**Sürdürülebilir Çevre Dergisi**
*Dergi Sayfası: https://dergipark.org.tr/tr/pub/cevder*
DOI: 10.62816/cevder.1491367
*Araştırma Makalesi / Research Paper* *Cilt 4 (1), sh. 29-40, 2024*

# Innovative Nanofibrous Air Filters: Advancing Air Quality and Health Protection

Ali TOPTAŞ
atoptas34@gmail.com

Textile Technologies and Design Faculty, Istanbul Tech. Univ., 34437 Istanbul, Türkiye

Arrival Date: 28.05.2024 / Accepted Date: 15.06.2024

## Abstract

Air pollution is a significant global health concern, causing respiratory diseases, cardiovascular disorders, and various cancers. The increasing population, industrial activities, fuel emissions, and construction activities contribute to the formation of particulate matter, leading to air pollution. The inhalation of fine particulate matter (PM2.5) and various toxic gases substantially exacerbates these health risks. Traditional air filtration systems, while relatively effective at capturing larger particles, fall short in capturing nanoscale pollutants. To address these deficiencies, nanofibrous air filters have emerged as a significant innovation. Due to their large surface area and high porosity, nanofibrous filters can effectively capture smaller particles and harmful gases. Research has demonstrated that nanofibrous filters exhibit high efficiency in filtering PM2.5 and smaller particles, as well as bacteria, and viruses. Furthermore, the long-term use of these filters presents a significant potential to reduce health risks associated with air pollution. This study emphasizes the critical importance of developing and implementing nanofibrous filter technology and the innovative research in this field to improve air quality and protect public health. The widespread adoption of this technology is viewed as an effective strategy to mitigate the adverse health effects of air pollution and create healthier living environments. In this context, the study presents insights into the current and future applications of nanofibrous air filters.

***Keywords:*** Air pollution, Air filtration, Nanofibrous filters, Electret filter

# Yenilikçi Nanolifli Hava Filtreleri: Hava Kalitesinin Geliştirilmesi ve Sağlığın Korunması

Ali TOPTAŞ
atoptas34@gmail.com

Tekstil Teknolojileri ve Tasarım Fakültesi, İstanbul Teknik Üniv., 34437 İstanbul, Türkiye

Geliş Tarihi: 28.05.2024 / Kabul Tarihi: 15.06.2024

## Özet

Hava kirliliği, küresel ölçekte solunum yolu hastalıkları, kardiyovasküler rahatsızlıklar ve kanser türleri gibi ciddi sağlık sorunlarına neden olmaktadır. Artan nüfusa, endüstriyel faaliyetlere, yakıt emisyonlarına ve inşaat faaliyetlerine bağlı olarak oluşan partikül maddeler hava kirliliğine neden olmaktadır. Özellikle, ince partikül maddelerin (PM2.5) ve çeşitli toksik gazların inhalasyonu, bu sağlık risklerini önemli ölçüde artırmaktadır. Geleneksel hava filtreleme sistemleri, büyük partikülleri yakalama konusunda nispeten etkili olsalar da nano boyutta kirleticilerin tutulmasında yetersiz kalmaktadır. Bu eksiklikleri gidermek amacıyla, nanolifli hava filtreleri önemli bir yenilik olarak ortaya çıkmıştır. Nanolifli filtreler, geniş yüzey alanları ve yüksek porozite özellikleri sayesinde daha küçük partikülleri ve zararlı gazları etkin bir şekilde yakalayabilmektedir. Yapılan araştırmalar, nanolifli filtrelerin PM2.5 ve daha küçük partiküllerin yanı sıra çeşitli toksik gazların, bakteri ve virüslerin filtrasyonunda yüksek verimlilik gösterdiğini doğrulamaktadır. Ayrıca, bu filtrelerin uzun vadeli kullanımı, hava kirliliğine bağlı sağlık risklerini azaltmada önemli bir potansiyel sunmaktadır. Bu çalışma nanolifli filtre teknolojisinin ve bu alanda yapılan yenilikçi çalışmaların geliştirilmesi ve uygulanmasının, hava kalitesini iyileştirme ve halk sağlığını koruma açısından kritik önem taşıdığını vurgulamaktadır. Bu teknolojinin yaygınlaştırılması, hava kirliliğinin olumsuz sağlık etkilerini hafifletmek ve daha sağlıklı yaşam ortamları oluşturmak için etkili bir strateji olarak değerlendirilmektedir. Bu bağlamda, nanolifli hava filtrelerinin mevcut ve gelecekteki uygulamaları için çalışmalar sunulmaktadır.

***Anahtar Kelimeler:*** Hava kirliliği, Hava filtreleri, Lifli filtreler, Elektret filtre

## 1. Introduction

The increasing global population, rapid urbanization and industrialization, widespread use of agricultural chemicals and harmful substances, and the rise in motor vehicle usage have led to significant environmental issues (Roser, 2023). Foremost among these issues is air pollution, which has become a global threat. Air quality is a critical factor that directly affects human health. According to the World Health Organization (WHO), approximately 10 million people die prematurely each year from diseases related to air pollution (e.g., pneumonia, chronic obstructive pulmonary disease, lung cancer). Of these deaths, 4.2 million are attributable to outdoor air pollution, while 3.8 million result from indoor air pollution (Kumar et al., 2023).

Air quality is determined by the concentrations of pollutants in the air, such as particulate matter (PM), nitrogen oxides (NOx), sulfur oxides (SOx), carbon monoxide (CO), and carbon dioxide ($CO_2$) (Năstase et al., 2018). Particulate matter (PM) comprises a mixture of solid and liquid particles, including carbon, heavy metals, polycyclic aromatic hydrocarbons, soil particles, sea salt, and radioactive substances (Yadav & Devi, 2018). The chemical and physical properties of PM are related to particle size and emission source. The United States Environmental Protection Agency (USEPA) classifies PM as particles with diameters less than 1 μm (PM1), less than 2.5 μm (PM2.5), and less than 10 μm (PM10) (Vijayan et al., 2015). Smaller particles, particularly PM2.5 and PM1, can easily penetrate the bronchi and lungs, causing chronic respiratory diseases such as lung cancer, asthma, chronic obstructive pulmonary disease (COPD), bronchitis, and cardiovascular diseases (Taneja et al., 2008).

