylphalate (DOP) Aerosol Removal	Fiber Diameter: 0.3-1.5 µm	- Permeability of Air: 500-1000cm3/cm^2.sec - Filtration efficiency : 40-50%	40
Melt-Blown	Polypropylene	Filtration of Aerosol	Multi layer Fibrous Membeane Fiber diameter: 1.1 µm Porositry: 0.98 Thickness: 5.5mm	- Quality Factor : 0.05/Pa - Fraction Efficiency: □0.8	58
Electrospinning	Polyethersulfone/ barium titanate	Particulate matter (Diameter <2.5µm)	Maximum Pore Size: 42µm Thickness: 30.7 µm Porosity: 52.3 µm Filter Weight : 4.32 g/m2	Air Permeability : 743 mmsec$^-$ Pressure Drop: 67 Pa Filtration efficiency: 99.9%	58
Electrospinning	Polyacrylonitrile Mw: 150KDa	Filtration of Aerosol	Fiberdia.:420nm Filterweight:1.15-1.8g/m^2	- Pressure drop: 30 Pa at face of Velocity 10 cm/sec - Quality factor : 0.1 for the particle with diameter 30nm	59
Electrospinning	4,4- Methylenebis (Phenylisocyanate) MD- Based Polyurethane	VOCs adsorption and desorption	Fiber Diameter: 300 nm	- Absorption and desorption is completely reversible - Sorption capacity of Toluene :40%	60
Electrospinning	Polyamide	By the Car exhaust remove PM2.5 Particles	Operating Temperature: 25-270oC	- PM2.5 Index>300 - Quality Factor: 0.08 - Pressure Drop at the Flowrate of 0.2 m/s : 45 Pa	61
	Polyvinylpyrrolidone		Operating Temperature: 25-150^{o}C	- Removal Efficiency: 94% - Pressure Drop at the Flow rate of 0.2 m/s : 71 Pa - Quality Factor =0.04	
	Polyacrylonitrile		Operating temperature: 25-230 ^{o}C	- Removal Efficiency =99% - Pressure Drop at the Flowrate of 0.2 m/s : 71 Pa - Quality Factor = 0.10	
Electrospinning	Ammonium tetrathiomolybdate/ polyacrylonitrile Composite	Polydisperse aerosol of solid KCL nano/micro particles (0.3-12 □m)	Mean fiber diameter= 331 Packing density = 0.03 Basis weight = 4.3 g/m2	- Particle 300 nm filteration: Filtration efficiency : 91% - Filtration efficiency : 94% for PM2.5 - Pressure diameter : 101 pa	62
Coated on non-woven mat and Electrospinning	Polyethylene Oxide	Dust (0.6-180 micro meter)	Fiber diameter = 85 nm Non-woven mat coated Total thickness = 2572µm Membrane pore size = 40.44 µm	- Filtration efficiency : 78% - Pressure drop: 28 Pa	46
Spunbond Techniques	PE/PP BCS	Aerosol removal	Thickness: 27 Fiber Diameter : 325 nm Filter weight : 200 g m^2	- Filter efficiency : 98.94% - Pressure drop: 37.92 Pa - Holding Capacity: 10.87gm^{-2}	Imp1-11
Electrospinning	Nylon 6	Capturing Particle >50nm	Fiber Diameter : 50-150 nm Operating temp:25 ^{0}C	- Filtration efficiency: 92% - Feed rate : 10, 15, 50 µl/min	Elect tech

Electrospinning nd Hydrogen Bond crosslinking	Polyvinyl alcohol (PVA) - tannic acid (TA	particulate matter 1.0		- Filtration efficiency :99.5% - pressure drop : 35 Pa - Quality factor : 0.15 Pa-1	cui2 021
Electrospinning	poly(lactic acid)(lactic acid) (PLA	Aerosol particles	Fiber diameter; 260 nm	- Filtration efficiency: 99% Pressure	58ta ble

VIII. Carbon nanomaterials (CNMs): forms and mode of action

Three main groups of organic carbon nanomaterials—fullerene (Kroto et al., 1985), carbon nanotubes (CNTs) (Iijima, 1991; Iijima and Ichihashi, 1993), and the graphene family—have a variety of uses based on their unique functional processes (Novoselov et al., 2004). Fullerene demonstrated a lower intensity in the adsorptive activity compared to the other two CNM classes, but both CNTs and the graphene family were found to possess a high adsorption capacity that enables them to remove various contaminants, particularly in air treatment (Bergmann and Machado et al., 2015; Tonel et al., 2015). (See Fig. 2). Because of their various pore diameters, CNTs can, for instance, separate methane from carbon dioxide in an exhaust system. They then capture these greenhouse gases, which are frequent air pollutants in areas with coal mining and energy production. Studies have shown that graphene oxide and its reduced form are effective at treating a variety of pollutants, including heavy metals, synthetic colours, and antibiotics (Chowdhury and Balasubramanian, 2014). (Li et al., 2013).The use of CNM in physical/chemical treatment as well as the creation of effective, sensitive, and selective adsorbent devices for environmental sanitization are supported by a number of features. CNMs are distinguished by chemical stability, low density, structure diversification, and responsibility for being generated on a wide scale, according to many research.

