Can innovative air filtration technologies replace conventional filters in reducing exposure and health risks from airborne pollutants?

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Abstract

Air pollution has posed a persistent threat to human health since the industrial revolution, and despite recent improvements, remains a significant risk. While most individuals in developed cities experience limited direct health impacts, the long latency and indirect mechanisms of air pollution cause its effects to frequently be underestimated. Additionally, exposure trends strongly follow socioeconomic inequality, with poorer areas often facing higher levels of pollution. Conventional filtration systems such as HEPA filters are widely used to mitigate exposure, but are limited in scope, for example being unable to remove gaseous pollutants. This project aims to evaluate the potential of nano- and bio-engineered filters to complement and/or replace conventional systems, using a critical literature review comparing lab-scale studies of various filters and their filtration efficiency, pressure drop, safety, and sustainability against established standards. The project concludes that innovative filtration systems have a strong replacement potential overall, with nano-engineered and hybrid nano-bio-engineered filters showing the greatest potential.

Contents

Introduction

As society has grown increasingly aware of air pollution and its strong correlations to many diseases, the need for effective control and treatment has become an urgent environmental and medical concern.

Air pollution remains the single largest environmental health risk in Europe and a major cause of death and disease, responsible for roughly 7 million premature deaths per year, worldwide (European Environmental Agency, 2025)[1]. It is exceedingly difficult to safeguard against, and particles can be small enough to be absorbed into the bloodstream, potentially causing systemic damage across the body. It is clear to see that air pollution is a growing, major public-health crisis, particularly affecting children, the elderly and those with pre-existing cardio-pulmonary conditions. While recent awareness and mitigation strategies have caused pollution levels to drop to a much safer level in many developed cities, a high level of risk still exists in many areas around the world. New research published in the Environmental Science: Atmospheres Journal 2025 shows that air pollution across the UK has significantly dropped between 2015 and 2024, but that safe limits are nonetheless exceeded too frequently (Weber, 2025)[2].

Despite the significant emissions improvements in sectors such as urban transport, energy production, and industry, climate change is increasing the incidence of extreme weather events and air pollution therefrom; 1.6 million acres of land have burnt across

[1] This source is reliable – it is published by the EEA, an official website of the EU, and draws on research by e.g. WHO.

[2] This source is reliable – it is published in an indexed journal, and was peer reviewed across two rounds.

the EU since the start of 2025 (at the time of writing), and rising temperatures are only worsening such heatwaves, increasing the speed at which wildfires spread (Rowlatt, 2025)[3]. Wildfire smoke is around ten times as toxic as regular air pollution caused by fossil fuels (Stanford, 2025)[4]. Another example is desertification, driven by increasing temperatures and longer drought periods. Soil dries out and loses its structural integrity, leading to erosion and increased particulate matter (PM) production in the area. Desert dust periods such as the transboundary transport and deposition of sand from the Sahara, have the same effect (WHO, n.d.)[5].

In 2024, toxic smog reached a peak in New Delhi, causing all primary schools to shut temporarily, a ban on non-essential construction, and flight disruptions. A study across 13,000 cities showed that breathing in high levels of fine particulates such as in New Delhi for as little as a few hours causes more than one million premature deaths. Even

highly developed, cleaner cities such as London are not entirely safe from such risks. In east London, toxic fires have routinely occurred in the summers at an illegal landfill site, for two decades, potentially causing the known elevated levels of respiratory and lung diseases in the area (Keane, Havering Council facing legal action over fires at toxic landfill site in Rainham, 2024)[6]. Such conditions have led to “the first death caused by

[3] This article is reliable – it is published by the BBC, off the back of research from Imperial.
[4] This article is reliable – it involves a panel interview with leading environmental health experts.
[5] This source is reliable – it is a reference page published by the World Health Organisation.
[6] This source appears reliable – Local GPs are quoted as concurring, and soil analysis from 2023 backs up claims.

excessive air pollution ever recorded" of a nine-year-old in 2013, who lived 25m from the South Circular Road in London.

Therefore, more effective air filtration at the point of emission, and at the point of exposure, either on a larger scale in urban infrastructure, schools, and workplaces, or in a personal setting in homes or professional kitchens, is urgently needed. Air filtration is not a comprehensive solution; most air filters target only particulates and not gases, and even for filtration of only particulates, well thought-out implementation is needed and often lacking. However, widespread and thorough implementation of such systems offers hope for cleaner cities and healthier living. There is no single global solution to air pollution, and this project does not attempt to suggest one. However, considering the importance of reducing human exposure, it asks: **Can innovative air filtration technologies replace conventional filters in reducing exposure and health risks from airborne pollutants?** My focus on this area arises from long standing interests in medicine, engineering, and the environment, and I plan to pursue a career in sustainable and biomedical technologies. Air pollution mitigation lies at the intersection of these sectors and is therefore a relevant topic for this project.

The development of truly groundbreaking air filtration technologies requires innovation from the forefront of science and engineering, from bio- and nano- engineering, to quantum mechanics and machine learning. This dissertation focuses on bioengineered and nanoengineered solutions as replacements or complements to conventional systems such as HEPA filters. Broadly speaking, new technologies can be divided into three categories; Material science-based filters rely on cutting edge nanoengineering such as graphene or thin fibre mesh-based structures. Bioengineered filters use biological elements such as microorganisms or enzymes to transform and break down pollutants instead of just trapping them, whereas electricity-based filters use electrostatic technology, photonics (UV) and ions (“plasma”) to trap or often destroy pollutants, but are the most controversial around safety, often due to ozone emitted in the process. As the technical complexity of these designs increases, careful monitoring of unintended long-term harm is vital, as innovative technologies have a propensity to carry with them unknown health effects, as pans with a PFOA non-stick coating did when they initially came onto the market.

The following literature review will initially give more detail on the current environmental and health issues faced from air pollution, the varying types of air pollution, their sources, suitable filtration methods, and their interactions with the body. My research will then move on to the evidence for each emerging technology, and how they compare to conventional solutions, with an emphasis on efficacy and safety. Lastly, I will move on to a well-balanced discussion analysing the potential for replacement in different contexts. In-text citations follow APA 6th edition, and source reliability evaluations are presented in footnotes for clarity.

Literature Review

Socioeconomic Contexts of Air Pollution

There is strong evidence linking lower GDP per capita and lower socioeconomic status with increased exposure to air pollution, which is especially relevant in developing countries, but also in developed countries in the EU; in large parts of Europe, poorer people are more likely to live next to busy roads or industrial areas and therefore face higher levels of exposure to air pollution. Regions with lower GDP per capita, which tend to occur in (south)-eastern Europe, are found to have higher levels of PM2.5[7], which is largely driven by their higher consumption of low-quality solid fuels like coal and wood, in low efficiency ovens, for domestic heating. This higher exposure translates into higher numbers of premature deaths attributable to air pollution in these areas. The most deprived people in society often have poorer overall health and less access to high quality medical care, further increasing their vulnerability (EEA, Unequal exposure and unequal impacts, 2019)[8].

The worst air pollution still tends to be found in developing countries, especially in countries undergoing massive economic growth, such as China – Shanghai is classed as a developed city in a developing country, with an Air Quality Index[9] rating of 153,

[7] **PM is split into two size groups, PM10, where particles are smaller than 10 micrometres in diameter (but larger than 2.5 micrometres), and PM2.5, where particles are between 2.5 and 10 micrometres in diameter.**

[8] This source is reliable since it is associated with the EU.

[9] (AQI), measuring PM2.5

placing it within the “unhealthy” range (IQair, 2024)[10]. In China’s case, they intentionally prioritised economic growth over their impact on the environment until around 2008 due to a commonly held belief, that the west had had their turn to grow economically even if it meant polluting the environment, during the industrial revolution, and that they should have that same opportunity, since “it was now their turn” (Bloomberg, 2022) (VICE, 2012)[11].

Aside from this aspect of *choosing* to continue unsafe mining activities or large-scale coal burning, polluting practices are common in developing countries, especially in dense informal settlements, as these practices are often survival driven. In areas where the government is unable to provide infrastructure and services to collect waste, households are only left with one sensible option to continue living: to illegally burn rubbish, despite it creating highly toxic smoke in the process. Although this practice reduces short term health hazards from rubbish, such as vermin, and may also allow them to extract recyclable materials, in the long term it leads to severe health and environmental effects. Another example is Bangladesh, which has some of the world’s worst air pollution (237 AQI at the time, “very unhealthy”). Limited access to healthcare, and lack of protective equipment mean respiratory diseases that would be treatable in developed countries often result in severe disability or premature death, making pollution far deadlier in this context. There are also significant social and economic

[10] this is a reliable source, since it comes from a leading manufacturer of air purifiers.
[11] These sources are both reliable, since they come from well renowned media companies, with Bloomberg being required to be formally accredited to act as a legitimate news source by the SCC in Washington.

costs, causing reduced productivity and vicious cycles of poverty. This concurs with evidence from the EEA (2019) linking lower socioeconomic status to higher exposure.

By contrast, many busy, developed cities demonstrate that low levels of air pollution can be achieved when technology is combined with policy. Cities such as Munich (32 AQI) (IQair, 2024), London (23), and Zurich (15) maintain "good" air quality through strict emissions policies such as the Ultra Low Emission Zone (ULEZ), investment into electric transport, monitoring, and research. The ULEZ expansion in 2023 has so far led to around a 27% drop in roadside Nitrogen Dioxide levels, the levels of PM2.5 are 31% lower than they would be without ULEZ (London, 2025)[12].

Types of Air Pollution

Outdoor (or ambient) **air pollution** encompasses all possible pollutants, including some typically associated with indoor environments. While many of these, such as cleaning products, have a negligible impact outdoors, others are more significant. For example, asbestos can be significantly hazardous in an outdoor setting if the materials containing it (such as insulation or tiling) are damaged or disturbed, causing fibres to spread. Areas where uncontrolled construction or demolition involving asbestos has taken place have recorded respiratory issues among other health issues, for example in Westgate, UK, where tests confirmed the presence of asbestos in the dust (GRANT, 2025)[13]. However, it is important to note that this is very rare, and asbestos removal is normally treated with the utmost caution. **Indoor air pollution** often contains many of

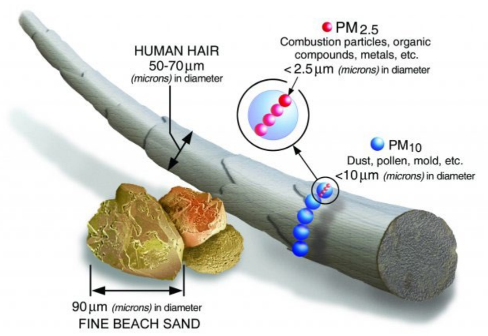
[12] This source is trustworthy since it is independent air quality analysis published through the Mayoral press release.

[13] This source seems reliable – the website specialises in redevelopment of land, with multiple other articles on contaminated land.

the same pollutants as outdoor air, not least due to infiltration of outside air, but concentrations are usually much higher due to cooking and heating processes, and chemicals used in cleaning. Indoor air pollution is particularly concerning since people are exposed for long periods, and it alone contributes to over 3 million deaths annually worldwide, which in 2020 included 237,000 children under 5 (WHO, 2020)[14]. Around 2.4 billion people are exposed to dangerous levels of indoor air pollution from open fires or stoves, and the effects of indoor air pollution are greatest in developing countries where indoor burning of biomass such as wood, coal and dung releases harmful pollutants. Counterintuitively, homes which are energy-efficient and airtight (as many new-builds are), can trap pollutants, requiring a stringent level of ventilation and filtration (usually through a HVAC system) to be implemented. Even without obvious sources such as burning of improper fuels, air pollution in homes is pernicious and very hard to entirely avoid, whether in older, renovated homes, or luxury new builds.

Air pollution can be divided into two main categories: particulate matter (PM) and gaseous pollutants.

Particulate matter is a mixture of microscopic solid particles and liquid droplets found



in the air. Some particles are large enough to be seen under the naked eye, at least when they are in a sufficiently high concentration. This is apparent at the exhausts of cars without catalytic converters. PM is the main component of haze, smoke, and airborne dust, and can cumulatively build up in the respiratory tract. Energy consumption was the main source of PM in 2020. **PM2.5** arises mainly from

[14] Reliable since direct statistics from the World Health Organization.

combustion processes or chemical processes within the atmosphere, whereas **PM10** mainly arises from **natural sources** such as wind-blown soil, sea spray and pollens, or construction and quarrying (Aurelie Charron, n.d.)[15]. All sizes of particulate matter can be classed as either primary or secondary. Sources of primary particulate matter in the environment include combustion of fossil fuels, agitation of existing particulates (such as from tilling of land, quarrying and stone crushing, unpaved roads, and fields), smokestacks and fires, and construction sites. The main PM emissions from cars are generated during diesel combustion (which is then filtered), and from fugitive particulate emissions from engine crankcase ventilations[16]. Diesel generated PM is made up of unburned carbon (soot) from the fuel, which serves as a nucleus, with additional constituents such as sulphuric acid, condensed water, and soluble hydrocarbons collecting in a group on the outside of the particle. They are often made up of several components, including acids (e.g. nitrates and sulphates), organic chemicals, metals, soil or dust particles, and allergens (i.e. fragments of pollen or mould spores). Secondary PM may be formed in the atmosphere from complex chemical reactions of gases and are therefore indirectly formed when gases from the combustion of fuels react with sunlight and water vapour. Examples include sulphur dioxide, and nitrogen oxides. Indoor sources of both include tobacco smoke, broiling or frying food, burning candles or oil lamps, fireplaces, and fuel burning space heaters.

[15] This source appears reliable since it originates from the division of environmental health at the University of Birmingham.

[16] Air-fuel mixture and combustion gases leak from the cylinders into the crankcase, past an engine's piston rings. The resulting mixture of lubrication oil, mist and gases is called blow by. this mixes with oil mist and other contaminants which are harmful to the environment, so it is filtered before discharging it to the environment (or returning to the engine's intake). https://www.solbergmfg.com/en/resources/blog/crankcase-ventilation-system-for-engine-in-the-pow

Some combustion sources are known to also emit **ultrafine particles (UFP)** which are less than 0.1 micrometres in diameter. Some evidence from laboratory-based studies suggests that **UFP** exhibit higher toxicity per unit mass than larger particles in the respirable size range, such as **PM2.5** (Peters et al. 1997). This classification of PM may have been overlooked in the past because UFP make up a tiny proportion of the total mass of PM using traditional measurements, but despite this they may be the largest contributor to particle count and surface area, which are likely to be determinants of toxicity. (Stanek et al. 2011). We know that PM2.5 more easily infiltrates the bloodstream in comparison to PM10. Similarly, UFP more easily evades lung clearance mechanisms compared to PM2.5. There is limited epidemiological evidence that distinguishes the risk of UFP from other respirable particles, and no UFP guideline levels currently exist.

Gaseous pollutants include a wide range of chemically reactive or toxic gases present in all air. Some of the most significant to health include nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), and volatile organic compounds (VOCs)[17]. Typical sources include complete or incomplete combustion of fossil fuels, smelting processes, solvents, cleaning products, and agricultural activities. Secondary gaseous pollutants can also form in the atmosphere, for example, ozone is created through a reaction between VOCs and nitrogen oxides. The deterioration of air quality which leads to unhealthy conditions is contributed to by PM and ground level ozone[18].

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[17] VOCs are emitted as gases from certain solids or liquids and are consistently higher indoors (up to 10x higher) than outdoors. VOCs are responsible for the odors of scents and perfumes (and are not harmful in these concentrations), as well pollutants.