A significant portion of the world's population resides in urban centers, spending most of their daily lives indoors. Indoor air quality is adversely affected by pollutants from outdoor air and inadequate ventilation (Yang et al., 2021). Indoor air comprises gases such as oxygen, nitrogen, carbon dioxide, and hydrogen, and the ratios of these gases determine indoor air quality. Indoor air pollution is influenced by factors including outdoor air quality, human activities, population density, materials used, and indoor design (Kumar & Kumar, 2012). Poor indoor air quality can lead to various health issues such as coughing, nosebleeds, breathing difficulties, eye irritation, headaches, stomach discomfort, and allergic reactions (Pichatwatana et al., 2017). Therefore, it is essential to remove or filter these particles from the air. Filtration involves passing air through filter surfaces with nano- or micropores to separate particulate matter. High-Efficiency Particulate Air (HEPA) or Ultra-Low Penetration Air (ULPA) filters are used in environments such as intensive care units, operating rooms, and patient areas in hospitals to filter the air (Schroth, 1996). Additionally, it is crucial for individuals working in high PM environments to use face masks.

Nonwoven surfaces with nano- and micropores are used in the production of filtration surfaces like filters and face masks to minimize the harmful effects of inhaled air.

Since the pore sizes on the surface formed by microfibers are very large, filtration efficiency is low. Capturing very small particles is not possible with traditional filters. This situation has led to the development of nanofiber filters as a solution to traditional filters. The pore sizes in nanofibrous surfaces are also at the nanoscale, making it possible to filter nanoparticles with these filters. Consequently, nanofibrous filters offer higher filtration efficiency than microfibrous filters for air filtration. Filter surfaces composed of very fine nanofibers (below 65 nm) can achieve high solidity values through dense packing of nanofibers (Bui et al., 2022). This condition increases the pressure drop, causing the filter surface to clog quickly and preventing effective particle filtration, which hinders the easy passage of air through the filter surface (Barhate & Ramakrishna, 2007). To prevent rapid clogging of filter surfaces and high pressure drop values, filter surfaces combining nano- and microfibers are utilized (Gungor et al., 2022). In bimodal filter structures, the presence of both nano- and microfibers results in air flow values that span a wide Knudsen range, allowing easier air passage through the filter surface. The presence of mechanically stronger microfibers in the filter surface enhances mechanical durability. Using bimodal structures, filters with high filtration efficiency, low pressure drop, and high mechanical durability can be achieved (Lin et al., 2022). Early studies on bimodal filter structures in the literature are mainly based on simulations or theoretical calculations. Initial studies on bimodal fiber production were achieved using the melt blowing method. These studies demonstrated surfaces composed of "island-in-the-sea" type fibers obtained from two different polymers with varying melting temperatures and molecular weights, either extruded separately, from a single extruder, or converging at the die orifice (Soltani & Macosko, 2018). Additionally, there are studies in the literature where bimodal structures are formed by layering thick fiber layers and thin fiber layers (Wang et al., 2017). Noteworthy studies in this area include those incorporating nanonets in their structure (Robert & Nallathambi, 2020). Furthermore, there are bimodal studies that combine electrospinning and melt blowing (MB) methods to create filter surfaces. These studies utilize various polymers. Fibrous surfaces produced from solutions can be made from synthetic polymers like polyvinylidene fluoride (PVDF), polyacrylonitrile (PAN), thermoplastic polyurethane (TPU), polyamide-6 (PA-6) , polyamide-6.6 (PA-6.6), polyvinyl alcohol (PVA), polytetrafluoroethylene (PTFE), or from naturally derived polymeric materials such as gelatin, collagen, chitosan, carboxymethyl cellulose (Han et al., 2017). Fibrous surfaces obtained from melts using the MB method can be produced from various thermoplastic polymers like polyester (PET), polypropylene (PP), polybutylene terephthalate (PBT), polylactic acid (PLA), or naturally derived materials such as glass wool (Kilic et al., 2015).

In this study, air pollution and air pollutants will be mentioned and the filtration performance and applications of nanofibrous air filters will be examined. After the production processes and structural features of nanofibrous filters, bimodal filters and electret filters are explained, the effectiveness of these filters on PM2.5 will be evaluated with experimental data. Additionally, the potential health benefits of long-term use of these filters and their advantages over existing filter systems will be analyzed. Finally, the role of widespread use of innovative filters in improving air quality will be discussed.

## 2. Air Pollution

All gases, particles, and microorganisms that degrade overall air quality and harm human health are generally referred to as pollutants. Multiple factors contribute to the formation of pollutants, including outdoor air, materials used in the environment, human density and activities, design and equipment, cleaning agents, temperature, humidity, and HVAC (Heating, Ventilation, and Air Conditioning) systems. To prevent air pollution, it is essential first to eliminate the sources of pollution and then to clean the air and the environment. Unless the source of pollution is entirely eradicated, pollutants will continue to recur even if they are temporarily removed from the environment. Air quality can be improved through natural ventilation achieved by using breathable walls in buildings. To fully ensure air quality, it is crucial to have detailed knowledge about pollutants. This section examines pollutants under two main headings.

### 2.1 Particle pollutants

Industrial activities, fossil fuel consumption, materials used in indoor design and equipment, HVAC systems, building materials, carpets, furniture, and office supplies interact with outdoor air, leading to the formation of particulate matter (PM) and indoor air pollution. PM refers to a mixture of solid particles and liquid droplets suspended in the air (Chuang et al., 2014). These particles vary widely in size; while particles such as dust, smoke, and soot are visible to the naked eye, much smaller particles can only be observed with a microscope. The size of the particles is crucial concerning their health effects. Fine particles can penetrate deeper into the lungs and may contain organic matter and heavy metals. The atmospheric lifespan of particles varies by size; PM2.5 and PM1 particles can remain airborne for extended periods, whereas PM10 particles settle quickly (Li et al., 2015).

Outdoor sources of PM include construction activities, dust emissions, and fossil fuel usage. In residential areas, transportation plays a significant role in increasing PM2.5 levels. Gasoline and diesel engines emit approximately 1 kg and 1.5 kg of particulate matter per cubic meter of fuel consumed, respectively, with 80% of these particles being smaller than 1 μm (Toptaş et al., 2021). Outdoor PM can be transported indoors by airflows, and indoor sources of PM include tobacco use, burning candles or incense, wood or coal burning, and cooking activities (especially grilling or frying). A significant portion of smoke consists of respirable particles small enough to remain in the lungs.