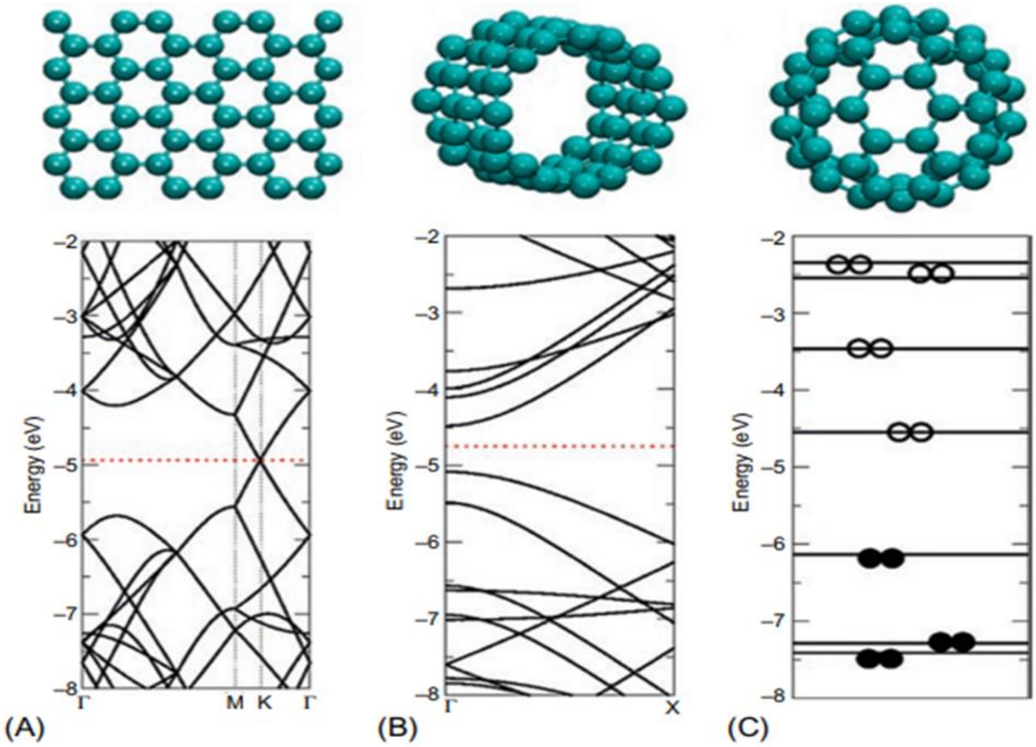


Figure .5 Carbon nanomaterials (CNMs) come in a variety of forms with different electrical levels. The Fermi energy is represented by the horizontal red dashed lines. Graphene, carbon nanotubes (CNTs), and fullerene, in that order.

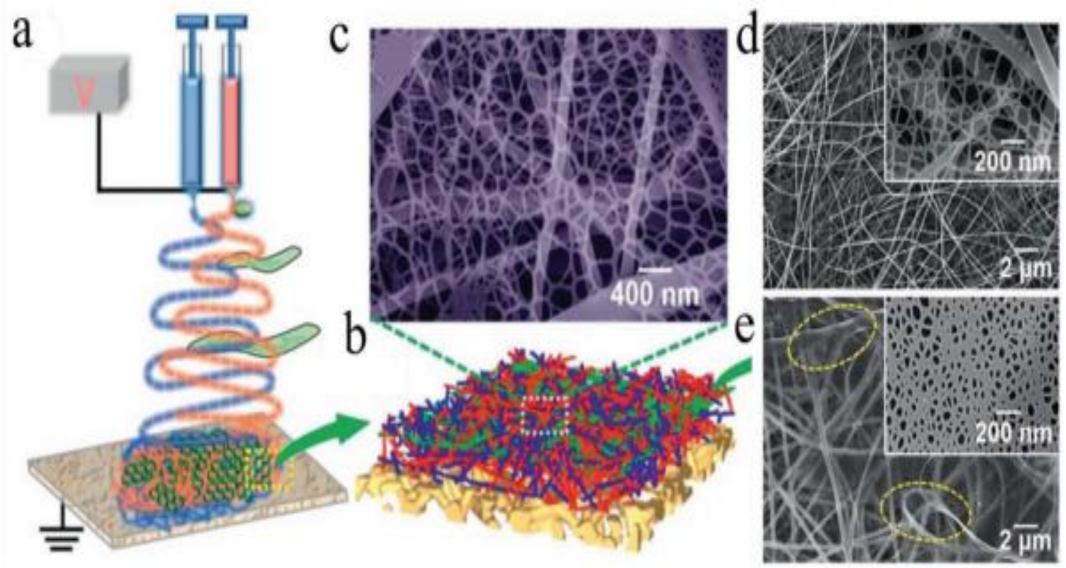
The investigations on water treatment and other remediation procedures (Machado et al., 2011, 2012; Prola et al., 2013; Wang et al., 2011) were made possible by the optimal textile features regarding their average pore diameter, total pore volume, and high surface-to-volume ratio. The surfaces of CNM structures also have significant adsorptive sites and are known to be amphoteric, meaning they can be protonated or deprotonated (positively or negatively charged). This has the potential to increase the number of oxygen-containing functional groups on the CNM surface, which improves their chemical adsorption ability (Gupta and Saleh, 2013; Ren et al., 2013).