[18] Trioxygen, an inorganic molecule with formula O3, allotrope of Oxygen which is much less stable than O2. Formed from dioxygen by UV light and electrical discharges within Earth's atmosphere. It's present in

Nitrogen oxides are commonly produced through combustion reactions, and ground level ozone levels are often significantly higher near emitters such as gas power stations, or AI data centres if gas turbines are used. During the summer, levels of both PM and ozone are elevated, and this combination can be deadly for people at risk. Gases are often orders of magnitude smaller than PM, can diffuse through materials easily, and are often invisible even in a high concentration. They are therefore harder to filter since conventional mechanical filters cannot trap the molecules. In an indoor setting, gases tend to persist, whereas PM often settles or is removed by ventilation.

Sources of Air Pollution

Overall, the major outdoor sources of pollutants include residential energy (gas) for cooking or heating, vehicles, power generation (grid), and industry. **Airborne microplastic particles** are another component of air pollution which are of concern, since they are carriers for potentially toxic chemicals, and are delivered deep into our bodies when breathed in. They are between 5mm, and 1 nanometre in size, and often originate from manufactured sources such as scrubbing granules in cleaning products, or the natural wear and tear of plastic items such as bags, tyres, disposable cutlery and clothing. As normal plastic fibres break down, they form jagged particles which are highly reactive and well suited to transporting pollutants, toxic chemicals, viruses, and bacteria on them (The Sunday Times, 2022)[19]. The notion of microplastics being a

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its highest concentration in the ozone layer of the stratosphere, where it absorbs most of the sun's radiation.
It's oxidizing potential causes ozone to damage mucous and respiratory tissues in animals, and tissues in plants, above concentrations of 0.1ppm. This makes it a potent respiratory hazard and pollutant near ground level, although beneficial in the ozone layer.

[19] This source is reliable since it was published very recently, and it is an article published by a reliable mainstream newspaper, with research and quotes from Imperial university, who are conducting multiple research projects funded in part by the government, into this area.

significant contributor to PM2.5 is new, since until recently scientists thought PM was mainly comprised of carbon. Microplastics are found almost everywhere in the world, being identified within all households, and 98% of indoor samples which were tested (Global news, 2020)[20]. They are found not only in major cities, but also in remote areas far away from human civilisation, such as the arctic and mountain ranges, showing the full extent of the airborne plastic issue. Many plastic fragments (and therefore microplastics) were found in the Piranesi mountains of southern France, where only a few small villages lie within 95 kilometres of the study site. The area was found to have 365 microplastic particles dropping from the sky per square meter, per day (Allen et al. 2019, University of Strathclyde, CNRS – Toulouse)[21]. "Plastics are everywhere, they are in what we eat, what we drink, and in the air we breathe." – Professor Frank Kelly, director of environmental research group at Imperial. Due to their ubiquity, it is difficult to reduce the level of microplastics and therefore PM2.5 through traditional methods of decarbonisation, such as electrification of transport. Even if every vehicle in London was replaced with electric cars, there would still be a PM2.5 problem because of the tyres, which are largely comprised of plastic.

The concentration of microplastics in homes are high in comparison to outdoors, and this poses an increased health risk, especially when coupled with increased exposure time in comparison to outdoors; people spend up to 90% of their time indoors, and as much as 60% of their time specifically in their homes. There is also a false notion that the air in our homes is cleaner than outside and under our control, which may be the

[20] This source appears reliable since it has good factual reporting and sourcing.
[21] This source is reliable since it comes from a research university in Scotland, which was the first technological university in the UK.

case for the most common contaminants, but this is not the case for microplastics. Additionally, we cannot easily control the level of such microplastics, since they are produced by everyday materials such as décor or clothing which shed small sized fibres. Small (5-250nm) fibrous particles are the most common, making up 90% of all microplastics found, and they could pose the most harm due to their small size, with a similar etiology to smaller particulates in general, of being able to easily infiltrate the bloodstream (University of Hull, 2021)[22]. One notable example, which was recognised early on, is bisphenol A (BPA), a plastic mainly present in air, which is a suspected potent estrogenic endocrine disruptor, and therefore decreases male fertility (Radwan, 2018)[23]. It promotes heart arrhythmias in women due to alteration of calcium handling which is vital for the heart. There is also an association with cardiovascular diseases (Yan, 2011)[24].

Plastic fumes can also have serious effects, in some cases causing long term and irreversible effects such as occupational asthma, or short-term severe irritation to the eyes, nose and lungs (HSE, n.d.)[25]. **Plastic burning or melting** creates these fumes, and a plastic with a higher melting point can equate to the release of more toxic compounds upon melting (Atmospheric Environment, 2013)[26]. Potential other sources of plastic fumes could include cutting through ropes using a heated knife or melting and forming

[22] This source is reliable since it comes from a renowned university in the UK, but the article is also on their own study so there may be bias.
[23] This source is reliable since it is a recent study done by the American journal of men's health, which is published on the National Library of Medicine website, an official website of the US government.
[24] This source is reliable since it is also available on the National Library of Medicine (NLM) website, and each author is highly qualified in their field.

[25] This source is reliable since it comes from Britain's national regulator for workplace health and safety and is a website of the UK government.
[26] This source is reliable since it's published by Elsevier.

plastic using a heat gun. **These plastic fumes are toxic** to rats, mice and other mammals (Schaper, 1994)[27]. In addition, many 3D printing filaments contain additives – e.g. to provide colour, flexibility or electrical conductivity, which may release additional toxic VOCs and UFPs when heated. **Polymer fume fever** is a condition caused by exposure to such fumes, which causes flu like symptom such as cough, difficulty breathing, fever, muscle and joint aches, and headaches. Similarly, **exposure to fumes from welding** materials can cause metal fume fever, which has the same effects (Poison control, n.d.)[28]. Inhalation of tin oxides can cause pneumonia, and inhalation of freshly formed metal oxides can also cause metal fume fever (cooperhandtools, n.d.)[29]. **Soldering fumes** are another cause for concern, and old fashioned lead solder produces toxic lead oxide fumes which is absorbed into the bloodstream through the skin, stomach and lungs, and can give rise to serious chronic health effects and acute illness as lead accumulates in the body (Warwick university, n.d.)[30]. Newer, safer solders also have drawbacks. Rosin solder causes fumes which, without ventilation, can cause eye, throat and lung irritation, headaches, and nosebleeds. Inhalation of fume from rosin in solder or solder fluxes can cause or aggravate asthma, and it is now regarded as one of the most significant causes of occupational asthma in Britain. When occupational asthma from this is fully developed, the effects are permanent and irreversible. Continued exposure, even to very little amounts of fumes containing rosin

[27] This source is reliable since it's an official website of the US government.
[28] This source is reliable since they are an independent, non-for-profit organisation, focused on managing poison exposures reported to US poison centres.
[29] Reliability of this source is questionable since it is an equipment website, this information may be anecdotal.
[30] This source is reliable since it is an information page created by a university well known for its engineering department.

can then cause asthma attacks, making that person unable to solder with rosin-based solder ever again (HSE, n.d.).

Another large polluter in homes is inefficient fuel used for cooking, heating or lighting. This is most common in low- and middle-income countries due to their affordability, and their availability not relying on infrastructure such as gas piping. Around a third of the global population cooks using open fires or inefficient stoves fuelled by kerosene, biomass, and coal, which generates household air pollution – responsible for an estimated 3.2 million deaths per year in 2020 (WHO, 2025)[31]. Women and children, typically responsible for household chores involving inefficient fuel, bear the greatest health burden from the use of polluting fuels and technologies in homes. Cookstoves themselves are a major cause of illness in developing countries. One example is kerosene, a type of paraffin which has been a key household fuel since the mid-19th century and has since been replaced by electricity and natural gas in developed countries. However, in developing countries this flammable hydrocarbon remains in widespread use for cooking and lighting. It is purported as a cleaner alternative to solid fuels, biomass, and coal, and an estimated 500 million households worldwide still reportedly use fuels such as kerosene for lighting. Well known hazards include inadvertent poisoning, fires and explosions. Although the effects of exposure are less well studied, they have the potential to emit significant amounts of fine particulates (PM2.5), carbon monoxide, nitric oxide, and sulphur dioxide. Portable kerosene room heaters are still used in both developed and developing countries, despite some governments banning them due to the risk of carbon monoxide poisoning. There is

[31] This source appears reliable – it is a factsheet compiled by the World Health Organisation and was regularly updated.

evidence that exposure to these combustion products may impair lung function and increase infectious illness, asthma, and cancer risks. Kerosene is commonly used in countries where solid fuels such as biomass and coal are major household energy sources, often burned indoors without chimneys or smoke hoods. Exposure to combustion products from all solid fuels are associated with health effects including COPD, lung cancer, cataracts, pneumonia, cataracts, and tuberculosis (Fullerton, 2007)[32]. The literature on human exposure to the products of household kerosene combustion is sparse, but it is known that there are many potentially health-damaging pollutants emitted in the burning process, so it is likely that it has far reaching effects on the body. It is usually burnt through incomplete combustion, which produces a different array of combustion compounds due to the lack of oxygen, compared to if it was burnt with complete combustion. This produces not only a greater array of combustion products but also potentially more toxic combustion products. An example is polycyclic aromatic hydrocarbons (PAHs), which are mainly produced through the incomplete combustion of kerosene. More than a dozen PAH compounds have been associated with cancer and other adverse health outcomes, with benzo[a]pyrene (BaP) being considered a Class 1 carcinogen (IARC, 2010)[33]. This ties into the earlier discussion of informal waste burning in dense settlements, reinforcing its potential for producing toxic smoke and elevating cancer risks.

[32] This source is reliable – this article was published in "Transactions of The Royal Society of Tropical Medicine and Hygiene", through Oxford Academic, was sponsored by Elsevier, and is now indexed in PMC.

[33] This source is reliable since it is from a book published by the International Agency for Research on Cancer.

Photograph: Copyright © IARC by Georges Mollon

Historical image of young chimney sweep: Copyright © Mary Evans Picture Library London, United Kingdom; used with permission

Chemical structures (from lower left to upper right): Benzo[*a*]pyrene, dibenzo[*a,l*]pyrene, naphtho[2,1-*a*]fluoranthene

A review on household use of kerosene confirms that "kerosene cooking is widespread in many developing countries, especially in urban populations, where biomass needs to be purchased, and electricity and LPG are expensive or unreliable" (Division of Environmental Health Sciences, 2013)[34]. In their review of existing literature on the topic, they make an interesting point, that "exposure" has differing interpretations, and in the context of inhalable pollutants, one should primarily consider the pollutant concentration at the interface between the human and their environment, e.g. right at the level of the person's head. If exposure is measured using monitoring on a personal scale rather than an areal scale, a more accurate indication of exposure is formed. There is also a lesser-known risk associated with natural gas stoves commonly used in developed countries. In 2023, New York State became the first state to ban gas stoves and other gas-powered appliances in new homes, partly due to this. They emit pollutants when burned, most significantly nitrogen dioxide, that irritate human airways and can cause or exacerbate respiratory problems. There is also an issue of unburned gas leaking from stoves, which contains benzene, a known carcinogen. The process of cooking, regardless of fuel source can also create fumes, particularly PM2.5, all of which are responsible for up to 3.8 million premature deaths every year. There is evidence that cooking in homes without sufficient ventilation may increase the risk of developing lung cancer, such as a study which found

[34] This source is reliable since the study was peer reviewed and accepted for publication by " Journal of Toxicology and Environmental Health, Part B" - which has 158k annual views/downloads.

that exposure to the fumes from cooking oil increases the risk of lung cancer (Journal of cancer research and clinical oncology, 2018)[35]. A further review of studies involving cancer cases in China revealed that different cooking methods also have different effects, e.g. stir frying increased the risk of lung cancer, whereas deep frying did not, likely due to the lesser extent to which particulates are aggravated and therefore become airborne in the case of deep frying. However, not all studies are concordant on this matter, which could be due to how much variation there is in how people cook even when using the same method. Some people may use a far higher heat for stir frying than others. A study in Taiwan compared the quantity of aldehydes[36] produced by different cooking methods. It was suggested that sunflower oil fumes, as well as methods such as deep frying and pan frying, have a higher risk of producing more aldehydes, whereas oils that are higher in saturated fat and lower in unsaturated fat, such as palm oil or rapeseed oil, and gentle cooking methods such as stir frying, do not produce as many, or as harmful, aldehydes (Chiung-Yu Peng Dr. P.H, 2017)[37]. Although these studies disagree on an optimal cooking technique for air pollution mitigation, gentle cooking methods should create fewer pollutants. Studies have also shown that exposure to these cooking oil fumes during pregnancy could have adverse effects on newborns, such as reduced weight at birth (Enviromental Research, 2018)[38].

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[35] This source is reliable since it is published on the website of one of the foremost academic publishers, Springer, and the study was originally published by a well-known peer-reviewed medical journal.
[36] A broad class of reactive compounds, many of which are toxic to humans.
[37] This source is reliable since it is published by another of the most renowned academic publishers, Elsevier, in the format of a journal on hazardous materials.
[38] This source is reliable since it is published in association with renowned publishers, Elsevier, and NIH.

Human Cost and Biological Mechanisms

Epidemiology and Scale of Impact

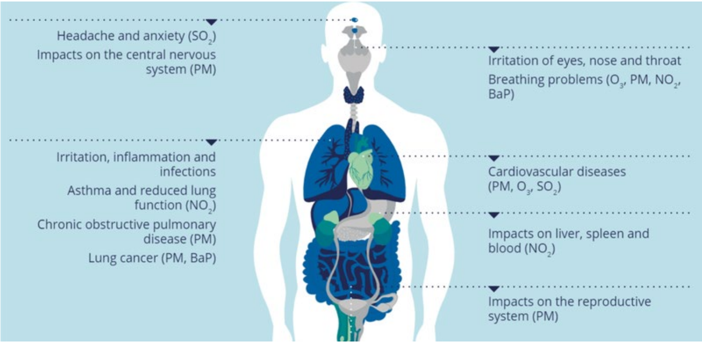
Health problems in children and adults can occur both because of short- and long-term exposure to air pollutants. Some pollutants cause adverse effects at any exposure level, making it especially important to prevent exposure. Air pollution damages health during childhood and increases the risk of diseases later in life (European-Enviromental-Agency, 2023)[39]. While the staggering global burden is well known, regional data within Europe show the practical scale of the problem. In 2020, there were around 238,000 premature deaths due to PM2.5 exposure in the 27 EU member states. This represented a 45% reduction compared to 2005, but the figures remain unacceptably high nonetheless (EEA, Health impacts of air pollution in Europe, 2021). This corroborates other sources such as (Weber, 2025) emphasising that worldwide risks remain high.

The landscape in the UK shows how air pollution silently drives premature deaths and wastes billions in hidden healthcare costs - in the recent past, around 4,000 premature deaths per year were associated with air pollution in London. Between 2017 and 2025, PM 2.5 alone is estimated have cost the NHS and social care system at least £1.54 billion (when only data with robust evidence for an association was included), and up to £2.81 billion (when data included diseases with emerging evidence). During the same time frame, nitrogen dioxide (NO2) invoked costs of between £60.81 million and £2.75 billion (Public Health England, 2018)[40]. Both PM2.5 and NO_2 impose a very high cost on the NHS, but PM2.5 has a noticeably greater impact when considering only robust

[39] Refer back to previous EEA citation – reliable for the same reasons – official website of the EU.
[40] This source is reliable since it comes from a source other than the NHS, and it is published by the UK government.

evidence. Particulate matter, carbon monoxide, ozone, nitrogen dioxide, and sulphur dioxide are among the most damaging air pollutants to health. However, out of all pollutants, PM2.5 (fine particulate matter less than or equal to 2.5 micrometres in diameter) continues to cause the most substantial health impacts and premature mortality, with the particle size being directly linked to their potential for harm (European Environmental Agency, 2025). In 2021, 97% of urban populations were exposed to concentrations of particulate matter[41] equal to or less than 2.5 micrometres in diameter (PM2.5) above the health-based guideline level set by the World Health Organization (EEA, 2023). This epidemiological data quantifies the scale of the problem, but mechanistic insights are needed to understand why some pollutants are so much more harmful than others, and to analyse effective preventative approaches such as air filtration.