Particulate matter comprises a mixture of organic and inorganic substances, including aromatic hydrocarbon compounds, heavy metals, nitrates, and sulfates (Ravindra et al., 2001). Considering these PM sources, indoor air quality may vary periodically. Particularly during periods of high fuel consumption, increased traffic, and construction activities, indoor air quality is expected to deteriorate. Due to the different formation mechanisms of PM, their content and health effects also vary. PM can contain toxic elements and semi-volatile organic compounds, posing significant health risks. Inhaled PM can cause respiratory irritation, allergies, and asthma, while asbestos fibers can accumulate in the lungs, leading to asbestosis and cancer (Rouf et al., 2022). The health effects of PM depend on particle size, concentration, physical and chemical properties, and exposure duration. The concentration of PM and exposure time in the air determines air quality.

### 2.2 Bioaerosols

Bioaerosols are a general term for airborne organic materials of biological origin, such as bacteria, fungi, viruses, pollen, algae, flies, and insects. Microbiological organisms that contribute to air pollution and facilitate disease transmission fall under the category of bioaerosols. These organisms can be classified as either single-celled or multicellular. Bioaerosols may include species that can cause disease or act merely as carriers (Li et al., 2017).

Bioaerosols typically thrive and spread in dirty, wet, and humid environments, including ceilings, furniture, and carpets. Additionally, ventilation systems such as air conditioners, steam-producing sources, beds, and pets can also be sources of bioaerosols. They can be transported from the external environment through air or inanimate objects and can also be carried as parasites on living organisms. Under suitable environmental conditions, millions of bioaerosols can form in a short period (Moon et al., 2014).

Bioaerosols can cause poisoning, allergies, and infectious diseases in humans.

The type and severity of the diseases caused by bioaerosols in humans depend on various factors such as the individual's immune level, the microorganisms' resistance to defense mechanisms, and air quality. Preventive measures to protect against bioaerosols should be implemented both at the individual level and by eliminating these aerosols from the environment (Zhang, 2004). Regular cleaning and maintenance of the filters and ducts of ventilation systems are essential to prevent the formation and proliferation of these microorganisms.

### 2.3 Effects of indoor air quality on health and performance

Air quality is a critical factor that significantly impacts human health and performance. Industrialization, increased vehicle traffic, and environmental factors can adversely affect air quality, thereby influencing individuals' health and performance. Consequently, air pollution and air quality are actively researched and addressed topics in the fields of medicine and environmental sciences. Air pollution is a problem caused by the emission of various pollutants into the atmosphere. These pollutants include particulate matter (PM), nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$), carbon monoxide (CO), ozone ($O_3$), and volatile organic compounds (VOCs). As shown in Figure 2.1, in particular, PM1 particles can cause inflammation and oxidative stress in lung tissues, causing damage to cells and deterioration in lung functions. This can trigger the development of respiratory diseases such as chronic bronchitis, asthma and COPD, or cause existing diseases to worsen. Additionally, these fine particles can pass from the respiratory system to the circulatory system, increasing the risk of cardiovascular disease and increasing the risk of heart attack and stroke. PM1 particles may increase the risk of lung cancer by causing DNA damage in lung tissue. It can disrupt the gas exchange process by damaging the alveolar walls, and disrupt the functioning of the immune system by interacting with immune cells, reducing resistance to infections and increasing the risk of infection (Maurya, 2019).

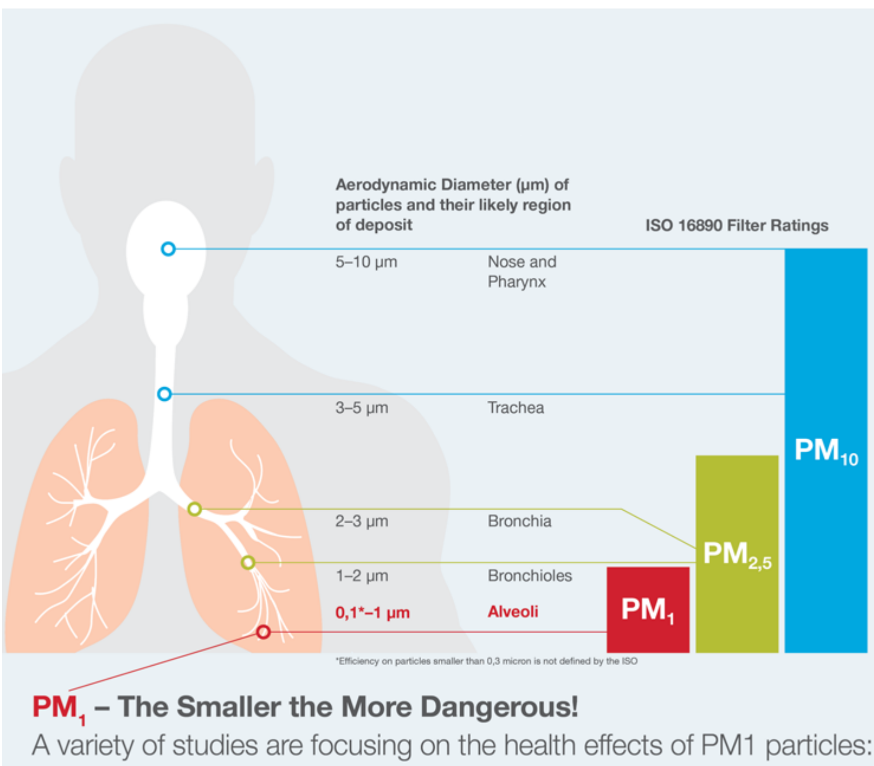



**Figure 2.1.** Locations accessible to PMs in the respiratory system (Maurya, 2019).

Air pollution is a particularly pronounced issue in large cities and industrial areas. Emissions from human activities such as vehicle emissions, industrial facilities, energy production, and domestic heating can significantly affect air quality. The release of these pollutants into the atmosphere can form clouds and enter the body through respiration. The effects of air pollution on human health are varied. Particulate matter can cause respiratory infections and diseases, while ozone can lead to asthma attacks and breathing difficulties. Nitrogen dioxide and sulfur dioxide can cause lung damage and cardiovascular diseases. Volatile organic compounds (VOCs) increase the risk of respiratory diseases and cancer. Air pollution affects not only physical health but also mental health and performance. Inhaling polluted air can cause symptoms such as mental fog, headaches, and fatigue, which can distract individuals and negatively impact their performance.