Materail Used for air filter membrane

Pore size and packing density must be optimised for the systematic study of PM purification materials since they have a significant impact on the penetration and adherence of the target fine particles (dictated by the resistance to air flow)

Fabrication of Nanofibrous Air Filter membrane

The creation of an amphiphilic PVDF-g POEM double comb copolymer-based nanofibrous air filter membrane involved the use of an electrospinning machine equipped with an indoor-box high electric field generator and a grounded collector. The double comb copolymer solutions were initially drawn into a syringe connected directly to a multi-nozzle system with one or five metallic spinneret tips (25G) to achieve the appropriate polymer mass area loading. The electrospinning process involved carefully controlling the double comb copolymer jets to emerge from the tip and gather on a collector positioned 16 cm away. The feed rate was maintained at 1 mL/h, and a high DC voltage of 28 kV was applied. For air filtration effectiveness investigations, the nanofibers were electrospun directly onto a PET membrane substrate. The entire electrospinning procedure was conducted at a temperature of 25 °C and a relative humidity of approximately 20% [Moon et al., 2021]. Zhang et al. combined electrospinning/netting, a staple-fiber-intercalating procedure, and microwave heating to produce microwaved polyamide-6/poly(mphenyleneisophthalamide)-nanofiber-net (PA-6/PMIA NFN) membranes for efficient air filtration. 1D nanofibers and 2D Steiner-tree nanonets made up the PA-6 NFN membrane. The PA-6 NFN membranes that were created after embedding PMIA staple fibres showed microwave fluctuation and high-loft architectures. The PA-6/PMIA NFN membrane could filter 300-500 nm airborne particles with an efficiency of 99.995%, a low pressure drop of 101 Pa, a desirable QF of 0.1 Pa-1, and a large dustholding capacity of >50 g m-2, which meet the requirements for treating the real PM pollution. These properties are made possible by the extremely small pore size of the 2D nanonets and the large surface area offered by the microwaved structures.



Figure; Fabrication method for fibrous N6-PAN nanofiber-net air filters. The production of N6-PAN NNB composite membranes on a nonwoven substrate is depicted in the following diagram: a. b) A nonwoven substrate and an N6-PAN NNB membrane are used to represent the filter media. d) A typical membrane FE-SEM picture. FE-SEM images of N6 nanofiber/net membranes at 12.5 wt% (d) and 17.5 wt% are shown in figures d and e. (e). Images that have been magnified are inset. Reproduction permitted. [7] 2015 Royal Society of Chemistry Copyright

The weight and density of the fibres are also taken into consideration as important elements impacting how well an air filter can purify the air. A nylon-6-PAN nanofiber-net binary (N6-PAN NNB) membrane with a very low weight was created by Wang et al. Different membranes were produced by varying the solution concentration, as shown in Figure 5a, which also illustrates the fabrication process. The structure and filtration properties were significantly influenced by the bulk solution properties that were controlled by altering the N6 content, as shown in Figures 5d, e. An N6-PAN NNB-membrane air filter with a 2/2 N6/PAN ratio demonstrated great filtration efficiency (99.99%) and a significant QF of 0.1163 Pa1 even at high air flow rates.

By electrospinning silicon dioxide nanoparticles (SiO2 NPs) modified with -glycidoxypropyltrimethoxysilane (GPS) as the charge enhancer and polyvinylidene fluoride (PVDF) as the matrix polymer, an air filtration material with a remarkable electrostatic effect is created, according to Xingxing and his team's research. The idea behind it is that GPS-modified SiO2 NPs can be evenly dispersed throughout PVDF fibres, producing a lot of stable interfacial charges. The resultant PVDF/GPS@SiO2 nanofibrous membrane exhibits amazing electret effect with a surface potential of 12.4 kV and high filtering performance with a quality factor of 0.14, which has never been reported before thanks to the monodisperse state of GPS@SiO2 NPs.