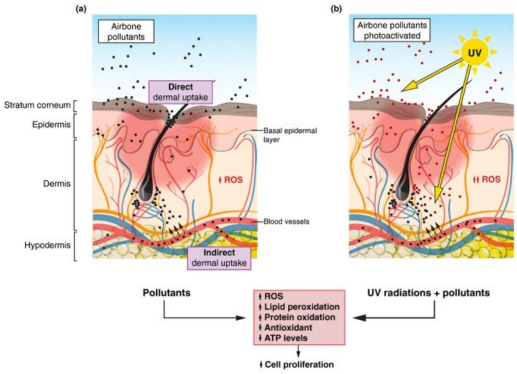
Air pollution's main pathway of exposure is inhalation and people tend to be more concerned about this than, for example, skin exposure (airly, n.d.)[42]. This is understandable, since the inhalation pathway causes systemic effects such as cardiorespiratory diseases. However, it can also have significant effects on the skin and eyes.



[41] While PM10 can include PM2.5, for the purposes of this research, PM10 refers to particles between 2.5 and 10 micrometres in diameter.
[42] Evaluated shortly (next page).

Effects of Pollution on the Skin

The most common skin irritants from air pollution are volatile organic compounds[43], polycyclic aromatic hydrocarbons[44], oxides[45], ozone, particulate matter, and cigarette smoke. Pollutants can activate cutaneous metabolism (chemical reactions in the skin) pathways, which induce oxidative stress by lowering the number of antioxidants in the skin. Oxidative stress plays a major role in the aging of skin, so pollutants can therefore intensify skin aging, such as facial lentigines (benign spots which occur with age on sun exposed areas of the skin) and wrinkles. UV radiation also causes oxidative stress, so the combination of these two may contribute to even greater damage to the skin, but more research is needed to confirm this. Pollutants can cause protein oxidation (breakdown of key structures i.e. collagen, in the skin), cell death, a reduction in cell proliferation (therefore reducing skin renewal and wound healing) and ATP levels, all of which contribute to impaired repair and a weakened skin barrier. All these mechanisms are interlinked with the effects previously mentioned. Effects of air pollution are encountered in all layers of the skin, not just in the uppermost layer (stratum corneum) through direct topical exposure, but also indirectly in the dermis and basal epidermal layers, due to the systemic blood distribution of inhaled or ingested pollutants which have been metabolised by the body. Chronic exposure to pollutants



[43] (VOCs), e.g. aerosols, solvents, disinfectants, air fresheners
[44] (PAHs), which are introduced via natural emissions, e.g. volcanic eruptions and forest fires, but also from the incomplete combustion of some organic substances related to humans, such as waste incineration, vehicle emissions, and coke and asphalt production
[45] Primarily nitric oxide (NO), and nitrogen dioxide. Can cause ozone formation, damage crops and also increase insect pests on plants.

can lead to dehydration of the skin, disruption of the skin microbiome[46], skin barrier damage (increased by disruption of the skin microbiome), skin cancer (mutagenicity), contact dermatitis, acne (through increased sebum production and smog particles trapping bacteria inside pores), and worsening of the symptoms of chronic inflammatory skin diseases such as eczema, seborrheic dermatitis, and psoriasis (airly, n.d.) (Araviiskaia, 2019)[47]. The air pollutants most damaging to eye health include carbon monoxide, nitrogen dioxide, sulphur dioxide (both oxides), asbestos, benzene, particulate matter, heavy metals, dioxin[48], and CFCs[49]. Smoke (a form of PM) is an irritant, and when in contact with eyes, its tiny particles can melt into your tears, coating the surface of the eye and causing harmful effects. The most common eye issue from air pollution, is dry eye syndrome[50], where the eyes can't produce enough tears or meibum[51] (caused by meibomian gland dysfunction). In high concentrations, these pollutants can cause at minimum, burning, redness, irritation, and eye watering, but with prolonged exposure this can develop into itching, discharge, gritty sensation, and an increased risk of infection. In the worst case they can cause visual difficulties, with impaired colour vision and refractive errors. Indoor air pollution has also been linked to

[46] Consists of bacteria, fungi, and viruses. This is essential to help fight off harmful substances and for the immune system. If it is disrupted, there can be an overgrowth of harmful bacteria.
[47] These sources concur, and both agree that air pollution harms skin health, identify PM, PAHs, and VOCs as key pollutants which damage skin, and note that chronic exposure matters. The Airly source is less rigorous and omits some complexities while still reliable for general effects, whereas the Araviiskaia (PMC) article includes clinical studies and caveats, and is reliable since it is published on the National Library of Medicine database.
[48] Dioxin is a persistent organic pollutant (takes a long time to break down), which is highly toxic and can cause cancer, reproductive and developmental problems, damage to the immune system, and can interfere with hormones.
[49] chlorofluorocarbons - can cause eye and skin irritations.
[50] As a result, it cannot be moisturised properly, and redness soreness, inflammation, and sensitivity of the eye to light, wind and smoke appear.
[51] Secreted by the Meibomian glands, this oil-like substance coats the aqueous layer of the eye and provides tear film stability. If this is not produced, excess tears will be produced to try to compensate.

the development of cataracts. Since pollutants can trigger allergies, they can indirectly cause allergy-related symptoms in the eyes (airly, n.d.).

Effects of Pollution when Inhaled

PM2.5 are a cause for particular concern since their small size allows them to evade the body's natural defences, penetrate deep into the alveoli, and in many cases, enter the bloodstream. This ability to reach the systemic circulation distinguishes fine particles from larger PM10 particles, which tend to affect only the eyes, nose, and throat. Once absorbed, PM2.5 and gaseous pollutants trigger the same mechanisms observed in the skin – oxidative stress, inflammation, immunosuppression, and mutagenicity[52]. These processes affect the cardiopulmonary system and virtually every other organ, causing damage to tissues and cells (WHO, n.d.). Air pollution therefore contributes to both all-cause mortality and specific diseases - which are often difficult to attribute to a single source of exposure, since they develop over many years. Diseases such as COPD can be triggered by chronic exposure to air pollution, yet their onset latency may be multiple decades. This latency, and difficulty of association, makes the true impact of air pollution easily underestimated both clinically and in policy (Dean-E-Schraufnage, 2018)[53].

Effects on the Respiratory System

Short term exposure (over hours or days) to high levels of PM can reduce lung function, trigger acute conditions such as bronchitis, respiratory infections and aggravated

[52] Agent which permanently changes genetic material (usually DNA) in an organism, and therefore increases the frequency of mutations, which can lead to a higher risk of cancer. Can be a carcinogen. Substances are classed as carcinogenic if after exposure (inhalation), they induce malignant tumours, increase their incidence or malignancy, or shorten the time of tumour occurrence (i.e. how fast it grows).

[53] This source is reliable since it is a review conducted by the Forum of International Respiratory Societies' Environmental committee, and it is published through NLH, an official website of the US government.

asthma, and can aggravate lung disease. In otherwise healthy individuals, such exposures are more likely to cause temporary symptoms, including chest tightness, shortness of breath, coughing, phlegm, and irritation of the eyes nose and throat. Chronic exposure[54] to air pollution, particularly PM2.5, increases the risk for (usually non-communicable) diseases with a longer onset, such as COPD (chronic obstructive pulmonary diseases), lung cancer, and pneumonia. During the summer, levels of PM2.5 and ozone are elevated, creating an additive or even synergistic (greater than additive) burden on respiratory health, and this combination is known to drive significantly higher hospital visits and mortality during these months. Formed in the atmosphere via secondary reactions involving NOx and VOCs, ozone is highly oxidising and directly damages mucous membranes and the lungs. The synergistic relationship could be due to PM2.5-induced inflammation worsening the oxidising effects of ozone, or vice versa. Epidemiological evidence supports this: Liu et al. found that in cities with high levels of co-exposure to PM2.5 and ozone, mortality from cardiopulmonary causes was significantly larger than would be expected from summing the individual risks (Liu, 2023)[55]. PM2.5 having such severe impacts on the body may in part be due to that harmful organic toxins condense on fine PM, as mentioned in relation to microplastics. These toxins have been shown to cause the types of cellular change which can lead to cancer, and chronic inhalation exposure to diesel fumes therefore poses a lung cancer hazard, as evidenced by the “Group 1” carcinogen classification by the International Agency for Research on Cancer (IARC). Lung cancer remains the deadliest form of cancer, with more people dying from it each year than of colon, breast, and prostate

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[54] i.e. experienced by people living for many years in areas with high particulate levels
[55] This source is reliable since it is published in the British Medical Journal and uses a large data set.

cancers combined. Chronic exposure has also been linked to the development of chronic bronchitis, reduced lung function, and premature death.

Effects on the Cardiovascular System

Chronic exposure is also strongly linked to cardiovascular diseases such as stroke and ischaemic[56] heart disease[57]. In people who already have heart disease, short term exposures have been linked to heart attacks and arrythmias, causing serious problems in a short period of time, with little warning[58]. Those with cardiopulmonary conditions like heart diseases, emphysema, asthma or COPD, and congestive heart failure[59], as well as those with factors which increase the risk of heart attack (i.e. high blood pressure or elevated cholesterol levels) are at the highest risk, and have much higher hospital admissions for cardiopulmonary symptoms, decreased lung function, and potentially death, on days with elevated PM levels when air quality is poor. Diabetes may also cause an increased risk, which could be because those with the condition are more likely to have underlying cardiovascular diseases.

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[56] A less than normal amount of blood flow to part of your body, meaning your tissues aren't getting the oxygen they need. Can lead to heart attack and strokes.

[57] Coronary heart disease: heart problems caused by narrow heart (coronary) arteries that supply blood to the heart muscle, often caused by a buildup of calcified plaque called atherosclerosis, but it can also be caused by a blood clot or constriction of the blood vessel.
<50% narrowing (early) CHD don't experience limitations of blood flow or symptoms. If it progresses, i.e. left untreated, it can get worse. Symptoms most likely to occur when demand for oxygen increases, i.e. exercise or emotional stress.
When the blood flow to the heart muscle is completely occluded, the heart muscle cells die, called a heart attack or myocardial infarction. (NCBI, 2010)[reliable source since it is an official website of the US government].

[58] Symptoms such as chest pain or tightness, palpitations, shortness of breath, or unusual fatigue, may indicate a serious problem.

[59] [59] Complex clinical syndrome, characterized by inefficient myocardial (middle muscular layer of the heart wall) performance, resulting in compromised blood supply to the body, i.e. a disorder that impairs ventricular filling, or ejection of blood to the systemic circulation. Risk factors include smoking and second-hand smoke exposure. The disease results in a 35% risk of death in the first year, comparable to that of some cancers overall.

Other Systemic Effects

There is increasing evidence for many other adverse effects, including adverse pregnancy outcomes (low birth weight, pre-term deliveries, the baby being small for its gestational age, and possibly foetal and infant deaths), other cancers, diabetes, cognitive impairment, and neurological diseases. WHO provides evidence of links between air pollution and type 2 diabetes, obesity, Alzheimer's disease and dementia. Air pollution was officially classified as carcinogenic in 2013 (International-Agency-for-Research-on-Cancer, 2013)[60]. This concurs with certain constituents of air pollution such as diesel fumes being known carcinogens.

Vulnerable Populations

Those more at risk include children, since their bodies are still developing, they spend more time at high activity levels outside, and they're more likely to have acute asthma or respiratory diseases. The elderly, due to potential undiagnosed cardiopulmonary diseases or diabetes, and pregnant women. Genetics, co-morbidities[61], nutrition, and certain sociodemographic factors (see earlier section – (EEA, Unequal exposure and unequal impacts, 2019)) can also increase risk. For those with lung disease, short term exposure can trigger increased irritation, leading to a temporary obstructive breathing pattern, potentially manifesting itself as coughing, chest discomfort, shortness of breath, or unusual fatigue.

[60] This source is reliable since it is a research group led by the world's leading experts and is a part of WHO.

[61] The simultaneous presence of 2 or more diseases / medical conditions in a patient.

Air Filtration

This research highlights the need for stronger and more widely implemented strategies to mitigate air pollution both at the point of emission and within the environments where populations are most exposed. For this to be achieved, mitigation will have to be approached from several angles; as with geoengineering, developments in the realm of air filters along cannot justify continued emissions, especially due to the increasingly unequal exposure this would create between those able to afford such solutions, and those not. More comprehensive and effective air filtration technologies are becoming an ever more critical component of public health protection and preventative medicine and offer one of the most direct methods of reducing harm. An air filter could be any type of mechanism which removes unwanted pollutants or specific particles in the air, but most commonly it is composed of fibrous or porous materials which focus on removing particulates such as smoke, dust, pollen, mould, viruses, and bacteria from the air (Wikipedia, 2009)[62].

Conventional Filters

The most common higher-grade filter is a HEPA (high efficiency particulate air) filter, which is a type of pleated[63] mechanical air filter, and is comparatively affordable. They have a wide variety of applications, including homes, aircraft, medical facilities, and use in clean rooms for integrated circuit board fabrication. This last example demonstrates

[62] This source is not entirely reliable since this article in particular needs additional citations for verification, and their explanation for the "HEPA" acronym slightly goes against what the US department of energy defines it as. This source is still however useful to gain subjective opinions, such as what an air filter is thought to be.

[63] A filter made from folded (pleated) material designed to increase the total surface area, leading to a higher particulate holding capacity, and rate of airflow in comparison to flat filters. Pleated filters can either refer to a pleated design, e.g. used in a HEPA filter, or a general form of filter which has no specific efficiency rating, but usually does not meet HEPA level performance.

their effectiveness, since there is so little tolerance for PM in clean rooms. According to the European standard[64], the filter must remove 99.95% of particles which have a size equal to or greater than 0.3 micrometres (i.e. PM10) and is theoretically able to remove at least 99.7% of dust, pollen, mould, bacteria, and any airborne particles with a size of 0.3 microns (micrometres). The specification of 0.3 microns is chosen since it is the "most penetrating particle size (MPPS)", meaning that particles of any other size are trapped with even higher efficiency, which is why the actual efficiency of the filter is at least the calculated efficiency for the MPPS (Enviromental Protection Agency, 2025)[65]. HEPA filters are generally composed of a mat of randomly arranged polypropylene or fiberglass fibres, which are each composed of tangled bundles of fine fibres. This filter system stops large particles in the same manner a kitchen sieve works, and with smaller particles it works based on the principle that they can't keep up with the motion of the air, due to the sudden and violent twists which are required as the air flows between randomly arranged fibres and microfibers. For the smallest particles, they are filtered by the principle of Brownian motion (they have very little inertia and move randomly due to collisions with the surrounding air particles). This random movement causes many of them to collide with the fibres where they are held. One of the many advantages of HEPA filters in comparison to its counterpart filters, is the fact that it even captures particles that are smaller than the filter's pore size, unlike other filters, due to adhesion between the particle and the filter surface. As efficient as HEPA filters are at filtering very fine particles effectively, they cannot filter out gases or odour molecules. To achieve that, an activated charcoal or similar filter would need to be used in addition

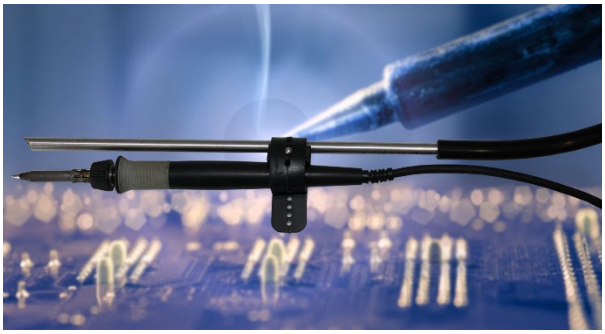
[64] European Standard EN 1822-1:2009, "High efficiency air filters (EPA, HEPA and ULPA)", 2009.
[65] This source is reliable since it is an official website of the US government, a different department of which also sets the standards of efficiency for HEPA filters.

or instead of a HEPA filter. The most common form in which this comes is an activated carbon prefilter. This works twofold, firstly it attempts to remove odour (although this is usually futile since the thickness and quality is insufficient), and it also extends the service life of the costlier HEPA filter, by filtering most of the larger dust, hair, PM10 etc from the air, before it reaches and saturates the HEPA filter. HEPA filters are very well suited to the biomedical industry, such as for preventing the spread of airborne bacteria and viruses and reducing infection. When used in this industry, HEPA filters are typically paired with high energy ultraviolet light units and/or panels within the HEPA filter, with an antimicrobial coating to kill live bacteria and viruses that are trapped. This bilateral approach can result in efficiency ratings as high as 99.995% in its given metric.