Research by the United Nations has revealed that 88% of people who spend a significant amount of time indoors experience various adverse effects associated with poor indoor air quality. Deteriorated indoor air quality not only harms individual health but also negatively affects personal performance and productivity of workers. Indoor air quality is defined by the United States Environmental Protection Agency (USEPA) as air that does not contain harmful concentrations at specified levels and where 80% of the people do not express dissatisfaction (EPA, 1997) of a healthy working environment.

It is important to note that health, comfort, and performance factors during work hours are critical not only for employees but also for employers. To ensure an efficient work environment, it is essential to provide employees with a healthy and comfortable indoor space. Cost-benefit analyses indicate that expenditures to improve indoor air quality can yield long-term benefits. One study observed that when the concentration of carbon dioxide ($CO_2$), a common indoor air pollutant, was at 600 ppm, decision-making performance saw a moderate and statistically significant decline at 1000 ppm and a more pronounced decline at 2500 ppm (Satish et al., 2012). In a study by Wargocki et al., the impact of changes in indoor air quality on the performance of 10-12-year-old students was examined in classrooms that provided 100% outdoor air intake and were mechanically ventilated. An increase in student performance was observed with changes in the outdoor air supply rate, demonstrating that indoor air quality has a significant effect on students' learning and performance (Wargocki & Wyon, 2013).

## 3. Air Filters

The filter surface is an advanced nonwoven textile product designed to filter a wide range of particles from the air flow, including microorganisms, fine dust, and pollen [52]. Achieving air quality with minimal concentrations of airborne particles, microorganisms, fine dust, and pollen in indoor environments is a goal of both academic and industrial significance. The increasing number of pandemic cases, environmental pollution, and the high demand for clean rooms and operating theaters have triggered significant growth in the filtration industry. Due to their high surface area-to-volume ratio, flexibility, small pore size, and controllable pore structure, nanofibrous surfaces are in high demand for various applications, including filtration, sensors, tissue engineering, wound dressings, energy generation and storage, and protective materials (Tayyab et al., 2020).

Nanofibrous surfaces are produced using various methods. These methods are fundamentally divided into two categories based on obtaining fibrous surfaces from polymer melts or solutions where polymers are dissolved in appropriate solvents at specific ratios. The melt blowing method is the most preferred technique for the industrial-scale production of fibrous surfaces with micron-level diameters. Methods such as electrospinning, solution blowing, centrifugal spinning, and electro-blowing are particularly favored for laboratory-scale production and research purposes.

### 3.1 Types of air filters and filtration media

Filtration media can be defined as environments that filter particles from air or other gases through a nanofibrous surface and a depth filtration layer in the reverse direction. This layer comprises a nanofibrous surface and a pre-filter surface where the nanofibrous surface comes into contact with the fluid during flow. Nonwoven fabrics, especially those made from melt-blown fibers, are used for pre-filtration. The determination of the filtration media type is generally dependent on the flow of the fluid with which the particles come into contact. It is categorized into two classes: depth filtration and surface filtration media. For depth filtration, particles tend to accumulate in the filter medium and penetrate into the network. In contrast, surface filtration collects particles on the surface of the network. It is known that spunbond or melt-blown webs, felts, and fabrics made from a variety of materials such as polyester (PET), polypropylene (PP), aramid, cellulose, and glass are used as filter media in depth filtration environments (Leung & Choy, 2018). The use of a static electric charge on the depth filtration media enhances the filtration efficiency of the melt-blown medium. The electrostatic filtration mechanism, as shown in Figure 3.1, is a system based on electrically charged particles to dramatically increase collection efficiency for a given pressure drop across the filter (Leung & Sun, 2020).

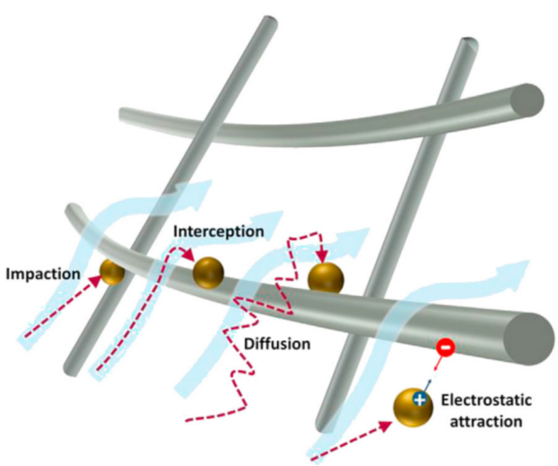



**Figure 3.1.** Filtration mechanism (Han et al., 2021)

Membrane is a type of surface filter that has become increasingly popular in certain applications such as liquid filtration involving liquid aerosols or harsh chemicals. They can be utilized in various fields due to their consistent filtration efficiencies. The filtration efficiency of a membrane is not dependent on the cake layer formed due to dust particles. Compared to depth filtration media, membranes may exhibit relatively high pressure drop and low dust capacity (Vijayan et al., 2015). Air filters composed of nanofibers can capture small particles more easily and experience less pressure drop due to the very small diameters of the fibers forming the structure. Decreasing fiber diameters positively affects the pore size distribution on the randomly formed surface of the fibers, leading to changes in the passing airflow, thereby reducing the pressure drop between the two sides of the filter and positively affecting pressure change (Yilmaz et al., 2011). While smaller fiber sizes lead to higher pressure drop, the interception and inertial effects compensate for the increase in pressure drop. Thus, for particle sizes above and below the micron level, better filtration efficiency can be achieved at the same pressure drop, or conversely, the same filtration efficiency can be achieved with smaller fiber sizes at lower pressure drop.