Dan Lv and his group has been Synthesised In this study, environmentally friendly thermal cross-linking and green electrospinning were used to create nanofiber membranes made of poly(vinyl alcohol) (PVA) and konjac glucomannan (KGM) that were loaded with ZnO nanoparticles. The resulting fibrous membranes exhibit higher photocatalytic activity and antibacterial activity in addition to having a highly effective air-filtration system. The ZnO@PVA/KGM membranes' filtering effectiveness for ultrafine particles (300 nm) was better than 99.99 percent, outperforming commercial HEPA filters.

Due to its effective Brownian diffusion and interception mechanism, nanofibers may efficiently catch very small nanoparticles in the air stream. Maze et al. revealed using simulation data that increasing the air flow temperature and reducing the fibre diameter of ENMs can improve their filtering effectiveness for nanoparticles.In a different study, Wang et al. compared nanofiber filters to regular fibreglass filters for the filtering of nanoparticles. [3]They showed that regular fibreglass filters function better than nanofiber filters for particles larger than around 100 nm, while nanofiber filters do not perform better than conventional fibreglass filters for particles smaller than 100 nm.

Here, we present a green electrospun and UV-cured chitosan/poly (vinyl alcohol) air filtering membrane that is user-friendly, multifunctional, and bio-based. With this environmentally friendly technique, toxic organic solvents that can leave behind residual chemicals that cause human health harm are avoided. To boost the efficacy of filtration, superhydrophobic silica nanoparticles are specifically added to the nanofibers to create a rough surface. In order to fulfil the goal of antibacterial treatment, Ag nanoparticles (NPs) are also created on the surface using UV reduction of AgNO3.

Using a one-step melt-blown fabrication process, Nanping Deng and his group successfully created a multi-scale micro/nano fibre membrane based on polypropylene and polystyrene for high performance air filtration.And they were successful in obtaining nonwovens that simultaneously demonstrated improved filtration performance and pressure drop reduction, including high air filtration efficiency of 99.87 percent, low pressure drop of 37.73 Pa, and acceptable quality factor of 0.18 Pa^{-1}.[7] ref pr By using a straightforward one-step approach to successfully prepare micro/nanofibres, new filtration and separation materials to lessen air pollution may be created.[7]ref pr

Here, a one-step melt-blown process was used to successfully produce the resulting micro/nano fibre membrane made of PP and PS with a striking diameter difference. Fig. 1 depicted a schematic of the detailed preparation method for the hybird membrane.[7]

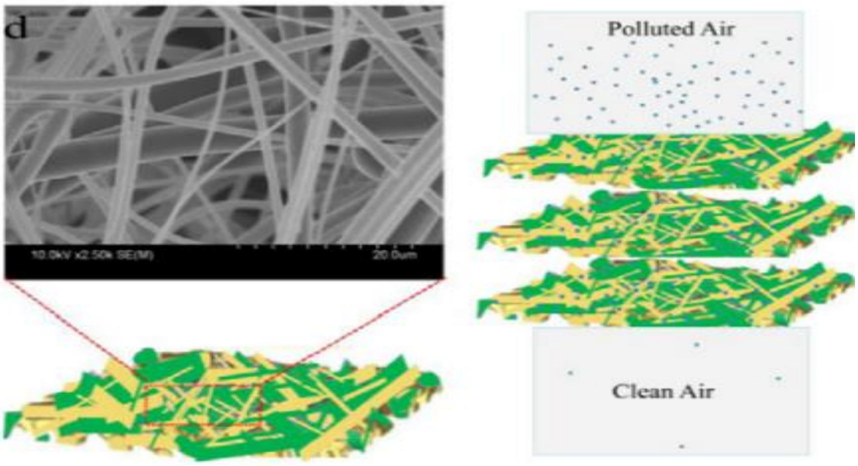


Figure ; Illustration of the idea of a fibre membrane-based multi-scale micro/nano structured filter medium.

As per Fig. The melt-blown nonwovens with PS content of 5 wt% demonstrated a quality factor of 0.18 Pa1 in Figure 7(d), which was higher than that of the other samples, further demonstrating the role of remarkable diameter differences and electrostatic adsorption force in improving the filtration efficiency without increasing the pressure drop. Overall, the PS addition increased the fibrous filtration effectiveness. PP-based membrane's capacity may be significantly boosted with a lot less pressure drop.