Filters can contain an absorbent or a catalyst such as charcoal instead, which may additionally remove odours and gaseous pollutants such as VOCs or ozone, which are both generally much harder to filter. Most charcoal filters intended to filter odour do not do so effectively in domestic filtration systems, since the required volume and density of carbon filter needed to remove odour would be too large for the system to operate efficiently, and the pressure needed would be too large. Activated charcoal filters uses activated carbon, a porous material made from biomass such as coconut shells, coal, wood, making it sustainable, an important consideration for air filters, particularly those which are disposable or semi disposable. One of the few examples of reuseable filters are metal mesh air intake filters, used for filtering very large particles out of the air to prevent them from entering the engines of vehicles. In most cases, such as with activated charcoal filters, air filters need to be absorbent to some extent, to capture particles which are too small to be caught by a solid material, meaning they intrinsically cannot be reuseable[66].

HEPA filters are well suited to countering common indoor pollution sources, such as particulates generated from cooking. They can capture droplets of cooking oil, food particles, and carbon particles from overcooking or incomplete combustion. For this application, a HEPA filter is most effective when combined with activated charcoal, which enables removal of odours, gaseous pollutants, and VOCs generated by certain fuels (e.g. kerosene) or high-temperature cooking methods such as stir-frying.

In DIY activities such as soldering, rosin fumes are the main concern, as lead solder is now rarely used. HEPA filters have been proven to be effective against such fumes, and "will give good protection if properly used" (A. E. JOHNSON, R. C. BROWN, 1998)[67]. To illustrate the how significantly the setup and quality of activated charcoal filters affect efficiency, there are two examples of such filters used against soldering fumes. Activated carbon filters used in the construction of very rudimentary "air purifiers" (a laptop fan on the back of the thin foam sheet) built into the soldering iron unit had virtually zero filtration efficiency and therefore protection against particulates or vapours. However, granular carbon filters in a "tip extraction system" effectively filtered pollutants (A. E. JOHNSON, R. C. BROWN, 1998).



[66] Meaning they will have to be replaced before the actual filter material wears down.
[67] This source is reliable since it's published by an oxford academic.

More recently, domestic 3D printing has emerged as a source of ultrafine particles and VOC emissions. Limited evidence suggests that hybrid HEPA–carbon systems can mitigate these pollutants. A recent report by the Chemical Insights Research Institute (2022) investigated the effectiveness of various filtration strategies for emissions from desktop 3D printing. A hybrid HEPA and activated carbon bed filter was highly efficient against particles, but far less effective for VOC removal (Insights, 2022)[68]. A study which investigated the concentrations of pollutants caused by 3D printing, concluded that the most effective countermeasures to these high UFP and VOC concentrations were, in descending order: high-flow spot ventilation, sealed enclosures around the printer with filtration, moderate-flow spot ventilation, and finally high-CADR stand-alone air cleaner with both gas and particle filtration within immediate proximity to the operating 3D printer. Upgrading central HVAC filtration is one of the least useful methods. This gives useful insight into just how critical point-of-emission air filtration can be for maintaining safe levels of air quality (Parham Azimi, 2017)[69].

ULPA (Ultra-Low Particulate Air) filters remove up to 99.999% of particles down to 0.12 micrometres, but they are more commonly found in specialised industrial and laboratory settings than in homes, due to their higher cost, and large airflow requirement. The MPPS of ULPA filters is around 0.1-0.3 microns, which is on the same scale as HEPA filters. Their greater filter density and advanced design allow such high efficiencies in the filtration of UFP, but this also causes a higher-pressure drop meaning

[68] This source is reliable since it was produced by a recognised, independent non-profit research organization focused on public health. However, it is a technical research report, not a peer-reviewed article.

[69] This source is reliable since it is affiliated with the U.S. EPA, was published in a peer-reviewed journal, used real time measurement of emissions, and recognises limitations.

more pressure and therefore, a stronger fan or compressor needed to maintain the same airflow. While ULPA filters capture a greater proportion of ultrafine particles, e.g. those produced during soldering or from plastic fumes, the practical advantage over HEPA filters in domestic scenarios is limited. A greater overall health benefit is often achieved by combining a HEPA filter with a high-quality activated carbon filter, which theoretically enables the capture of both particulates and gaseous pollutants. Standalone HEPA filters also remain more efficient for day-to-day use, given their lower resistance to airflow and greater suitability for domestic-scale systems. HEPA, activated carbon, and ULPA filters represent the bulk of conventional filtration media. The following section will consider how these can be adapted or supplemented for specific applications.

Complementary Technologies

Although conventional mechanical filters such as HEPA and activated carbon remain widely implemented due to their affordability and simplicity of use, they do not offer comprehensive solutions. They are unable to capture certain categories of pollutants or may not be able to capture a category to a high enough standard for specialist use such as in hospitals. A range of technologies have been developed and commercialised to fill this gap, which are often used in conjunction with conventional mechanical filters:

Ultraviolet light is used to purify air in a UV Germicidal Irradiation (UVGI) system, with the UV light killing bacteria, viruses, and some moulds, by damaging their DNA or RNA. This method is not typically effective in a hybrid domestic air purifier, since it is unfeasible for the light to be of a sufficient intensity, and the air exposed to it for long enough. Therefore, having both an effective UVGI system, and a high rate of airflow are mutually exclusive in a domestic air purifier. UVGI is commonly used in conjunction with HEPA filters in hospital air filtration (NHS, 2023)[70]. Another example is air ionisers, which work by releasing negative ions into the air, helping particulates clump together and land on surfaces inside the filter which can then be cleaned. This means particles which are too small to be filtered mechanically, such as those produced from tobacco smoke, will clump together, and then land on surfaces throughout the home where they can then be more easily cleaned up. Some ionising air filters use an alternative design which includes specially designed collection plates, which are oppositely charged in relation to the particles, meaning that the filter can fully remove (small but not large) particles, instead of simply making them easier to clean up. Studies have found that negative ions can stop the growth of viruses (International Journal of Molecular Sciences, 2018) and inactivate viruses in the air and on surfaces (Journal of Preventive Medicine and Hygeine, 2020). In addition, the negative ions produced offer many holistic health benefits, decreasing stress, regulating sleeping patterns, increasing immune function, and supporting mood (International Journal of Molecular Sciences, 2018)[71]. Disadvantages include being ineffective for asthma and allergies since they can't remove large particles from the air and only *clump particles together* in the first place. Ionisers emit ozone as a byproduct, which is innate to their mechanism since negative ions electrically charge airborne particles, producing ozone. Ozone is a powerful oxidiser which makes it effective against viruses, but it is also a high-level lung irritant and can be hazardous to health. These filters are usually used in tangent with other filtration methods such as HEPA filters, to remove these smaller particles which

[70] This source is reliable since it is published by the National Health Service.
[71] Both are reliable sources since they are from a highly respected database - the National Institutes of Health.

might otherwise slip through conventional filters. One notable positive of air ionisers is that since they do not become saturated with particulates, they require less frequent maintenance than mechanical filters, some of which need constant replacement.

Due to its virus filtering capabilities, HEPA filters were widely used during the COVID-19 pandemic, with a new and innovative air purifier setup being created under the pressure of efficient airborne virus removal being needed despite stretched supply chains and high cost of conventional air purifiers. This was an opensource, DIY air purifier design called the **Corsi-Rosenthal box**, brought into conception by a professor at the University of California Davis, Richard Corsi, and an engineer, Jim Rosenthal. It consists of 4 HEPA filters arranged in a cubic, with the bottom made of cardboard, and the top surface being sealed with a fan. The filter sides are sealed with tape, meaning when the fan is switched on, negative pressure inside the box forces air through the filters, purifying the surrounding air at a clean air delivery rate of 17-24 metres cubed per minute according to a 2022 study which used an extra filter on the side of where the cardboard normally is, at only around a tenth of the cost of a commercial air purifier.

Emerging Technologies

There are several emerging technologies for air purification, an example of which is NanoJet Technologies' water-based air purifier. It works without the need for any filters, instead using a sustainable water-based solution which can filter airborne viruses, allergens, and pollutants, without filters or chemicals. Trillions of nanoscale droplets are produced by the system, that surround and neutralise airborne contaminants, forcing them to descend as they are too heavy to stay airborne. These pollutants are then swiftly removed. The ultrafine droplets can also remain suspended in the air for extended periods for prolonged effectiveness, which makes it especially suited for combating small, persistent airborne particles such as smoke and viruses. (Gupta, 2025)[72]. Photocatalytic oxidisation (PCO) air purifiers are a new technology which claims to be able to remove VOCs from the air using a photochemical reaction, but this may inadvertently create chemical byproducts which are unpredictable and toxic. They also emit ozone and are not effective against particulate pollutants. Therefore, this is a technology which is probably much like air ionizers, in that it is promising, but needs more development to get to a stage where they can be implemented without health concerns.

Filtration Standards

Filter efficiency standards provide useful background for comparing conventional technologies to each other and to emerging technologies such as bio-engineered filters. In Europe, the EN 779 standard has been used to classify filters according to their ability to capture particulates, while in the U.S., the Minimum Efficiency Reporting Value (MERV) system is commonly applied, with ratings from 1–20. Residential air filtration systems typically use filters in the range of MERV 7–13. In both systems, higher ratings correspond to finer filtration, though this

Usage	Class	Performance	Performance test	Particulate size approaching 100% retention	Test Standard
Coarse filters (used as Primary)	G1	65%	Average value	>5 µm	BS EN779
	G2	65–80%	Average value	>5 µm	BS EN779
	G3	80–90%	Average value	>5 µm	BS EN779
	G4	90%–	Average value	>5 µm	BS EN779
Fine filters (used as Secondary)	M5	40–60%	Average value	>5 µm	BS EN779
	M6	60–80%	Average value	>2 µm	BS EN779
	F7	80–90%	Average value	>2 µm	BS EN779
	F8	90–95%	Average value	>1 µm	BS EN779
	F9	95%–	Average value	>1 µm	BS EN779
Semi HEPA	E10	85%	Minimum value	>1 µm	BS EN1822
	E11	95%	Minimum value	>0.5 µm	BS EN1822
	E12	99.5%	Minimum value	>0.5 µm	BS EN1822
HEPA	H13	99.95%	Minimum value	>0.3 µm	BS EN1822
	H14	99.995%	Minimum value	>0.3 µm	BS EN1822
ULPA	U15	99.9995%	Minimum value	>0.3 µm	BS EN1822
	U16	99.99995%	Minimum value	>0.3 µm	BS EN1822
	U17	99.999995%	Minimum value	>0.3 µm	BS EN1822

[72] this source appears reliable since it is from a news company specialising in engineering.

often comes at the cost of greater airflow resistance and higher-pressure requirements. The HEPA filter is widely regarded as the industry benchmark for domestic use with this framework, with only ULPA filters surpassing it in terms of filtration efficiency (Wikipedia, 2009). Both ratings provide useful benchmarks but are solely designed to evaluate particulate capture, and do not account for the multifaceted functionality which emerging filtration technologies claim. For example, bioengineered filters use microorganisms residing in the filter to biodegrade pollutants, potentially entirely breaking them down and avoiding any cross-media transfer of pollutants, e.g. pollutants being transferred into wastewater when the filter is cleaned. Newer and more relevant standards are replacing the aforementioned two: ISO 16890 has gradually replaced EN 779 as the global standard of particle filtration evaluation and provides a more realistic efficiency rating based on real particulate matter rather than laboratory test dust. Therefore, this is a step forward for quantifying why some particulate matter types cause such disproportionate harm in comparison to others. ISO 10121 evaluates the efficiency of gas-phase filters including activated carbon, addressing a critical gap in earlier standards; and a gap which is yet to be tackled in terms of domestic filtration. This is especially significant given the growing body of evidence on the health risks raised by domestic gaseous pollutants, including emissions from gas hobs, and VOCs in consumer products (Alblooshi, 2025)[73]. Meanwhile, EN 16798 shapes guidance on indoor air quality and ventilation performance, creating a broader framework for healthy indoor air quality. In combination, these newer standards help to quantify the performance of cutting-edge filtration technologies such as bioengineered and

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[73] Likely reliable – published in a legitimate academic journal – Frontiers in Toxicology and is peer-reviewed. There is transparency regarding conflict of interest. However, Frontiers in Toxicology has faced backlash over peer reviewing, leading to retractions of over 100 articles.

nanoengineered filters, but to gain a full picture, they must be evaluated alongside specific metrics such as microbial reduction assays (how well a filter can inactivate microbial organisms), chemical degradation tests (how well a filter can degrade or adsorb gaseous pollutants), by-product formation analysis (whether a filter, especially those with catalytic surfaces such as photocatalytic oxidation filters, produce harmful secondary compounds such as ozone), and long-term stability tests (how the filter's performance holds up over extended periods). These provide realistic expectations for how a filter performs in practice, against varying pollutants, and how the benefits and potential negatives weigh up. It is clear to see that most standards do not consider these factors.

Innovative Filtration Technologies

Advances in nanotechnology and biotechnology are shaping many industries, including the air filtration industry. While conventional filters such as HEPA and activated carbon remain the standard, the next generation of filters offer multi-faceted benefits including significant efficiency gains, inherent antimicrobial functionality eliminating the need for dual stage filtration (e.g. HEPA and UVGI), and greater sustainability – filters can break down pollutants on their own. This section reviews some of the latest literature on these technologies, focusing on nano- and bio-engineered solution, laying the foundation for analysing their potential to replace conventional solutions.