### 3.2 Performance criteria of air filters

Air filters are widely used in areas concerning human health (such as face masks and indoor air purifiers) and in places where low aerosol concentration is required (e.g., cleanrooms and sensitive instrument manufacturing facilities), hence, the most valued aspect is the effectiveness of filters. Filtration efficiency is defined as the ratio of particles collected by the filter, i.e., the ratio of the difference in number concentrations of particles between the upstream and downstream of the filter to the upstream concentration of the filter (Tang et al., 2017). This is expressed in Equation 1:

$$\eta = 1 - C_{down}/C_{up} \qquad (1)$$

Here, η represents filtration efficiency, $C_{down}$ represents the downstream particle concentration and Cup represents the upstream particle concentration. The mathematical expression for the quality factor (QF), which evaluates the quality of the filter sample considering both η and ΔP (pressure drop), is given by Equation 2 (Givehchi et al., 2016).

$$QF = -\frac{ln(1-\eta)}{\Delta P} \qquad (2)$$

**4. Innovative Air Filters**

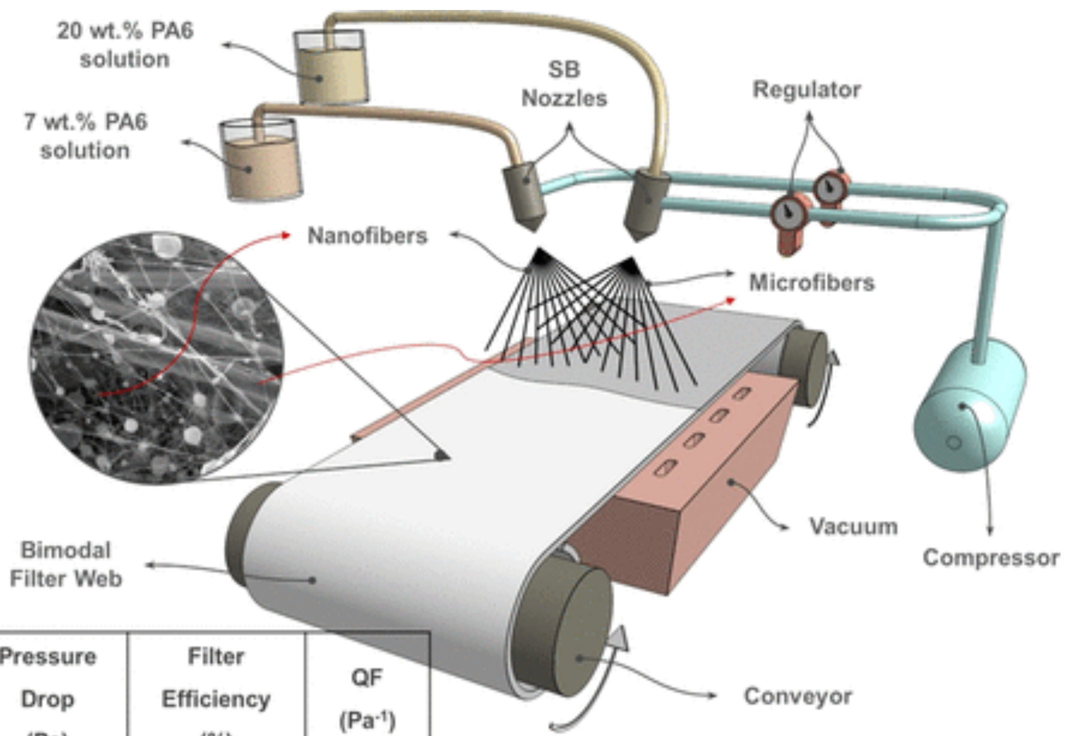
Nanofibrous filters, electret air filters, and bimodal structures have emerged as significant components in the production of innovative air filters. Nanofibers offer effective particle capture capabilities due to their high surface areas and fine structures. These fibers are produced using methods such as electrospinning, solution blowing, centrifugal spinning, and electro-blowing, providing high efficiency in air filters through their micro-scale pore structures. Nanofibers play a critical role, particularly in filtering PM2.5 and smaller particles.

Electret air filters enable particle capture through electrostatic attraction using materials with permanent electric charges. These filters have advantages such as low pressure drop and high filtration efficiency. As electret materials can retain electric charges for extended periods, filters of this type may have longer lifespans compared to traditional mechanical filters. The performance of electret filters depends on the dielectric properties of the materials used and the distribution of electric charges.

Bimodal structures are created by combining two different filter layers to capture particles of different sizes and properties, or by uniformly distributing fibers with two different average diameters in one layer. These structures provide effective filtration across a wide range of particle sizes. Typically, the first layer in bimodal filters is designed to capture large particles, while the second layer targets smaller particles. This dual-layered structure enhances overall filter performance while minimizing pressure drop.

When nanofibers, electret air filters, and bimodal structures are used together, they can significantly enhance the effectiveness and efficiency of air filtration systems. The high surface area and fine pore structure of nanofibers, when combined with the electrostatic capture capability of electret filters, can achieve high filtration efficiency across a broad range of particle sizes. Meanwhile, bimodal structures support the multi-stage filtration capabilities of these systems by effectively capturing both large and small particles. These innovative approaches hold great potential for improving air quality and reducing adverse health effects.

In studies conducted within this scope, the filtration efficiencies of nanofibrous surfaces obtained by spraying PA6 solution on the same surface with different concentrations using two solution-blowing nozzles have been investigated as shown in Figure 4.1. The quality factors of bimodal fibrous filter surfaces obtained by homogeneously depositing nanofibers obtained with a 7 wt % solution and microfibers obtained with a 20 wt % solution on the same surface were much higher than those obtained from surfaces with only nanofibers or only microfibers. This demonstrates the impact of bimodal fibrous surfaces on filter performance (Gungor et al., 2022).




| Sample | Pressure Drop (Pa) | Filter Efficiency (%) | QF ($Pa^{-1}$) |
|---|---|---|---|
| SB-U-N | 265 | 99.413 | 0.01939 |
| SB-U-M | 21 | 15.898 | 0.00824 |
| SB-B | 168 | 98.891 | 0.02680 |

**Figure 4.1**. Bimodal fibrous study (Gungor et al., 2022)

In another study, filters with nanofiber/nanonet structures were produced using the electro-blowing method from solutions containing different ratios of PVDF and polyethylene glycol (PEG) polymers. In this study, it was found that increasing the content of water-soluble, low-molecular-weight PEG in the solution and applying a water bath process to remove the PEG from the structure, as designed uniquely within the scope of this thesis, resulted in reduced fiber diameters and more porous structures. The PVDF (3:7) sample with the highest PEG content exhibited structures resembling nanofiber/nanonets arranged in clusters with average diameters of around 170 nm and 50 nm. The filtration efficiency of this developed sample showed a 3.6% increase in value after the corona discharge process, and a 60% improvement in the quality factor. Consequently, as shown in Figure 4.2, the PVDF (3:7) sample demonstrated the successful production of nanofiber-based filters with a very high η value (99.57%), a significantly low ΔP (158 Pa), and thus a preferred quality factor (QF) of 0.0345 (Toptaş et al., 2023).