Typically, synthetic fibre polymers generated from petroleum wastes are used to make air filter media.Polyamide, polypropylene Polyester, and glass fibre are the synthetic fibre polymers that are most frequently utilised.It is abundantly obvious that synthetic polymer fibres have a number of drawbacks when compared to natural polymer fibres obtained from plant fibres in this study (Manzo et al., 2016). First, they frequently necessitate time-consuming production procedures and are not recyclable or degradable.In the course of production, greenhouse gas emissions are also produced (Sandi et al., 2018). Contrarily, natural fibres like cellulose (Ramesh et al., 2017) have a number of benefits such being simple to obtain because they develop naturally (Wang & Pan, 2015) and requiring low-cost manufacturing procedures (Rehman et al., 2019). Additionally, they are environmentally beneficial and aid in absorbing air pollution (Offord et al., 2016).

Polypropylene(PP) is the homo-polymer that is widely used for production of non-woven fabric. In the manufacture of polypropylene resins, considerable advances have been made. In this paper, thermal behavior of polypropylene granules.

In their study, [Hengzhang Dai et al., 2021]. developed nanofibrous membranes by incorporating Graphene oxide (GO) and polyimide (PI) into a PAN-containing solution. The inclusion of GO and PI significantly enhanced the adsorption capability and thermal stability of the electrospun nanofibrous membranes. These membranes, composed of thin nanofibers, exhibited good airflow permeability, indicating their potential as effective filter materials. In comparison to pure PAN nanofibers and commercially available filtering materials, the PAN/GO/PI nanofibrous membranes demonstrated improved filtration performance, achieving a clearance efficiency of 99.5%, which was 11% and 3.7% higher, respectively. Furthermore, these membranes exhibited a substantial decrease in pressure, with a 79.8% and 37.4% reduction. Importantly, even after thermal treatment at 300°C, the PAN/GO/PI nanofibrous membrane maintained exceptional clearance efficiency at 99.2%

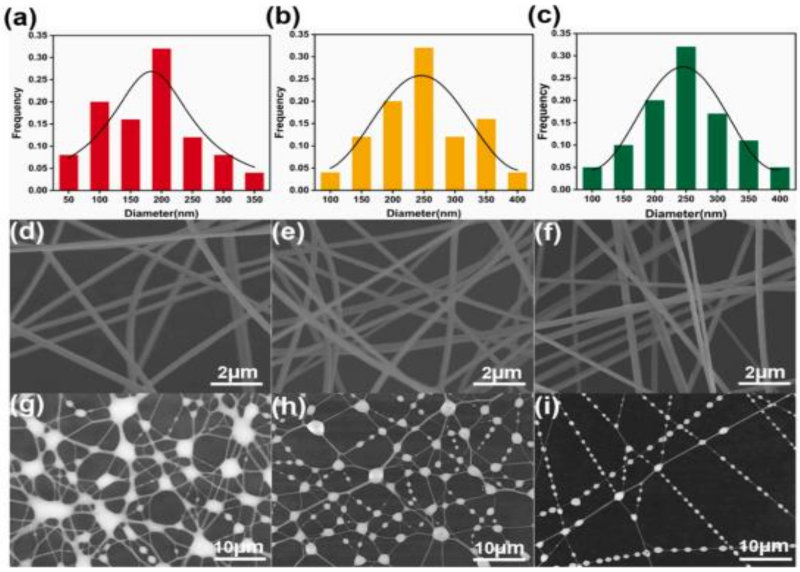


Fig. 2. Diameter statistics of (a) PAN, (b) PAN/GO, and (c) PAN/GO/PI-6 nanofibers. SEM images of (d) PAN, (e) PAN/GO, and (f) PAN/GO/PI-6. SEM images of (g) PAN, (h) PAN/GO, and (i) PAN/GO/PI-6 nanofibers after $PM_{2.5}$ adsorption.

Rashid and his group have successfully proven a simple and efficient method for manufacturing Electrospinning created an electret nanofibrous filter medium with better wearing comfort characteristics. The composite NFMs as-prepared were given a high degree of spontaneous polarisation by $BaTiO_3$ NPs. injection of power and improved stability of the charge storage system, which permit the electret NFMs to capture Electrostatic attraction produces PM2.5. Additionally, the electret NFM showed a significant porosity, and the air and it was discovered that moisture permeability was linearly related to porosity. In addition, 3D computer To learn more about the distribution of the airflow field and the pressure drop of Throughout the filtration process, the NFMs. the NFM1.5 showed greater after being heated to 200 oC for 45 minutes, it had a high level of filtration efficiency (99.99%), a low pressure drop (67 Pa), and a minimal base weight (4.32 g/m2), which solidified its practical applications in personal protective equipment.23, equipment. It was noteworthy that the NFM1.5 showed a steady radiative dissipation capability for cleaning up air pollution.