Nano-engineered Solutions

Nanofiber Membranes

Conventional filters are often made from mats of relatively thick fibres, often a few micrometres in diameter. These can capture larger dust particles well, but struggle with very small particles, such as the ultrafine particulates which cause the most damage to health (Schraufnagel, 2020)[74]. Nanofibers in comparison are made from extremely thin fibres, with diameters in the order of nanometres (i.e. 1000x smaller than conventional filter fibres), hundreds of times thinner than a human hair. Thousands of tiny fibres are layered across each other, forming a web-like mat with very small pores. Advantages include the ability to catch much smaller particles due to smaller pore size, much larger surface area due to thin fibres, and high porosity (80%-90%) (Tang, 2016)[75], which allows air to flow through them with little resistance – meaning there is only a small

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[74] This source is reliable – a review articles summarising the known and proposed health effects of UFPs, often defined as particles with a diameter <= 0.1 micrometres. It is published in a recognised peer-reviewed journal, but since it was published in 2020, new research may have challenged some conclusion.

[75] Reliable source – used a both theoretical and empirical approach, published by SAGE (respectable published in environmental areas), and acknowledged that adding nanofibers has trade-offs between pressure drop and fine particulate efficiency. The paper does not discuss standalone nanofiber membranes.

pressure drop (Leung, 2020)[76] – crucial to domestic air purifiers and face masks (Kim H. B., 2020)[77]. Smaller pore size is correlated to the minimum particle size a filter can capture, however if pores are too small, airflow resistance increases. The optimum pore size therefore depends on how energy efficiency and filtration efficiency are balanced.

The method of production for nanofiber membranes can vastly affect performance, since it determines fibre diameter, uniformity, pore size and structure, and mechanical strength. There are many fabrication techniques, but the most significant is electrospinning, due to its simple manufacturing process and its ability to create ultra-fine fibres with easily controlled porosity, enhancing filtration performance (Verma, 2023)[78]. Electrospinning makes use of electrostatic forces to stretch a polymer solution or melt as it solidifies. A polymer solution or melt is placed into a syringe with a nozzle and subjected to a strong electric field. Under this field, the polymer is ejected from the nozzle and deposited onto a collector, forming a nanofibrous membrane. It is widely regarded as a simple, low-cost, and effective method for producing polymer nanofibers. In the electrospinning process, fibres are charged as they are formed through the electrostatic forces. However, if nothing else is done, this charge dissipates once the fibre mat is formed. A method can be used to retain these charges within the fibres, so that they continue to attract airborne particles and therefore increase filtration efficiency, and filters treated in this way are known as electrets. Such filters are

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[76] This source is reliable since it is archived in PMC, meaning it passed peer review and is part of the scientific record. It shows that a 6-layer configuration of electret nanofiber membranes achieved very high particle capture while maintaining a low-pressure drop (26 Pa). A greater or equal to 95% capture efficiency for 0.3 micrometre particles (MPPS) was observed, and the capture efficiency for PM2.5.
[77] Reliable source – peer-reviewed research article in the AAAR flagship journal, which is very reputable in the field of filtration. It analyses how characteristics such as filtration efficiency and pressure drop interrelate. There is no field testing, but only theoretical and lab-based principles, so may be limited.
[78] This article is reliable – it is published in a reputable materials and filtration journal via ScienceDirect, and focuses on biopolymers used in electrospun fibre membranes for PM2.5 dust protection.

especially useful in ion-rich environments, including construction sites, where airborne particulate load is high (Gough, 2021)[79].

Electret fibres are specifically engineered and treated in a way, so that they hold a permanent or quasi-permanent charge. This can be done through specific, charge-retentive polymers such as PVDF (Kang, 2021)[80], and/or through post treatment charging. Although some electrostatic capture can occur in non-electret membranes due to charged particles in the air passing through, this effect is weak and short-lived.

Pore size is a critical determinant of filter performance, not only due to a smaller pore size being able to physically obstruct pollutants with a larger diameter. In both electret and non-electret nanofiber membranes, there is an exponential (i.e. super-linear) relationship between filtration efficiency and decreasing pore size. This is due to the way in which the geometry of the fibre net changes, and relies solely on mechanical, not electrostatic, properties. When the fibre diameter, and therefore the pore size, decreases: the surface area per unit mass of fibres increases, the pore structure tightens exponentially leading to far more fibres per unit area and a greater chance of interception, and the single fibre efficiency improves – which is compounded since penetration through a filter layer is multiplicative across fibres (through simple probability theory).

In electret membranes, the improvements in efficiency seen are even steeper, with a larger efficiency gain for each decrease in pore size. On top of the mechanical effects of

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[79] This review article is reliable – it is published in ACS (American Chemical Society) Omega, which is peer reviewed and has a high impact factor of 4.3.
[80] This source is reliable – a peer reviewed research article published in Polymers, Basel. MDPI carries out fast but documented peer reviews, which have drawn some scrutiny for editorial rigor. However, Polymers remains highly indexed. It is a study based on face masks, in a lab, so may not translate into other applications of filters, such as air purifiers.

smaller pores, this also brings particles closer to the charged surfaces of the fibres, where the electrostatic forces can act upon them disproportionately stronger (Rajupet, 2022)[81]. Electrostatic force is inversely proportional to the square of the distance between the two charged objects, so if the distance is reduced to half of the original distance through making the pores smaller, the force acting upon the particle will be four times as large. However, the efficiency is not *also* a squared function of pore size, due to the many mechanisms at play.

Other desirable physical characteristics include high surface roughness, good connectivity, and a low gram weight. High surface roughness means uneven textures at the nanoscale, and this both increases the effective surface area, giving more opportunity for particles to stick through mechanical interception and electrostatic attraction, and creates more disturbances in the air stream around the fibres, increasing collision probability. Good connectivity refers to a continuous, evenly distributed web structure, rather than weakly bonded areas, or areas with fibres clumped together. This ensures sufficient mechanical stability preventing deformation and keeps electrostatic capture as high as possible. Low gram weight equates to a low mass per unit area, meaning a lower pressure drop with the same functionality, and higher energy efficiency. This makes it easy to layer nanofibers on top of conventional filters without significantly increasing bulk or hampering energy efficiency. At present nanofiber membranes are exclusively used as a thin layer on top of a conventional filter,

[81] Very reliable source – peer-reviewed, recent, published in a leading journal for particle filtration, directly quantifies Coulombic forces and how electrostatics enhance capture of nano-scale particulates.

enhancing ultra fine particulate capture without significantly increasing airflow resistance.

Another important metric is the quality factor (QF). As previously discussed, there is often a trade-off between desired filtration efficiency and pressure drop – and therefore energy use for filters. The QF combines both into a single metric, and a higher value therefore means better overall performance – higher capture efficiency at lower resistance. The PVDF electret nanofiber multilayer membrane from the (Leung, 2020) study reported a QF of around 0.109 P/a. QF values for HEPA or semi-HEPA filters are typically on the order of 0.01 P/a – Kim et al. reported a HEPA QF value of around 0.015 P/a (Kim H.-J. , 2021)[82]. This indicates a very strong performance, with efficiency nearing the level of HEPA filters, while maintaining a far lower pressure drop. Leung et al. reported a pressure drop of around 26 Pa, which is very low in comparison to pressure drops in typical unused HEPA filters – which were found to range from 45 to 115 Pa in "Characteristics, Pressure Drop, and Capture Efficiency of New and Repeatedly Washed Heavily Loaded HEPA Filters" (SMIGIELSK, 2018)[83]. Overall, electret nanofiber membranes demonstrate higher quality factors than conventional HEPA filters. Their customisability in terms of the morphology and dimensional characteristics, and electrostatic modifications, shows promise at least for integration with pre-existing

[82] This source is reliable – it was published in the Applied Sciences Journal, an indexed journal meaning the paper is peer-reviewed and citable. It includes a real commercial HEPA as a benchmark. However, Applied Sciences is sometimes criticised for less stringent review rigour compared to elite journals such as Aerosol Science and Technology.

[83] Reliable source – published in the International Journal of Occupational Hygiene, using empirical data. However, the filters tested are industrial HEPA filters und high velocity so don't necessarily reflect PACs (portable air cleaners) or HVAC systems exactly.

filters such as HEPA, if not as a standalone filter – this is yet to be seen as the technology evolves.

Nano Coatings

While nanofiber membranes represent morphological and structural innovation in air filtration, nano coatings provide a functional enhancement to filtration. Nanoscale active materials are added to the surface of existing fibres, exerting additional properties such as antimicrobial activity, or boosting existing properties such as hydrophobicity. Often, heavy and transition metals with biocidal[84] properties are employed. More than 30 heavy metals can potentially exert effects on microorganisms, and many of these have been known for centuries to possess anti-infective properties (acting against infection to some extent). Silver (Ag) is the most heavily studied and is used both in filters and dressings. Ag+ ions bind to a group in proteins, disrupting membranes and interfering with DNA replication. Copper (Cu) has also been used historically, e.g. for water vessels, and is still in use, e.g. for antimicrobial touch surfaces. It works through directly rupturing membranes, generation of ROS (reactive oxygen species) and protein damage. Zinc / zinc oxide (Zn / ZnO) is used in sunscreens, nanoscale coatings, and wound dressings, and works through the disruption of enzymes, as well as by generating ROS under UV and visible light. Other examples which don’t technically qualify as “heavy metals” include gold (Au) and iron oxides (Fe2O3 or Fe3O4). Titanium (TiO2) is widely used in medical implants, due to high

[84] Chemical substance or microorganism intended to destroy or render harmless any harmful organism.

biocompatibility[85], osseointegration[86], and its strength to weight ratio. Its stable surface layer not only enables safe contact and bonding with bone but also provide photocatalytic antimicrobial properties. As a material it is inert, but when exposed to UV (or visible light if doped) it becomes a photocatalyst[87], creating ROS which oxidise and destroy bacteria, viruses, fungi, and organic pollutants. In the doping process, nitrogen, carbon, or transition metals can be added, changing the chemical properties of the material, and shifting the photocatalytic activity into the visible light range (Asahi, 2014)[88]. Still, it requires illumination and cannot operate in the dark. This need for illumination differentiates photocatalytic coatings such as TiO2, ZnO, and Fe2O3 from the ion-releasing heavy metals like Ag and Cu, which act continuously regardless of light.

The strengths of all these metals or metal oxides are effective and simple mechanisms against harmful organisms and pollutants. However, there is a risk of nanoparticle leaching and ecotoxicity, as well as an increase in filter cost. This increase in cost is not often quantified, but it was reported, “the higher the concentration of Ag added to modify the substrates, the greater was the removal of E. coli” in water, in a study in the International Journal of Environmental Research and Public Health. (Mpenyana-Monyatsi, 2012)[89]. This source claims that these coatings are economically viable in

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[85] “Biocompatibility is the term used to describe the state of affairs when a biomaterial exists within a physiological environment, without adversely and significantly affecting any of the other body of environment and material (Williams, 1981).” (S. Ramakrishna, 2003)
[86] “Osseointegration refers to a phenomenon where an implant becomes so fused with bone that they cannot be separated without fracture.” (Hudecki, 2018)
[87] A material that can absorb light energy to accelerate a photoreaction without being consumed.
[88] This source is reliable – it is in a highly prestigious review journal – Chemical Reviews, which is fully peer-reviewed and indexed. It has thousands of citations indicating it being standard reference material.
[89] This study is reliable, it uses real experimental data and explores applying silver nanoparticles at various concentrations to various substrates, to test the removal of E.coli and other species from water.

water filtration contexts, which is a useful parallel for air filter coatings. Nanoparticle leaching refers to the release of nanoparticles or their ions into the surrounding environment. In the context of filters, this could be caused by moisture, mechanical abrasion, or chemical exposure, and it can in turn cause reduced biocidal action, as well as potential health and environmental risks. For example, some proportion of metal nanoparticles turn into metal ions, which can diffuse away, or entire nanoparticle pieces may break off if adhesion is weak. Among others, silver nanoparticles can undergo oxidative dissolution, releasing Ag^+ ions which diffuse away (Reidy, 2013)[90]. Ecotoxicity refers to the harmful ecological effects which some nanoparticles exert when released: e.g. bioaccumulation, and toxicity to soil microbes, aquatic organisms, and plants. On the molecular level this can include oxidative stress, membrane damage, enzyme inhibition, and genotoxicity (Rana S. , 2013)[91]. Advantages of surface nano coatings over embedded nanoparticles include strong surface activity and tuneable functionality, while drawbacks include risks of leaching, and weaker long-term adhesion. Nanoparticle coatings and nanoparticle embedded filters represent two, similar strategies for implementing the functionality of nanomaterials into conventional filter designs. Both use the same classes of nanomaterials, but coatings employ nanoparticles on the surface of fibres, whereas embedded filters use these particles incorporated into the filter material itself. Both are strategies, not filter types, and either

[90] This source is reliable, at least for the specifics of silver. It is published in a peer-reviewed, indexed journal – Materials – MDPI. MDPI faces some quality control criticism, but Materials is one of MDPI's stronger journals, with an established impact factor of around 3-4.

[91] Fairly reliable source – peer-reviewed, archived in PubMed Central confirming this, published in the International Journal of Nanoscience (IRSN Toxicology), but it is over 10 years old, and although still mechanistically accurate, no longer representative of the cutting edge. IRSN was not a high-impact journal.

or both can therefore be applied to conventional microfibre filters or to nanofiber membranes.

Nanoparticle-Embedded Filters

This encompasses a class of filters, where nanoparticles are incorporated into the filter structure, taking advantage of the unique properties of these materials to enhance conventional filters. Similarly to coatings, embedded nanoparticles can trap and neutralise microorganisms, degrade pollutants, or improve filter durability, but with a reduced risk of particle loss compared to coatings. Through careful choice of filter media, filtration performance can be customised for the application. These can be divided into polymeric fibre filters (Khdary N. H., 2023)[92], ceramic filters, carbon-based filters, and composite filters. Ceramic based filters may be used for industrial systems where heat resistance is valued, whereas hospital ventilators may use lightweight, antimicrobial polymeric fibre filters. Similarly to other nanofiltration technologies, nanoparticle used also plays a strong role in the performance, and it is important to note that the same nanoparticle can be used for both strategies (i.e. embedding *and* coating). Metal and metal-oxide based nanoparticles are commonly used in embedded systems just as they are in coatings. However, two additional categories of nanoparticles are frequently used: carbon-based, and polymeric. These materials are also applied as coatings, but they are more commonly embedded, since the improved stability and reduced likelihood of dispersion suits their properties particularly well. In membrane science, “separation performance” refers to the balance between filtration

[92] This is a reliable source for nanoparticle embedded polymer filters for water. It is a general review and is published in Membranes – MDPI.

efficiency[93] and permeability[94]. Inorganic nanomaterials (which includes metals and metal oxides, but not carbon- or polymer- based materials) can significantly improve both, but they are hindered by difficulty of large-scale production, and poor compatibility with polymeric matrices, inhibiting their practical, industrial use (Khdary N. H., 2023)[95].

Nanomaterials which are used in embedded filters can broadly be split into three categories: organic, inorganic, and carbon based. Organic nanomaterials include polymeric or biopolymeric materials such as dendrimers – highly branched polymers which can capture heavy metals, as well as a wide range of non-polymeric materials such as cyclodextrins – rings of glucose units which can capture VOCs. The unique properties of organic nanomaterials arise from the combination of unique nanoscale properties, with the functionality of organic molecules (Musa, 2025)[96].

Nanocellulose is another example of a functional organic nanomaterial – it is derived from natural polymers in wood, plant, and bacterial strains. Desirable features include hydrophilicity (attraction to water molecules, relevant in water filtration – hence why membranes developed from nanocellulose are often used in water treatment plants), non-toxicity, and enhanced strength (Khdary N. H., 2023). Other examples of functional organic nanomaterials include chitosan, a biopolymer derived from chitin, often found in the shells of crustaceans. This material carries a net positive charge, allowing it to

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[93] How effectively pollutants are removed.
[94] How easily air (or water) passes through.
[95] This is a recent, reliable review article, giving a good overview of state-of-the-art embedding technologies. It is published in the Membranes journal and is peer reviewed. However, this article mainly discusses membrane separation, which is not specific to air filtration systems.
[96] This is a reliable review – it is published in a peer-reviewed journal, Polymers, and investigates carbon-based nanomaterials in polymer composites, alongside other nanomaterials. It is recent, and defines a classification or organic, inorganic and carbon-based nanomaterials. However, it reviews polymer composites in a broader sense, e.g. in structural or functional applications.