In another study, bimodal filters were obtained through the homogeneous distribution or layered use of nano- and microfibers on the filter surface. The effect of bimodal structural design was investigated by comparing the filtration performances of various layer configurations and different diameter fibers produced by melt blowing (MB), solution blowing (SB), and electro-blowing (EB) methods (Figure 4.3). While maintaining the basis weight of the filter samples at 30 gsm, the use of four-layer (4L) structures resulted in increased air permeability compared to single-layer samples (L). The 4L sample thus created had a pressure drop value of 148 Pa and the highest filtration efficiency (99.52%).

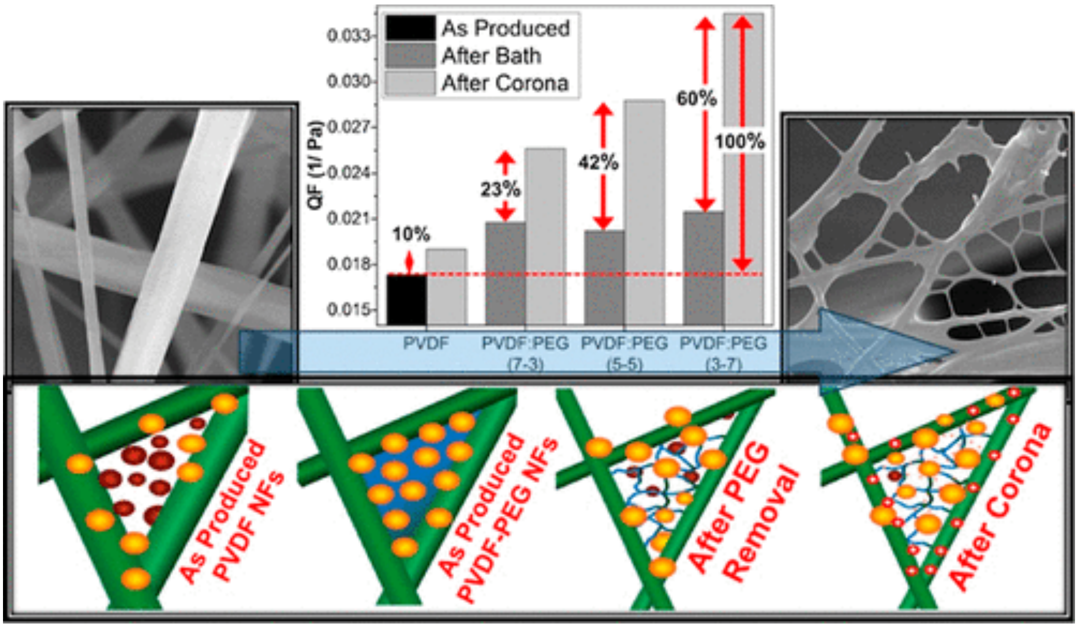



**Figure 4.2.** The effect of nanonet structures on filter performance (Toptaş et al., 2023)

Furthermore, replacing the MB layer in the 4L structure with a bimodal surface (BM) layer obtained by homogeneously incorporating SB nanofibers into the MB increased the filtration efficiency to 99.61% while ΔP remained almost the same. The application of corona discharge treatment to the filter surface produced by melt blowing using PVDF masterbatch resulted in the highest filtration efficiency (99.99%) in the 4BML sample with a bimodal structure. Even after one month, the filtration efficiency of these samples remained at 99.90%, demonstrating that bimodal fiber distribution provided the highest advantage in electret filters (Toptas et al., 2024).

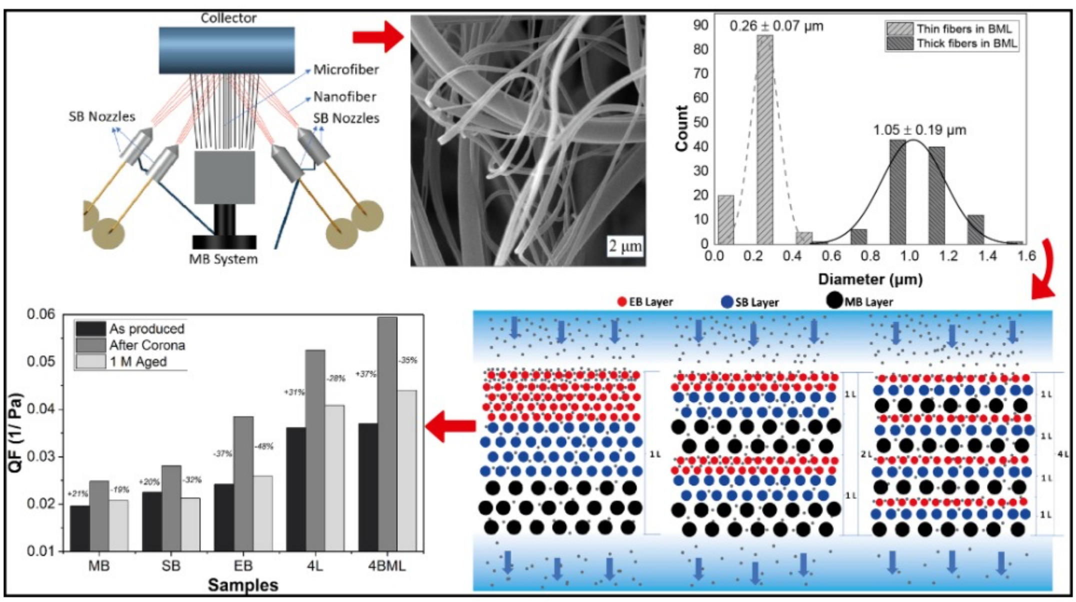



**Figure 4.3.**The effect of bimodal and electret structures on filter performance (Toptas et al., 2024).

Studies show that electret filters provide effective filtration for much longer periods of time. Although they showed very high filtration values at first, filtration efficiency may decrease over time as a result of relaxation, the presence of moisture in the air and blockages. Compared to traditional filters, they still exhibit high filtration performance for months. In the study conducted by Zhang et al., this result was demonstrated by showing 98.5% filtration efficiency even after 2 months (Zhang et al., 2020).