Applications

1. Electrospun nanofibers for the removal of volatile organic compounds

Electrospun nanofibers for the elimination of unstable natural compounds Electrospun nanofibers had been explored for the adsorption of risky organic compounds (VOC) gifts inside the air by numerous authors [5-7]. Scholten et al suggested that adsorption and desorption of VOC with the aid of electrospunnanofibrous membranes.

(ENMs) became quicker than traditional activated carbon [5]. Cyclodextrins can form non-covalent host-guest inclusion complexes (CD-IC) with numerous molecules which include unsafe chemical compounds and polluting materials. They were included in poly (methyl methacrylate) PMMA ENMs via Uyar et al and tested that VOC which includes aniline, styrene, and toluene may be removed [6]. ENMs have additionally been explored for the adsorption of VOCs in the bio-remedy sewage via Xu et al [7]

2. Antibacterial Nanofiber Air Filters

A novel reusable bilayer fibrous filter consisting of electrospun superhydrophobic poly(methyl methacrylate)/polydimethylsiloxane fibers as the barrier for moisture ingression and superhydrophilic chitosan fibers for a PM capture efficiency of over 96% at optical transmittance of 86%.

3. Nanofibers in Protective Clothing (PC)

Water vapor transport properties of ENMs are similar to fabric substances and consequently, they can be carried out in defensive clothing packages. Although increased filtration performance for aerosol become observed for ENMs, anexceptionally better-pressure drop became pronounced [23]. Reactive natural materials ((3-carboxy-four-iodosobenzyl) oxy-bcyclodextrin) [24] and nanoparticles [25] have been incorporated into nanofibers with the aid of blending with polymer answers accompanied by using simple electrospinning and tested for decontamination of chemical battle marketers (CWA).

4. Removal of Nanoparticles in the air by ENMs

The nanofibers have the capacity to seize very small nanoparticles within the air circulate due to their efficient mechanism of Brownian diffusion and interception. Maze et al stated via simulation records that the filtration efficiency of the ENMs for nanoparticles may be progressed with the aid of lowering the fiber diameter and growing the drift temperature of the air.

Filtration performance of nanofibers

According to filtration theory, non-slip flow dominates in typical HEPA filters. However, The slip flow mechanism becomes prominent when the nanofibrous layer is deposited on the traditional filter (Fig. 2) because of the ability of lower fibre sizes to disrupt airflow [8]. Figure 1 illustrates this point. deep filtration is occurring on the 3a traditional filter media (dust loading), whereas dust particles are surface-loaded on the nanofiber coated on a standard filter.

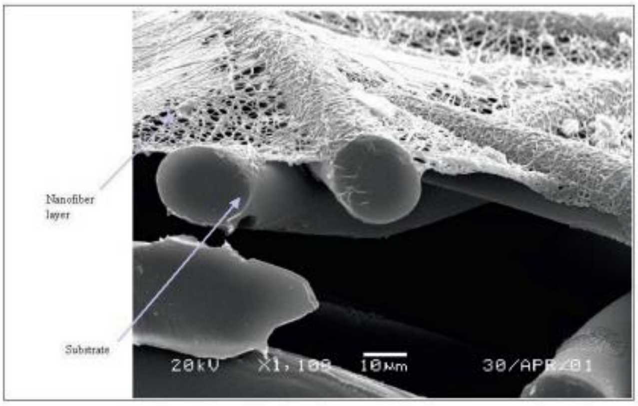


Figure. Electrospun Nanofibers on a polyester substrate. Reproduced with Permission from Certainly, let's delve deeper into some of the mentioned applications:

Drug Delivery Systems

Electrospun nanofibers offer a high surface area-to-volume ratio and porous structure, making them ideal for drug delivery systems. They can encapsulate and release pharmaceutical compounds in a controlled manner, improving drug solubility, stability, and bioavailability. The flexibility in designing nanofiber matrices allows for tailored drug release profiles.

Energy Storage Devices

Nanofiber-based materials contribute to advancements in energy storage devices. For example, electrospun nanofibers can be used as separators in lithium-ion batteries, enhancing ion transport and improving overall battery performance. They also find applications in supercapacitors, offering high surface area and electrical conductivity.

Water Filtration

Nanofibers play a key role in water filtration applications. Their small pore size and high porosity enable efficient removal of contaminants, bacteria, and even nanoparticles from water sources. Nanofiber-based membranes are used in water treatment processes, providing a sustainable and effective means of purifying water.

Sensors and Diagnostics

Functionalized nanofibers can be tailored for specific sensing applications. For instance, nanofiber-based sensors can detect gases, chemicals, or biological molecules, making them valuable in environmental monitoring, healthcare diagnostics, and industrial safety. The large surface area of nanofibers enhances the sensitivity of these sensors

Catalysis

Nanofiber-supported catalysts have a large surface area, facilitating catalytic reactions. This application is crucial in industries where efficient catalysis is required, such as chemical synthesis and environmental remediation. Nanofiber catalysts can improve reaction rates and selectivity.