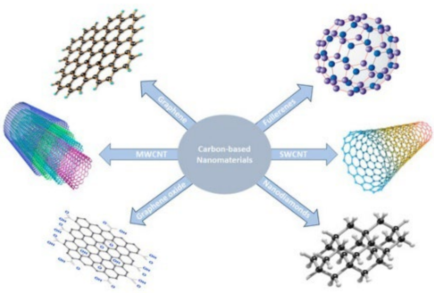
bind to negatively charged bacterial cell membranes, causing membrane disruption and disruption of DNA or RNA synthesis. Combined with being biodegradable and non-toxic, this makes it an appealing material for reducing microbial load in air filtration systems, without the potential environmental and human exposure risks associated with heavy metals. Recent work demonstrated the rapid and sustainable fabrication of chitosan nanofiber air filters using needle-less electrospinning, showing how chitosan can be embedded into filters for effective antimicrobial air filtration (Li S. , 2025)[97].

Polyethyleneimine (PEI) is a synthetic polymer with a high density of amine groups, giving it a strong positive charge, which enables it to interact with bacterial membranes or viral envelopes, rapidly inactivating pathogens such as SARS-CoV-2 or influenza (Baselga, 2022)[98]. Other organic nanomaterials which offer promise include Polydopamine (PDA) which forms a versatile adhesive coating which is able to immobilise antimicrobial agents in place, improve filter durability, and has mild inherent antimicrobial properties. These properties have also been successfully implemented to aid respirator disinfection (Jeong, 2022)[99]. An example of a hybrid organic and non-organic nanomaterial is metal-organic frameworks (MOFs), crystalline porous materials, with metal ion clusters being linked by organic ligands[100]. These compounds have similar properties to inorganic metal-based nanomaterials but offer the additional advantages of a much higher surface area (at least 5 times as great as metal-based nanomaterials), tunability since pore size can be altered, and the ability to treat a

[97] This source is reliable – it is published in a peer reviewed journal by the American Institute of Physics.
[98] This source is reliable – it is published in the peer-reviewed MDPI Materials journal.
[99] This source is reliable - it is published in the peer-reviewed MDPI Applied Sciences journal.
[100] A substance that forms a complex with a biomolecule to serve a biological purpose.

greater array of pollutants than metal-based nanomaterials (VOCs, gases, and microbes rather than only microbes) (Li P. , 2019)[101].

Inorganic nanomaterials can be classified as metal or ceramic based nanomaterials – one such is silica (SiO2). These have been successfully integrated into polymer-based filters to attain enhanced properties (Nallathambi, 2022) (Radha, 2024)[102]. Nanoclay can also be classified as an inorganic based nanomaterial, offering strong mechanical, thermal, and sustainable properties (Musa, 2025).



Carbon-based nanomaterials offer great promise for many applications, including filters, and involve carbon atoms arranged in unique structures at the nanoscale level. Desirable properties include high electrical conductivity, high chemical stability, acceptable aspect ratio (surface to volume ratio), biocompatibility, and very high mechanical properties. This makes it a strong contender for functional composite development (i.e. embedded nanoparticles), as well as for surface coatings (Khdary N. H., 2023). Graphene is a recently discovered carbon-based material, which consists of a single layer of graphite. It offers excellent mechanical and electrical properties when used in a nanocomposite and appears to be a building block for other carbon-based nanomaterials such as carbon nanotubes. It is intrinsically impermeable which in theory would exclude it being used in filtration systems. However, due to real-life material defects such as grain boundaries or cracks,

[101] This source is reliable – it is published in Nature, arguably the most prestigious journal.

[102] Both sources are reliable, and concur in the broader sense, that embedding of inorganic nanoparticles successfully improves properties. The 2022 study demonstrated embedding of silver nanoparticles and achieved PM filtration efficiency of around 99.41%. It comes from an indexed, peer-reviewed journal, published by Springer. The 2024 study is published in Sustainable Chemistry for Climate Action, by Elsevier, and concluded that silver nanofiber membranes are promising.

molecules are allowed to pass through (M, 2024)[103]. In the contexts of nanocomposites, its impermeability isn't a disadvantage, at least when graphene oxide (GO) is used – this contains oxygen functional groups and interlayer spacing which allows sufficient permeability. Instead, the graphene component enhances properties such as mechanical strength or antimicrobial activity. Hangdong Chen et al. described how graphene oxide and polyimide (a high-performance polymer), incorporated into PVDF (a charge retentive polymer) nanofibers, significantly improved "adsorption performance and thermal stability," while being lightweight and having good permeability. This filter had a PM2.5 filtration efficiency of 99.6%, with a pressure drop of 123 Pa, far outperforming the commercial filter that they used as a benchmark, which has an 88.3% filtration efficiency and a 478 Pa pressure drop – almost four times larger than the PVDF nanofiber filter (Chen, 2024)[104].

Graphene oxide is highly hydrophilic and therefore easily dissolves in water. This allows for easier processing since the material can be evenly dispersed in polymer solutions before the final forming process (e.g. electrospinning), meaning the fibres of the air filter will have an even distribution of embedded nanoparticles. GO can also be easily functionalised (Khdary N. H., 2023) (when other molecules, polymers, or nanoparticles are deliberately attached to the material), meaning its function can be fine-tuned, and its carbon-based nanostructure can be combined with an organic or non-organic nanomaterial to create a hybrid. For example, with silver, antimicrobial and adsorptive

[103] This is a reliable source – it was recently published and specifically covers graphene and its derivatives in air pollution. It is a mini review, so may not analyse as deeply as some other papers. It discusses how increased surface defects increases the adsorption of CO2.
[104] This source is reliable – it is published in RSC Advances, a reputable journal, and it directly studies a composite nanofiber membrane for air filtration. Outside of filtration efficiency, quality factor, mechanical strength, thermal stability, and repeated cycle stability data is recorded. The membranes are fabricated through electrospinning. However, this is one specific composite so may not be generalizable.

properties are combined. GO offers a large surface area to volume ratio, and excellent thermal stability and chemical reactivity (Khdary N. H., 2023).

Carbon nanotubes (CNTs) are cylindrical structures made up of rolled-up sheets of graphene. They have remarkable physical and chemical characteristics, including high strength and young's modulus (a measure of stiffness). They are being explored for advanced medical implants and devices due to their biocompatibility, strength, and electrical conductivity (Musa, 2025) – all properties which are important for air filtration – for example, electrical conductivity allows the functionalities of electrostatics, sensor integration, and self-cleaning mechanisms to be exploited. A recent study conducted by Cambridge University investigated the filtration properties of carbon nanotube filters. They exhibited outstanding properties, including a "high and nearly constant filtration efficiency" of >99.95%, a value which far outperforms even analogue carbon-based filters. As well as no MPPS – the penetration of particles remained constant, even when the CNT filters were thinned by more than 10x. Only the thinnest material produced showed a significant increase -partly owing to how dependent the performance is on defects at this thickness. This high filtration efficiency without an apparent MPPS was concluded to be a result of the CNT filter's nanostructure. It also investigated another advantageous property of CNT filters: their electrical conductivity, and therefore the possibility for resistive heating (heating through electrical current, which requires a sufficiently high resistance of the material), to deactivate viral components. This was shown to be successful with <1s of heating, and the hybrid filter was shown not to degrade during a years' worth of heating cycles (Issman, Filtration of Viral Aerosols via a Hybrid Carbon)[105].

In comparison to surface nano coatings, advantages of embedded nanoparticles include increased stability, less leaching, and better durability, whereas drawbacks can include a lower efficiency due to reduced surface exposure, and lower benefit per mass of particle.

Filter Media

While nanocoatings and nanoparticle embedding represent strategies for incorporating nanomaterials into filtration systems, much of their efficacy depends on the filter media; as mentioned previously, this can either be nanofiber-based or the conventional microfiber structure. In this section, differing microfibre structures will be discussed. These broadly speaking include polymeric fibre filters, ceramic filters, carbon-based filters, and composite filters.

Polymeric fibre filters are the most widely used in domestic and medical contexts. They are made from materials such as polyvinyl alcohol (PVA) (Türkoğlu, 2024)[106], which are often used for nanofibers produced through electrospinning, as previously discussed. Conventional HEPA filters use melt-blown polymer microfibres instead. Polymers have the advantages of having a low weight, flexibility, and ease of processing, but these are balanced by relatively poor thermal stability and poor chemical resistance – many cannot withstand the corrosiveness of chemical cleaners, making it harder to remove

[105] This source appears to be reliable – it is a study conducted at Cambridge University and stored in their repository. It may not be peer-reviewed, and there is no specific date, but we can infer that it was published at the latest in 2020.

[106] This source is reliable – it is published in the International Journal of Molecular Sciences, a peer-reviewed and indexed journal. It is very current and talks specifically about PVA based electrospun nanofibers.

accumulated organics and microorganisms (known as biofouling) (Mecha, 2023)[107]. Polymeric structures allow nanoparticles such as GO to be distributed evenly throughout the solution, before fibre formation, reducing clumps of nanomaterials, and improving qualities such as mechanical strength, and electrostatic effects. Functional groups can easily be added to polymers in the production process, allowing for customisation of specific characteristics such as adhesion and charge retention.

Ceramic filters on the other hand, are highly thermally and chemically stable, making them well suited to industrial processes such as exhaust gas filtration (Bardhan, 2001)[108]. Such materials include alumina, zirconia, or silicon carbide, all of which form porous structures with high mechanical strength. When this functionality is combined with nanoparticles such as silica, titanium oxide, or silver, durability can be combined with antimicrobial or photocatalytic activity – the former of which is even more relevant if the filter is to be sterilised, which can be done with ceramics. An article from Armin Reimers et al. investigated self-cleaning air filters based on graphene-enhanced ceramic structures and found that such a filter could capture more than 95% of both microorganisms and PM2.5 and could be repeatedly heated to >300C to kill microorganisms and prevent biofouling. They employed the electrical conductivity of graphene to monitor the airflow and loading status of the filter (i.e. when it needs to be replaced/cleaned) (Reimers, 2023)[109]. Drawbacks include brittleness, high weight, and

[107] This is a reliable review – it is published in an open access, peer-reviewed journal, Membranes. It discusses silver-nanoparticle impregnated membranes, and the authors have acknowledged the shortcomings of present data. Context is liquid membranes not air filtration.

[108] This source is published through Elsevier, in the “Current Opinion in Solid State and Materials Science”, so ought to be reliable. However, only the abstract is available, and very little other information is given.

[109] This paper is reliable – it is published in a reputable journal – Cell is a high prestige publisher, indicating rigorous review. It discusses the cutting-edge topic of using nanoparticles in innovative media.

high production cost. Therefore, they are a less likely candidate for portable or domestic applications.

Carbon-based filters generally use activated carbon fibres, carbon foams or cloths, which each have specialist uses. They all have very high total surface area and absorb pollutants strongly. The use case in which they are especially effective is against VOCs, odours, and gaseous pollutants. They have additionally been shown to effectively remove ozone (Khararoodi, 2022)[110]. These are simply the filters discussed earlier which are often used in combination with HEPA components. However, their performance can be further enhanced by the incorporation of carbon nanostructures such as GO or carbon nanotubes, as demonstrated by Cambridge research (Issman, 'Virus-killing' air filtration system unveiled by Cambridge scientists and engineers, 2021)[111]. Carbon based media offer additional features such as electrical conductivity, which can be advantageous as discussed. However, such structures may impose higher pressure drops than for example polymeric media and therefore may necessitate a hybrid approach with fibrous structures.

Composite filters combine multiple materials to balance the properties of each. Combinations will differ vastly depending on what the desired outcomes are, but a common strategy is layering an electrospun nanofiber mat onto a conventional filter. More advanced examples include embedding nanoparticles in polymer nanofibers, with an additional medium such as ceramic. Evidence from recent studies highlight their potential: PVDF nanofibers with graphene oxide achieved 99.6% PM2.5 efficiency at a

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[110] This is a reliable article – it is published in Buildings and Environment, a reputable, peer-reviewed Elsevier journal covering indoor environments, filtration, and air quality. It deals specifically with carbon-based filters and validates theory against experimental data.
[111] This is a fairly reliable article – it is from the engineering department which gives it some weight.

very low-pressure drop (Chen, 2024), while CNT-based composites provided >99.95% efficiency and enabled virus deactivation via resistive heating (Issman, 2021). Challenges include higher cost and more complicated fabrication, as well as long term durability issues – e.g. nanoparticle leaching, which is especially relevant in terms of ecotoxicity and not introducing any additional harm from the filter. However, they offer promising capabilities which wouldn't otherwise be possible, such as self-cleaning, gas and particulate capture, and high thermal and chemical resistance being combined into a single system.

Comparative Efficiency and Limitations

Overall, integrating nanomaterials into filters by one of the three above outlined methods improves various characteristics. Nanofiber membranes, especially those which are electrospun *and* hold a constant charge (electret) show higher quality factors than HEPA, balancing high capture efficiency with a lower pressure drop – the difference in pressure drop tends to be larger, and for nanofibers, it is often only a small fraction of the pressure drop of a HEPA filter. Nanocoatings and embedded nanoparticles tend to add functional benefits, and do not necessarily massively influence the quality factor. However, they allow performance to be extended past solely particulate filtration, and in some applications such as antimicrobial filters in hospitals, the addition of a photocatalytic nanomaterial layer can significantly differentiate a filter from others. Composite filters combining multiple of the three strategies tend to achieve the best performance in multiple metrics, for example GO-based PVDF membranes.

There are clear trade-offs in terms of cost and scalability of these technologies, especially with newer technologies such as carbon nanotubes. Coatings risk nanoparticle leaching, which both degrades the filter, and poses a health and environmental risk. There is a trade-off between pore size and pressure drop – the better the particulate efficiency, the higher the pressure drop. This can to some extent be mitigated by the aforementioned methods, improving quality factor, but there will always remain a trade-off. If carbon nanofibers are not used, the medium chosen plays an important role in determining properties. Polymeric filters are affordable, flexible, and easily modified, but have low heat and chemical resistance, making them harder to clean. Ceramics are durable and are well suited to industrial applications but are brittle and heavy. Non-nanofiber carbon-based filters are well suited to filtering gases but have a higher-pressure drop. Composite materials used for the medium are effective but complex and costly. All these factors lead the current use of nanomaterial filters to be enhancement of conventional filters, rather than replacement.