## 5. Conclusion

The increasing population and rapid industrial development have led to a growing need for clean air, and the use of filters plays a significant role in purifying the air. Since the fibers called traditional filters are at the micron level, the size of these filters is larger and they are insufficient to detect PM2.5 and smaller diseases that are dangerous to human health. In filter applications, the preference for the use of nanofibrous surfaces for mask purposes is largely attributed to the low pressure drop and high filtration efficiency, which enable comfortable breathing. In this context, this study highlights the importance of using ultrafine nanofibers, bimodal filter surfaces obtained by combining thin and thick fibers, and electret filters in air filtration. The bimodal structure consisting of nano- and microfibers creates new airflow channels by dispersing fine nanofibers within the thick fibers, resulting in increased porosity. This enhances filtration efficiency without significant increase in pressure drop, indicating more effective use of the filter. This success not only substantially reduces the pressure drop value that filter surfaces should have but also enhances the mechanical strength of the filter surfaces due to the microfibers contained in the structure. This makes nanofibrous filters used in mask applications more comfortable for users and allows for effective filtration of particles.

## References


Barhate RS., Ramakrishna S. (2007). Nanofibrous filtering media: Filtration problems and solutions from tiny materials, *Journal of Membrane Science,* 296(1), 1–8. https://doi.org/10.1016/j.memsci.2007.03.038

Bui TT., Shin MK., Jee SY., Long DX., Hong J., Kim MG. (2022). Ferroelectric PVDF nanofiber membrane for high-efficiency PM0.3 air filtration with low air flow resistance, *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* 640, 128418. *https://doi.org/10.1016/j.colsurfa.2022.128418*

Chuang YH., Hong GB., Chang CT. (2014). Study on particulates and volatile organic compounds removal with TiO 2 nonwoven filter prepared by electrospinning, *Journal of the Air & Waste Management Association,* 64(6), 738–742. *https://doi.org/10.1080/10962247.2014.889614*

Givehchi R., Li Q., Tan Z. (2016). Quality factors of PVA nanofibrous filters for airborne particles in the size range of 10–125 nm, *Fuel*, 181, 1273–1280. https://doi.org/10.1016/j.fuel.2015.12.010

Gungor M., Selcuk S., Toptas A., Kilic A. (2022). Aerosol Filtration Performance of Solution Blown PA6 Webs with Bimodal Fiber Distribution, ACS Omega, 7(50), 46602–46612. *https://doi.org/10.1021/acsomega.2c05449*

Han S., Kim J., Ko SH. (2021). Advances in air filtration technologies: Structure-based and interaction-based approaches, *Materials Today Advances*, 9, 100134. *https://doi.org/10.1016/j.mtadv.2021.100134*

Han W., Xie S., Sun X., Wang X., Yan Z. (2017). Optimization of airflow field via solution blowing for chitosan/PEO nanofiber formation, *Fibers and Polymers*, 18(8), 1554–1560. *https://doi.org/10.1007/s12221-017-7213-9*

Kilic A., Shim E., Pourdeyhimi B. (2015). Electrostatic Capture Efficiency Enhancement of Polypropylene Electret Filters with Barium Titanate, *Aerosol Science and Technology*, 49(8), 666–673. *https://doi.org/10.1080/02786826.2015.1061649*

Kumar P., Singh AB., Arora T., Singh S., Singh R. (2023). Critical review on emerging health effects associated with the indoor air quality and its sustainable management, *Science of The Total Environment*, 872, 162163. *https://doi.org/10.1016/j.scitotenv.2023.162163*

Kumar S., Kumar R. (2012). *Air Quality: Monitoring and Modeling*. BoD – Books on Demand.

Leung WWF., Sun Q. (2020). Electrostatic charged nanofiber filter for filtering airborne novel coronavirus (COVID-19) and nano-aerosols, *Separation and Purification Technology*, 250, 116886. *https://doi.org/10.1016/j.seppur.2020.116886*

Leung WWF., Choy HF. (2018). Transition from depth to surface filtration for a low-skin effect filter subject to continuous loading of nano-aerosols, *Separation and Purification Technology,* 190, 202–210. *https://doi.org/10.1016/j.seppur.2017.08.060*

Li Y., Chen Q., Zhao H., Wang L., Tao R. (2015). Variations in PM10, PM2.5 and PM1.0 in an Urban Area of the Sichuan Basin and Their Relation to Meteorological Factors, *Atmosphere*, 6(1), Article 1. *https://doi.org/10.3390/atmos6010150*

Li Y., Lu R., Li W., Xie Z., Song Y. (2017). Concentrations and size distributions of viable bioaerosols under various weather conditions in a typical semi-arid city of Northwest China, *Journal of Aerosol Science*, 106, 83–92. *https://doi.org/10.1016/j.jaerosci.2017.01.007*

Lin S., Fu X., Luo M., Zhong WH. (2022). Tailoring bimodal protein fabrics for enhanced air filtration performance, Separation and Purification Technology, 290, 120913. https://doi.org/10.1016/j.seppur.2022.120913

Maurya R. (2019, December 27). *Are PM1 Particles More Dangerous than We Think?* $H_2S$ Media. *https://www.how2shout.com/news/are-pm1-particles-are-more-dangerous-than-we-think.html*

Moon KW., Huh EH., Jeong HC. (2014). Seasonal evaluation of bioaerosols from indoor air of residential apartments within the metropolitan area in South Korea, *Environmental Monitoring and Assessment*, 186(4), 2111–2120. *https://doi.org/10.1007/s10661-013-3521-8*

Năstase G., Şerban A., Năstase AF., Dragomir G., Brezeanu AI. (2018). Air quality, primary air pollutants and ambient concentrations inventory for Romania, *Atmospheric Environment*, 184, 292–303. *https://doi.org/10.1016/j.atmosenv.2018.04.034*