These applications highlight the adaptability and versatility of electrospun nanofibers in addressing challenges across a wide range of fields, from healthcare and environmental protection to energy storage and industrial processes. The unique properties of nanofibers continue to drive innovation in diverse scientific and industrial application

Future prospects

The future prospects of nanomaterials (NMs)-based membranes, particularly in the context of air filtration, are immensely promising and transformative. As advancements in materials science and nanotechnology continue to unfold, NMs-based membranes are positioned to play a pivotal role in addressing the challenges associated with air quality, pollution, and emerging contaminants. In this narrative exploration, we delve into the multifaceted aspects that define the future landscape of NMs-based membranes for air filtration.Nanomaterials, characterized by their unique physical and chemical properties at the nanoscale, hold the key to revolutionizing air filtration technologies. These materials include nanoparticles, nanofibers, nanocomposites, and other nanostructures that exhibit enhanced surface areas, high reactivity, and tailored functionalities. Leveraging these attributes, NMs-based membranes are poised to surpass conventional filtration methods in efficiency, selectivity, and adaptability.One of the primary advantages of NMs-based membranes lies in their ability to achieve superior filtration efficiency and selectivity. The nanoscale features of these materials facilitate precise control over pore size, enabling the effective capture of particles, pollutants, and even nanoparticles. Enhanced filtration efficiency ensures the removal of finer particulate matter, including ultrafine particles that pose significant health risks.

The incorporation of nanomaterials with inherent antimicrobial properties adds an extra layer of functionality to air filtration membranes. Silver nanoparticles, for example, exhibit strong antimicrobial effects, preventing the growth of bacteria and fungi on the membrane surface. Additionally, the self-cleaning properties of certain nanomaterials contribute to the longevity and sustained performance of air filtration systems.NMs-based membranes offer the advantage of tailored surface chemistry, allowing for specific interactions with gases and volatile organic compounds (VOCs). Functionalized nanomaterials can selectively adsorb and capture target gases, providing a versatile solution for air purification in industrial settings, laboratories, and areas with high pollutant concentrations.

The lightweight and flexible nature of nanomaterials enables the fabrication of thin, compact membranes with high surface area-to-volume ratios. This characteristic is particularly valuable in portable air filtration devices and wearable technologies designed to enhance personal air quality. The flexibility of these membranes allows for integration into various form factors without compromising performance.NMs-based membranes contribute to the development of energy-efficient air filtration systems. Their reduced thickness and enhanced filtration properties can lead to lower energy consumption compared to conventional methods.

Moreover, the potential for sustainable nanomaterials, such as biodegradable polymers and environmentally friendly nanoparticles, aligns with the growing emphasis on eco-friendly solutions.The regenerative capabilities of certain nanomaterials further extend the lifespan of air filtration membranes. Nanoparticles with catalytic properties can participate in membrane regeneration processes, reducing fouling and enhancing the membrane's longevity. This feature is critical for maintaining consistent filtration performance over extended periods.As the era of smart technologies unfolds, NMs-based membranes can seamlessly integrate with sensor networks and data-driven systems. Real-time monitoring of air quality parameters combined with adaptive filtration systems ensures responsive and efficient pollutant removal. The synergy of nanotechnology and smart technologies holds immense potential for creating intelligent air filtration solutions.The adaptability of NMs-based membranes positions them as key players in addressing emerging contaminants in the air. Whether combating the spread of airborne viruses, mitigating the impact of industrial emissions, or responding to new environmental challenges, these membranes offer a versatile platform for targeted and efficient air purification.

As with any emerging technology, the widespread adoption of NMs-based membranes in air filtration requires careful consideration of regulatory frameworks and safety aspects. Understanding the potential risks associated with nanomaterials, such as inhalation exposure and environmental impact, is crucial for responsible and sustainable deployment. The of NMs-based membranes in air filtration is marked by innovation, efficiency, and adaptability. From enhancing filtration performance to contributing to sustainability goals, these membranes represent a paradigm shift in the quest for clean and breathable air. As research and development in nanotechnology progress, the transformative impact of NMs-based membranes on air quality management will undoubtedly shape the future of air filtration technologies.

Challenges:

The advent of nanomaterials-based air filtration membranes brings unprecedented potential for addressing air quality challenges. However, the journey toward widespread implementation is not without its hurdles. In this exploration, we delve into the multifaceted challenges that accompany the development and deployment of nanomaterials-based air filtration membranes.while nanomaterials-based air filtration membranes hold immense promise, overcoming the associated challenges is imperative for their successful deployment. Addressing issues related to safety, scalability, regulation, and environmental impact will pave the way for realizing the transformative potential of nanotechnology in mitigating air quality challenges. Ongoing research, collaboration, and a multidisciplinary approach are essential in navigating these challenges and unlocking the full benefits of nanomaterials-based air filtration membranes.