Bio-engineered Solutions

Biofilters

Since the early 1900s, biological methods of pollution degradation have been used for wastewater treatment and solid waste pollution treatment (Devinny, 2020)[112]. On this basis, biofiltration has emerged as an alternative to carbon-based filters, incineration, and scrubbers, to clean waste gas streams in a cost-effective manner. According to science direct, "a biofilter (BF) is a fixed-bed bioreactor packed with an organic carrier material in which degrading microorganisms are immobilized. The gas stream is usually

[112] This source is highly reliable – it is a landmark book on various aspects of biofiltration, written by three leading experts, and much of their data originates from primary research. Although it is dated, it lays out the basis of biofilters very well. It is published by Taylor & Francis group, renowned for scientific literature.

humidified before entering the BF reactor" (Cabrera, 2011)[113]. Biofiltration can be summarised as the following. A humid, polluted air stream is passed over a porous medium which could range from compost or wood chips to synthetic media, on which pollutant degrading cultures are seated. Pollutants dissolve into the biofilm (the thin layer of moisture where the microbes live), as air flows through. Similarly to other biological treatments, the core principle of degradation is the catabolic[114] reactions of microbes in the filter. Broadly speaking, biofilters succeed in applications where dilute, high-flow gas containing odours or volatile organic compounds is to be treated. The main selling point for biofilters is their ability to turn pollutants into carbon dioxide, water, and biomass (under optimal conditions). This allows for a fundamentally different model of filtration to all other filters – pollutants are often broken down in situ, rather than having to be removed from the filter matrix and processed separately as in other filters, with end-of-line processing often being at wastewater plants. In combination with a medium which can be used for long time periods if conditions are right, this differentiates biofilters as a far more sustainable filtration method (Devinny, 2020). There are a few variations on conventional biofilters, such as biotrickling (BTF) or bioscrubbing filtration systems, which operate on similar principles. Biotrickling differs in the media used and the way in which humidity is harnessed; whereas biofilters are packed with organic materials and humidify the polluted air in a separate chamber prior to entering the biofilter, biotrickling filters are packed with inert media, over which a liquid phase is poured, to the same effect as biofilters – removal of gaseous

[113] This source is reliable – it is published in a peer-reviewed, multi-volume academic reference work by Elsevier, whose authors are established researchers in biotechnology. It is slightly dated, but the basic principles haven't changed.
[114] "Catabolism breaks down large molecules into smaller units" – Wikipedia.

contaminants from the air. A liquid (often water) is continually trickled over the packing of biotrickling filter, and polluted air in its normal gaseous phase is simultaneously bubbled upwards through the packed bed. Pollutants in the air dissolve into the liquid, where they are biodegraded by microorganisms in the biofilm. Prior to the gas passing through the inert, packed layer, the packed layer is inoculated with either a single microorganism, or more commonly, a mixed microbial inoculum to provide a broader filtration capability (Devinny, 2020). This process, when carried out effectively, removes most VOCs, but also causes elevated CO2 concentrations due to microbial activity. An article on biofilters and biotrickling filters published in “Chemosphere” concluded the following. “The effective removal of VOCs in bio(trickling)filters depends on biological, chemical, and physical parameters such as microbial functionality and active biomass, VOC and nutrients bioavailability, temperature and moisture content, among others. Hydrophobic VOCs face the challenge of being less bioavailable. The lower mass-transfer rate from the air to the liquid phase limits their biodegradation and leads to poor removal performances in biological technologies” (Pineda, 2021)[115]. Limitations of biofilters include requiring a stable moisture level in the packing to keep the microbial biofilm alive and active, since dryness causes microbes to become inactive, and if it is too wet, pores flood and gas transfer rates drops. The way in which water or nutrient solution is applied across the bed also strongly influences how uniform the biofilm activity is (Danila, 2022)[116]. The use of fungi over bacteria has some advantages in BFs,

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[115] This review is reliable – it is published in Chemosphere, a long-standing, peer-reviewed, high-impact journal in environmental sciences. It is indexed in PubMed. It directly addresses one of the most important limitations of biofiltration – poor removal of certain VOCs.
[116] This is a reliable source – it directly discusses packing humidity and irrigation and compares both conventional biofilters (BFs) and BTFs. It is recent, and is published in Processes, a peer reviewed and indexed MDPI journal.

for example they are more tolerant of lower pH, dry conditions, and hydrophobic VOCs, making them especially good for pollutants such as toluene – a widely used solvent and thinner. Fungi can directly metabolise them instead of requiring them to be dissolved in water. Fungi can form filamentous mycelia that extend throughout the packing material. This growth provides enhanced access to VOCs that diffuse poorly in liquid and improves overall structure of the biomass (Marycz, 2022)[117].

Chemical scrubbers are widely used in industry to remove gases by dissolving them in a liquid with chemical reagents such as caustic soda. These scrubbers can easily be modified into biotrickling filters by swapping the chemical solution for nutrient solution and inoculating it with microbes. This makes the adoption of BTFs more accessible and scalable (Gabriel, 2003)[118].

Lastly, it is important to note that although BFs, BTFs, enzyme-based filters, biopolymer-based filters etc. are all presented in the same section, BFs, BTFs, and bio-scrubbing are fundamentally different to all other bio-engineered filters. All three of these systems use microbes as the singular method of degrading pollutants, and as such have no mechanical filter media as all other bio- and nano-engineered filters do.

Enzyme-Based Filtration

Such filtration systems use isolated enzymes to degrade pollutants directly, rather than relying on whole microbial communities. Enzymes are biocatalysts which can accelerate the breakdown of a specific target compound without the need to maintain a

[117] This source is reliable – it has had 48 citations, and is published in a Springer journal, implying it underwent peer review. It is recent and addresses hydrophobic VOCs.

[118] This article is reliable; it is stored in PubMed so is likely peer-reviewed and provides a practical example of retrofitting a chemical scrubber. However, it is older research and is specific to H2S – a sulphurous gas.

living microbial population – removing some of the challenges of other biofilters, such as maintaining constant conditions, nutrient supply, and preventing biomass clogging.

One of the leading examples of enzyme-based filtration is the use of oxidoreductases such as laccases and peroxidases. Oxidoreductases are a broad group of enzymes that catalyse electron transfer from one molecule to another. Practically, this means they can oxidise (take electrons away) or reduce (donate electrons) harmful compounds, changing their electronic structure, and therefore transforming them into less toxic, or more biodegradable forms (Athiappan, 2022)[119]. Since electron transfer underlies many biochemical reactions, oxidoreductases can act on a very wide range of substrates, making them useful in filtration systems that need to handle multiple pollutants – it takes advantage of the chemical stability of resistance pollutants. In this reaction process, energy is liberated, which is then used by microbes for their metabolism. This explains why many bacteria and fungi naturally produce oxidoreductases, making oxidoreductases broadly available in natural and engineering applications and therefore highly exploitable for biotechnological processes, such as wastewater treatment or air filtration. There is much research on this (Singh S. K., 2021)[120], mostly in relation to pollution filtration in water (Singh A. K., 2022) (Alneyadi, 2018)[121]. Both papers highlight the potential of oxidoreductase enzymes in pollutant remediation and demonstrate the improved resilience of enzymes by using solid supports. They report that oxidoreductases generally have strong potential for the degradation of endocrine-

[119] This is a reliable source – the book Rhizosphere Engineering is an edited volume with chapters on pollutant degradation. It is published by Academic Press, an imprint of Elsevier.
[120] This source is reliable – it is published by Woodhead Publishing, an imprint of Elsevier, and is relatively recent. It has been cited at least 72 times, and the editors are researchers in bioremediation.
[121] These are both reliable sources and concur in the sense that they both investigate the use of oxidoreductases for degradation of pollutants in water. They both come from peer reviewed, indexed journals.

disrupting-compounds (EDCs), which are a significant risk to health, but challenges such as cost, denaturation, and scale remain. Singh et al. illustrated how a combination of computational predictions and enzyme engineering could help screen and design better suited enzyme-pollutant pair in the future – matching specific enzymes to specific pollutants for maximum efficacy. Examples of pollutants best suited to oxidoreductase-based filtration include VOCs, phenolic compounds (such as BPA, whose endocrine disrupting effects are previously discussed), and even some recalcitrant pollutants – substances which are resistant to natural degradation. In terms of setup, enzyme-based filtration systems often immobilise the enzymes on a solid support such as activated carbon or polymer beads, ensuring stability and reuse – in a similar way to other biofilters. Polluted air (or liquid in many studies) flows through this enzyme bed, where the pollutants are catalytically degraded or detoxified (Singh S. K., 2021).

In a paper which investigated enzyme-integrated air filters for indoor air pollution, a nanofiber air filter was fabricated by electrospinning a polymer combined with graphene nanoplatelets, and further immobilising the enzyme glucose oxidase onto it, to remove airborne bacteria and microbes (bioaerosols) in indoor air. This is an excellent example of a combination filter, drawing upon technologies ranging from polymer nanotechnology, carbon nanotechnology, and enzyme-based biofiltration. The nanofiber structure was intended to provide the mechanical capture of aerosols, while the enzymatic production of hydrogen peroxide from glucose oxidise accounted for active antibacterial inactivation – aided by the antibacterial properties of graphene. An extremely high biocidal efficiency was found, reaching almost 100%, and far outperforming filters made from either *just* the same polymer (polyacrylonitrile, PAN), *or* a PAN filter with graphene nanoplatelets added. Similarly to how ozone and PM can work synergistically on the lungs, there is a synergy between the glucose oxidase (GOx) enzyme and the graphene nanoplatelets (GNP) – their combined antibacterial efficacy is higher than the sum of their parts. The peroxide produced weakens cells, making them more vulnerable to membrane damage, while graphene exposure enhances peroxide uptake and effectiveness. One important characteristic is moisture transmission, since the incorporation of both GOx and GNP altered vapor permeability minorly, which is relevant in real indoor air, where humidity is constantly present. They present the long-term stability (especially of the enzyme) under realistic indoor conditions, as an aspect which required further study. This is an invaluable study as it highlights how combining mechanical capture with active enzymes can overcome some of the limitations of conventional biofilters and pure mechanical filters, and it illustrates the balances between permeability (pressure drop), and antimicrobial efficiency, in real setups (Bassahinoglu-Aytek, 2025)[122]. Enzyme-based filtration is therefore still an emerging technology and is not yet widely implemented. It is particularly promising for the precision treatment of specific pollutants such as VOCs in industry.

Biopolymer Membranes

These are an emerging class of filtration materials which exploit natural polymers, used for the main structure of the filter. Biopolymer membranes offer sustainability, biocompatibility, and potentially biodegradability. They have been used in a wide range of filters including in homes, cars, and hospitals, and are affordable and widely

[122] This is a reliable source – it is a very recent, peer-reviewed study, published in Springer. It uses quantitative data, such as logarithmic reductions in bacteria, and comparison in performance to the components of the hybrid filter.

available. Their tuneable polymeric structure and ease of manufacture make them especially attractive as filters materials (Gough, 2021)[123]. In manufacture, proteins and polysaccharides from both animal and plant sources are typically used, including silkworm silks, animal wools, corn and soy proteins, and cotton cellulose. Biopolymeric materials are already in wide use in biomedical applications such as drug delivery and prosthetics due to strong biocompatibility and bioactivity[124].

Silk-based air filters have been used in hospitals, offices, and living spaces. It has components which give the material an overall charge that can interact with contaminants. Silk is one of the toughest mechanical materials found in nature, and its molecular weight can be decreased during processing making it highly useable (Gough, 2021). Wool-based filters rely on keratin, which when oxidised and converted to wool keratose, has very useful properties in filtration. In combination with silk fibroin (extracted from silk), greater than 90% filtration efficiencies for metal ions such as Cu2+ have been achieved (Gough, 2021). Such a filter could be applied to great benefit in metal ion heavy environments such as mines. Wool-based filters are also highly reuseable and maintains its greater than 90% efficiency even after being recycled six times, making it both sustainable and appealing to industrial parties in terms of cost.

Another widely researched biopolymer is cellulose, the most abundant biopolymer on Earth (Society, 2009). It is the main constituent of plant fibre, and cotton contains as much as 90% cellulose. It is very rigid, and its molecules arrange themselves to form microfibrils. Cellulose-based filters in this arrangement have crystalline structures,

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124 Obtaining specific effects after exposure to a particular substance: e.g. tissue uptake, metabolism, or physiological response.

resulting in stability and chemical resistance, at the cost of being more difficult to process – chemical processes such as oxidisation are often necessary (Gough, 2021). They can be fabricated into extremely fine, high-surface area membranes, which have high particulate capture efficiency due to their nanoscale fibre diameter. PM, VOCs, and CO2 can all be adsorbed by such filters, and longevity can be increased through hydrophobic treatment. A cellulose-based composite for air purification showed a ten-fold higher quality factor than that of commercial HEPA (Rana A. K., 2022)[125].

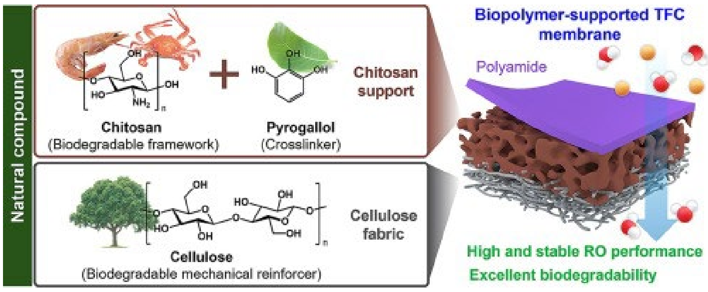
Chitin is the main structural material in the shells of shrimp and cabs. Two differing forms form either microfibers or nanofibers respectively. Chitin is treated with concentrated alkali solution to form chitosan via deacetylation. The higher the degree of deacetylation, the more positively charged groups on the chitosan backbone are exposed, an important factor in pollutant capture (Gough, 2021).

[125] This source can be deemed as reliable, since it is published in a journal (Industrial Crops and Products) which uses single, blind, peer-reviewing, and it is in the top 25% in relevant categories, in terms of impact factor.

biopolymer	filtering efficiency			pressure drop	ref
	pollutants	virus	bacteria		
silk	VOC 99.4% $PM_{2.5}$: 98.8% $PM_{0.3}$: 96.2% Cu^{2+}: 1.65 μg/mg	nucleopolyhedrovirus	*E. coli* *M. luteus*	98 Pa	(5,12,22)
keratin	HCHO: 70% Cu^{2+}: 2.88 μg/mg Cr^{3+}	N/A	*E. coli*: 99.9% *S. aureus*: 99.9%	N/A	(5,23)
soy	HCHO, CO: 90% $PM_{2.5}$: 99.8% $PM_{10-2.5}$: 99.99%	N/A	*E. coli*: 80% *B. subtilis*: 80%	136 Pa	(3,4)
zein	$PM_{0.1-10}$: >99.5% HCHO, CO: >70%	N/A	N/A	175–180 Pa	(24)
cellulose	$PM_{2.5}$: 99.0% $PM_{0.3}$: 93.3%	influenza A caliciviruses hepatitis A hepatitis C herpes simplex enterovirus astrovirus norovirus West Nile	*S. aureus* *E. coli*: 3 log reduction of CFU *C. freundii* *K. pneumoniae*	112.5 Pa/g	(1,2)
chitin, chitosan	NaCl aerosols: 92% $PM_{2.5}$: 100% removal from 999 μg m^{-3} in 33 min Cr(VI)	HIV-1	*E. coli*: 99.4% *S. aureus*: 99.5% *P. aeruginosa* *B. subtilis* *S. choleraesuis* *P. mirabilis* *S. enteritidis* *E. aerogenes* *Corynebacterium* *S. epidermidis* *E. faecalis* *P. gingivalis* *A. actinomycetemcomitans* *S. mutans*	147.6 Pa	(7,20,25)
starch	N/A	adenovirus 41 MS2 enterobacteria phage	*E. coli*: 100% *S. aureus*: 100%	1619 Pa	(1)

This table from "Biopolymer-Based Filtration Materials" by Gough et al. summarises findings, of the performance of various biopolymer filters. This highlights the overall versatility of cellulose and chitosan, both being able to provide broad virus, bacteria and pollutant coverage. Silk and cellulose are among the most breathable since they have a low-pressure drop, whereas soy, zein, and silk filter pollutants (PM and VOCs) the strongest. Starch has excellent biological properties but unusably high-pressure drop, while Zein has great PM removal but does not necessarily target microbes.