Öztürk S., Gerçek D., Güven İT., Gaga E., Üzmez ÖÖ., Ci̇van M. (2021). Kocaeli İzmit İlçesi'nde Partikül Madde (PM2.5) Konsantrasyon Seviyeleri, Mekânsal ve Mevsimsel Değerlendirilmesi, *Mühendislik Bilimleri ve Tasarım Dergisi,* 9(3), Article 3. *https://doi.org/10.21923/jesd.888896*

Pichatwatana K., Wang F., Roaf S., Anunnathapong M. (2017). An integrative approach for indoor environment quality assessment of large glazed air-conditioned airport terminal in the tropics, *Energy and Buildings*, 148, 37–55. *https://doi.org/10.1016/j.enbuild.2017.05.007*

Ravindra Mittal AK., Van Grieken R. (2001). Health Risk Assessment of Urban Suspended Particulate Matter with Special Reference to Polycyclic Aromatic Hydrocarbons: A Review, *Reviews on Environmental Health*, 16(3). *https://doi.org/10.1515/REVEH.2001.16.3.169*

Robert B., Nallathambi G. (2020). A concise review on electrospun nanofibres/nanonets for filtration of gaseous and solid constituents (PM2.5) from polluted air, *Colloid and Interface Science Communications*, 37, 100275. *https://doi.org/10.1016/j.colcom.2020.100275*

Roser M. (2023). Data review: *How many people die from air pollution?* Our World in Data. *https://ourworldindata.org/data-review-air-pollution-deaths*

Rouf Z., Dar IY., Javaid M., Dar MY., Jehangir A. (2022). Volatile Organic Compounds Emission from Building Sector and Its Adverse Effects on Human Health, In J. A. Malik & S. Marathe (Eds.), *Ecological and Health Effects of Building Materials* (pp. 67–86). Springer International Publishing. *https://doi.org/10.1007/978-3-030-76073-1_5*

Satish U., Mendell MJ., Shekhar K., Hotchi T., Sullivan D., Streufert S., Fisk WJ. (2012). Is CO2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO2 Concentrations on Human Decision-Making Performance, *Environmental Health Perspectives*, 120(12), 1671–1677. *https://doi.org/10.1289/ehp.1104789*

Schroth T. (1996). New HEPA/ULPA filters for clean-room technology, *Filtration & Separation*, 33(3), 245–244. *https://doi.org/10.1016/S0015-1882(97)84285-1*

Soltani I., Macosko CW. (2018). Influence of rheology and surface properties on morphology of nanofibers derived from islands-in-the-sea meltblown nonwovens, *Polymer*, 145, 21–30. *https://doi.org/10.1016/j.polymer.2018.04.051*

Taneja A., Saini R., Masih A. (2008). Indoor Air Quality of Houses Located in the Urban Environment of Agra, India, A*nnals of the New York Academy of Sciences*, 1140(1), 228–245. *https://doi.org/10.1196/annals.1454.033*

Tang M., Hu J., Liang Y., Pui DY. (2017). Pressure drop, penetration and quality factor of filter paper containing nanofibers, *Textile Research Journal*, 87(4), 498–508. *https://doi.org/10.1177/0040517516631318*

Tayyab M., Wang J., Wang J., Maksutoglu M., Yu H., Sun G., Yildiz F., Eginligil M., Huang W. (2020). Enhanced output in polyvinylidene fluoride nanofibers based triboelectric nanogenerator by using printer ink as nano-fillers, *Nano Energy*, 77, 105178. *https://doi.org/10.1016/j.nanoen.2020.105178*

EPA (1997). The Incidence and Severity of Sediment Contamination in Surface Waters of the United States: National sediment quality survey, Office of Science and Technology, U.S. Environmental Protection Agency.

Toptas A., Calisir MD., Gungor M., Kilic A. (2024). Enhancing filtration performance of submicron particle filter media through bimodal structural design, *Polymer Engineering & Science*, 64(2), 901–912. *https://doi.org/10.1002/pen.26593*

Toptaş A., Çalışır MD., Kılıç A. (2023). Production of Ultrafine PVDF Nanofiber-/Nanonet-Based Air Filters via the Electroblowing Technique by Employing PEG as a Pore-Forming Agent, *ACS Omega*, 8(41), 38557–38565. *https://doi.org/10.1021/acsomega.3c05509*

Vijayan VK., Paramesh H., Salvi SS., Dalal AAK. (2015). Enhancing indoor air quality –The air filter advantage, *Lung India : Official Organ of Indian Chest Society,* 32(5), 473–479. *https://doi.org/10.4103/0970-2113.164174*

Wang J., Zhao W., Wang B., Pei G., Li C. (2017). Multilevel-layer-structured polyamide 6/poly(trimethylene terephthalate) nanofibrous membranes for low-pressure air filtration, *Journal of Applied Polymer Science*, 134(16). *https://doi.org/10.1002/app.44716*

Wargocki P., Wyon DP. (2013). Providing better thermal and air quality conditions in school classrooms would be cost-effective, *Building and Environment,* 59, 581–589. *https://doi.org/10.1016/j.buildenv.2012.10.007*

Yadav I., Devi N. (2018). *Biomass Burning, Regional Air Quality, and Climate Change*. *https://doi.org/10.1016/B978-0-12-409548-9.11022-X*

Yang Z., Song Q., Li J., Zhang Y., Yuan XC., Wang W., Yu Q. (2021). Air pollution and mental health: The moderator effect of health behaviors, *Environmental Research Letters,* 16(4), 044005. *https://doi.org/10.1088/1748-9326/abe88f*

Yilmaz ND., Banks-Lee P., Powell NB., Michielsen S. (2011). Effects of porosity, fiber size, and layering sequence on sound absorption performance of needle-punched nonwovens, *Journal of Applied Polymer Science,* 121(5), 3056–3069. *https://doi.org/10.1002/app.33312*

Zhang H., Liu N., Zeng Q., Liu J., Zhang X., Ge M., Zhang W., Li S., Fu Y., Zhang Y. (2020). Design of Polypropylene Electret Melt Blown Nonwovens with Superior Filtration Efficiency Stability through Thermally Stimulated Charging, *Polymers*, 12(10), Article 10. *https://doi.org/10.3390/polym12102341*

Zhang Y. (2004). *Indoor Air Quality Engineering*. CRC Press.