Toxicity and Health Concerns:

A primary challenge in the use of nanomaterials for air filtration membranes revolves around concerns related to their toxicity and potential health impacts. The inhalation of nanoparticles, especially those with certain chemical compositions or sizes, may pose health risks. As these membranes are designed to capture particles, ensuring the safety of both production processes and the end-user environment is paramount.

Standardization and Regulation

The lack of standardized testing protocols and regulatory frameworks for nanomaterials-based air filtration membranes poses a significant challenge. Establishing universally accepted guidelines for evaluating the performance, safety, and environmental impact of these membranes is crucial for ensuring reliability and fostering public confidence in their use.

Membrane Lifespan

While nanomaterials contribute to enhanced filtration efficiency, there is a concern about their potential release into the air during the membrane's operational lifespan. Understanding the mechanisms and conditions under which nanomaterials may be released is essential to mitigate any unintended consequences and maintain the integrity of air quality.

Scalability and Cost-Effectiveness

The scalable production of nanomaterials-based air filtration membranes at a cost-effective level remains a substantial challenge. Nanomaterials often involve intricate synthesis processes and may have higher production costs compared to traditional materials. Achieving economies of scale without compromising the quality and safety of membranes is essential for their widespread adoption.

Durability and Long-Term Stability

Ensuring the durability and long-term stability of nanomaterials-based membranes under real-world operating conditions is a critical challenge. Factors such as fouling, mechanical stress, and exposure to varying environmental conditions can impact the performance and lifespan of these membranes. Developing robust materials that withstand these challenges without compromising filtration efficiency is a key research focus.

Consistency

Achieving reproducibility and consistency in the fabrication of nanomaterials-based air filtration membranes is a challenge that stems from the complexity of nanomaterial synthesis and membrane manufacturing processes. Variations in nanoparticle properties, dispersion methods, and membrane fabrication techniques can lead to inconsistent performance, hindering the reliability of these membranes.

Filtration Systems

Integrating nanomaterials-based membranes into existing air filtration systems poses a challenge due to the need for retrofitting and adaptation. Compatibility issues, space constraints, and the need for complementary technologies may arise during the integration process. Seamless incorporation into diverse air filtration setups without compromising overall system efficiency is a challenge that needs to be addressed.

Environmental Impact of Nanomaterial Production

The environmental impact of large-scale production of nanomaterials for air filtration membranes is a concern. The energy and resource-intensive processes involved in nanoparticle synthesis, as well as potential waste streams, raise questions about the overall sustainability of nanotechnology in air filtration. Striking a balance between the benefits and environmental considerations is essential.

Public Perception and Acceptance

Public perception and acceptance of nanomaterials in air filtration membranes play a pivotal role in their adoption. Addressing concerns related to safety, toxicity, and long-term effects is crucial for gaining public trust. Transparent communication about the benefits and risks associated with these membranes is essential to foster acceptance.

Multifunctionality and Trade-Offs

As nanomaterials-based air filtration membranes aim to offer multifunctional capabilities, trade-offs between various properties may arise. Balancing enhanced filtration efficiency with factors like pressure drop, permeability, and membrane robustness presents a challenge. Optimization strategies must be devised to achieve an optimal combination of properties without compromising overall performance.

IX. Conclusion

The reviewed research underscores the pivotal role of nanomaterials in revolutionizing air filtration technologies. The versatility of nanomaterials, particularly evident in electrospun nanofiber membranes, offers promising solutions for efficient and cost-effective air purification. The studies on catalysts, such as cobalt-based oxide catalysts, showcase innovative approaches to transform harmful vapors into safer gases. The exploration of diverse nanomaterials, including polyacrylonitrile (PAN) and polyetherimide (PEI), demonstrates their effectiveness in catching particulate matter and providing multifunctionality in air filtration.

Noteworthy advancements in the development of nanofiber membranes, incorporating additives like silver and polyimide, indicate a trend towards enhanced filtration capabilities and antibacterial properties. The combination of nanotechnology and metal-organic frameworks, as seen in Cu-based metal-organic frameworks (CuMOF), introduces multifunctionality, offering high-efficiency filtration and separation in complex environments. The comprehensive review suggests that nanomaterial-driven air filtration is a dynamic and evolving field, continuously pushing the boundaries of innovation. As we navigate the challenges of air pollution, nanomaterials emerge as promising candidates for addressing the intricate demands of efficient, long-lasting, and economically viable air filtration systems. The collective findings emphasize the need for continued research and development in nanomaterials, paving the way for a cleaner and healthier environment.

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