Composite biopolymer membranes allow for the combination of mechanical robustness, sustainability, and specific performance enhancements from bioactive components. The production of composite biopolymer-based membranes, whether for air or water filtration, can have a significantly lower impact on the environment than for example thin-film composite membranes, which are fabricated using a large amount of synthetic chemicals and organic solvents (Jung, 2025)[126]. In this case, their chitosan (CHS) and cellulose based membrane



allowed for greater performance than commercial ultrafiltration membranes. As with many other media, alginate or polylactic acid filters can also be functionalised with nanoparticles to provide additional, specific properties – like how enzymes can be combined with nanomaterials.

In a break-through study, Yuan et al. were able to integrate covalent organic frameworks (COFs) into supramolecular nanofibrous membranes, preparing recyclable filters for air purification. COFs are a type of molecular scaffold, with a repeating lattice-like

[126] This is a reliable source – it is published in the Chemical Engineering Journal which is peer reviewed. It is very recent and covers biopolymer based composite membranes, used however for water filtration.

structure, and tuneable porosity. They are very well suited to trapping or reacting with pollutants due to their large surface area, chemical stability, and customisable pores. When such frameworks are integrated into supramolecular[127] nanofibrous membranes – which have high porosity, low pressure drop, and high surface area, a hybrid filter is created. This composite filter can capture PM and other pollutants more effectively, and benefits from the structural strength of the nanofibers. "Excellent closed-loop recyclability" is attained through the production process (Yuan, 2025)[128]. The composites exhibit thermal reversibility, through the process of "thermally induced precursor crystallisation". This allows the membrane to regenerate itself upon heating, without loss of performance (OpenAI, 2025). A review by Souzandeh et al. highlighted not only the filtration limitations of non-degradable plastic or glass fibre filters, but also the polluting nature of the filters themselves, which end up in landfills (and, if not carefully designed could leach microplastics into air) (Souzandeh, 2019)[129].

Surat 'man et al. echoes these themes; traditional nanofibrous membranes such as PVDF are environmentally problematic, especially on a community scale. The lower mechanical strength and long-term durability of bio-based nano filters is acknowledged, especially stability under humidity. Mitigation strategies for PVA (polyvinyl acetate) and PLA (polylactic acid) based filters (which show high hydrophilicity and biocompatibility, but poor mechanical strength) include addition of cellulose or chitin as reinforcers, to improve mechanical properties. Filtration

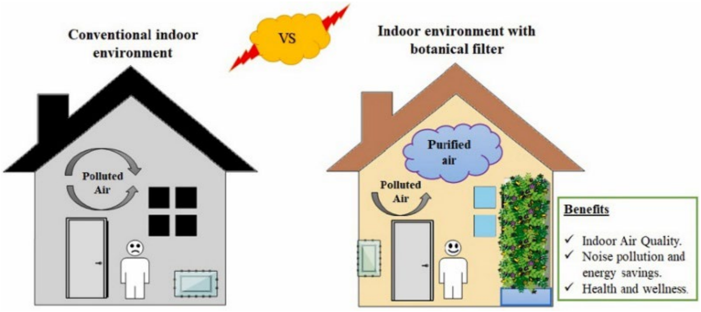
[127] (held together by non-covalent interactions, e.g. hydrogen bonds)
[128] This is a reliable source – it is published through RSC, who are well established. It is up to date and covers a never done before technique. However, it is carried out at the lab scale, so does not indicate scalability.
[129] This source appears reliable – only the abstract is available, however it is published in Polymer Reviews, an indexed, peer-reviewed journal – rated second in Polymer Science.

efficiencies of >99% for PM were achieved, while maintaining a low pressure drop. A zein-based nanofiber composite was found to have a 99.35% filtration efficiency for PM 0.3 under lab conditions (Surat'man, 2025)[130]. In terms of biodegradability, both enzymatic degradation and natural compost degradation are studied, with a focus on the toxicity of the byproducts. For example, PLA produces carbon dioxide, water, and a lactic acid monomer, which are all non-toxic – hence why it is a desirable biobased polymer. Complete degradation timeframes can be as short as 16 hours under lab conditions, if the membrane is carefully designed, and accelerated enzymatic conditions are used (Surat'man, 2025). In this study, a "green, electrospun, biodegradable nanofibrous membrane with high filtration efficiency was successfully fabricated," with over 75% of the polyester used being renewable sourced – successfully demonstrating a both sustainable and high efficiency filter. It is commented for background that single-use respirators are commonly sought after due to convenience, but that both the production and disposal of which implicate a large burden on the environment, as one would expect.

In a study by Wu et al. in Membranes, zein (a corn protein) is electro spun onto a craft paper substrate. To improve mechanical properties and moisture resistance, the zein is crosslinked (its polymer chains are chemically connected) using citric acid. The filter is pleated (folded) to lower pressure drop without lowering filtration efficiency. At first glance, the filtration efficiencies and pressure drop attained by their filters seem on the lower side in comparison to state-of-the-art synthetic (e.g. nanofiber) membranes. A 91.5% filtration efficiency was achieved with the unpleated zein composite, and a

[130] This mini review is reliable – it is published in a peer-reviewed and reputable journal: Nanoscale (RSC). It represents the leading developments as it was published in 2025.

95.4% filtration efficiency with the pleated version – with a pressure drop of around 75 Pa after pleating. Despite this mid-tier filtration efficiency, it displayed excellent composability – after being buried in controlled compost conditions for 28 days, the composite was fully decomposed (Wu, 2023)[131].



Botanical Filtration

In a landmark study by NASA, common indoor plants were investigated for indoor air pollution mitigation – both in the context of space habitats, and energy-efficient homes on Earth. 12 common indoor species were tested, including the Peace Lily and English Ivy, and pollutants such as benzene, cigarette smoke and formaldehyde were used. The basic thesis is that of using activated carbon filter to filter large volumes of polluted air, removing organic chemicals, pathogenic microorganisms, and possibly radon.

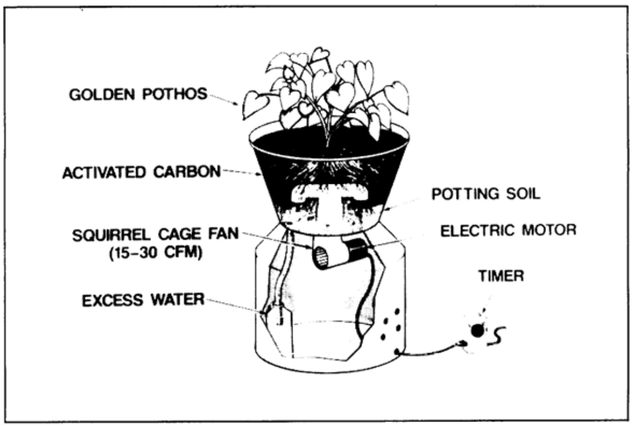


Figure 1. Indoor air purification system combining houseplants and activated carbon.

The plant roots and their associated microorganisms then work to clean the carbon filter, destroying ay viruses, bacteria, and organic chemicals, and converting all these

[131] This is a reliable study – it is published in a peer-reviewed open access journal – Membranes. However, their biodegradability test was carried out at 58C, which is far higher than ambient environments.

pollutants into new plant tissue. In the case of radon, it was believed that the decayed products would be retained in the plant tissue.

It was found that low-light requiring houseplants in combination with activated carbon plant filters were effective in improving indoor air quality, by removing trace organic pollutants from the air in energy-efficient buildings which are associated with the so called “sick building syndrome”. They found that the root-soil area seemed to be the most effective for removal of VOCs, and that air exposure to this area should therefore be maximised. It was also noted that the activated carbon filter should be considered “an integral part of any plan using houseplants for solving indoor air pollution problems” (Wolverton, 1989)[132]. The volatile plant metabolites (plant derived VOCs) produced through specific pathways (i.e. not respiration or photosynthesis) were highlighted as an area of future research by NASA, as not enough was known about their effects on humans. It is now known that some of these VOCs can be harmful and can cause long term issues.

It is important to note that further to this older study, there have been multiple newer studies assessing the same concept, with mixed results. A 2004 study concluded that the microorganisms in the soil of potted plants remove benzene from the air, and that some plants also contribute to this removal themselves (Orwell, 2004)[133]. A more recent 2014 review has a nuanced conclusion, stating that “While the plant's ability to take up VOCs is well documented in laboratory studies, the effect of plants on indoor air in

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[132] This source is somewhat reliable – it is authored by NASA scientists with peer-reviewed background in bioregenerative life-support systems. Later studies have replicated some but not all results. It is reliable as a proof-of-concept.

[133] This is a reliable source – it is published in the journal Water, Air, and Soil Pollution, which is peer-reviewed and well-cited. They exposed different plant species to benzene in a laboratory environment and measured removal over time.

complex environments like offices requires further investigations to clarify the full capacity of plants in real-life settings" (Cruz, 2014)[134]. A more recent article published in Nature, concluded that "potted plants do not improve indoor air quality" in typical buildings, where natural outdoor-to-indoor air exchange already removes VOCs at a rate that would need an unrealistically high density of plants by floor space (Cummings, 2019)[135]. However, this conclusion doesn't take into account that outdoor-to-indoor air exchange may be equally as harmful as no exchange in areas of high outdoor air pollution. This balance is well illustrated by the **SAMHE project** lead by Imperial College London, investigating air pollution in classrooms. They found that on days with elevated outdoor pollution, higher indoor particle levels also increased, even when windows were kept closed – there was only around a 30% reduction in particulate matter compared to outdoors. Common guidance to reduce exposure to indoor PM pollution includes using an air filter, avoiding fans which draw air from outside, and setting HVAC systems to recirculate and filter air. However, the findings from SAMHE highlight the nuance in this advice – as Dr Alice Handy explained: "Reducing ventilation will not stop outdoor PM2.5 entering classrooms. We saw high levels of particle pollution in classrooms during the weekends around fireworks night when schools and classrooms were closed. Ventilation is also important to lower carbon dioxide in classrooms, which is linked to attention and can reduce the risk of spreading infections" (Fuller, 2025)[136].

[134] This is a reliable source – it is published in a well-respected peer-reviewed journal, Environmental Science and Pollution Research International, and synthesises multiple studies without overclaiming.
[135] This is a reliable article – published in Springer Nature, in Nature, a highly respected peer-reviewed journal.
[136] This source is reliable – it comes from a reputable independent news source and is based on data from researchers at Imperial College London.

This evidence suggests that despite ventilation remaining necessary for health and cognitive performance, filtration is required to improve indoor air quality.

A recent 2023 review looked at the current body of research on active botanical biofilters, which includes technologies such as walls of plants (green walls), and other engineered plant systems, as green alternatives to existing filtration systems for air pollution. It reinforces the theory of "sick building syndrome", emphasising how the airtightness of modern buildings necessitates adequate indoor filtration, and that active botanical filters which force air through plant and substrate systems have much higher efficacies than passive potted plant setups. A striking filtration efficiency of 99.8% was reached for removal of acetone, using air recirculation through the biofilter wall. This review also reinforces the concept that removal occurs not only through leaf uptake, but also through substrate adsorption (i.e. the soil) and through microbial biodegradation in the substrate (Montaluisa-Mantilla, 2023)[137].

Summary

Overall, biofilters represent a green approach to efficient filtration of many air pollutants. To accelerate both climate mitigation and cleaner air, such technologies are needed. Alongside sustainable materials, high energy efficiency is needed to enable both the widespread uptake of filtration systems from a cost perspective, and to reduce impacts on the environment. They are a strong contender in the overall filtration market - the US biofilter market was already $10 million in 1996 (Devinny, 2020), and the global market has grown to around $2.4 billion by 2024.

[137] This is a reliable source – it is published in Chemosphere, a well-respected and peer-reviewed journal in environmental science. It is indexed in multiple databases such as PubMed and Elsevier. It is a review rather than original experimental work, so can suffer from selection bias.

One important factor for all filtration systems is that an optimal balance is found between filtration capacity, and size and therefore cost. For all filtration systems, an over-designed system will be expensive to construct and implement, and ultimately be a waste of air filtration resources, but in the case of biofilters this is especially pertinent. Air filtration efficiency generally drops when a biofilter is significantly underloaded, causing regulations not to be met (Devinny, 2020). Simultaneously, the time required for a certain filtration efficiency to be carried out is inversely proportional to the volume of the biofilter (i.e. a larger volume would lead to quicker filtration), but this relationship only holds for large pollutant loads containing hard to degrade contaminants – for which there is therefore a trade-of between space and efficiency (Devinny, 2020).

Due to the mechanistic and biological complexities of biofilters, a high level of academic knowledge and skill is needed not only for their design and implementation, but also for their everyday management. This raises questions around how feasible biofilters can truly be, until most of these processes are able to be automated.

Discussion

The extent to which emerging filtration technologies can replace conventional systems ultimately depends on three main factors. Firstly, *the level of improvement which users desire* in areas of filtration performance, energy efficiency, and sustainability. Different applications place varying emphasis on these criteria, and if improvements in one of these areas is not actively required, the uptake of emerging (and inevitably more expensive) technologies is unlikely. Secondly, whether novel bio- and nano-engineered filtration systems deliver meaningful and implementable improvements in comparison to established mechanical filters. Thirdly, how economically feasible such technologies are, particularly in regions or industries where the need for air filtration is the greatest, but financial means are the lowest. Replacement is only feasible if an optimal cost-benefit balance is found, and if performance in desired aspects is significantly higher than that of existing systems. When comparing such technologies to conventional filters, they key metric used will be the Quality Factor (QF), which as previously mentioned, takes both filtration efficiency and pressure drop into account.

Using HEPA as the foremost example of conventional filtration, high efficiencies, relatively low pressure drops, and therefore a good “quality factor (QF)” can be achieved - they theoretically attain at least 99.7% filtration efficiency for the most penetrating particle size. However, these high figures represent the upper limit of conventional filter performance, and common, simple pleated filters often perform far under this high but necessary standard. Aside from concerns around sustainability (HEPA filters cannot be recycled and are treated as contaminated waste) and versatility (their inability to filter gases or odours), their practical performance is often limited by human behaviour:

inconsistent maintenance and under-specification for the size and layout of spaces can mean that high laboratory efficiencies are rarely able to be translated into reduced exposure or consistently met regulatory standards. Therefore, the continued development of novel technologies such as bio- and nano-engineered filters remains essential. Bio- and nano-engineered filtration systems shift the paradigm in comparison to conventional filtration systems. Both stand out from other filtration technologies, since they can be applied to any component of the filter – as a fundamental structure of the filter (i.e. the medium), embedded at the surface of the medium, or applied as a functional surface coating. In addition, biofilters offer a fundamentally different model of filtration to *all* other filters since pollutants can be broken down in situ. This versatility characterises much of the innovation currently occurring in this sector but also introduces new practical constraints.

On the one hand, nano-engineered filters employ advanced technology such as carbon nanotubes – once only used for high profile applications such as space exploration, leading to incredibly high filtration efficiencies, and superior mechanical strength.

On the other hand, biofilters recruit biological components to clean polluted air, through the metabolic activity of organisms living in the filter. Due to the live nature of these, biofilters require great care and carefully controlled conditions, but boast specific advantages compared to most other filtration systems including nanofilters, mainly in relation to sustainability and filter reuse – which has additional economic incentives.

Biofiltration systems currently have an extensive list of conditions which need to be carefully controlled for them to operate well (or at all). On the other hand, nano-engineered filters require very few conditions to be kept at an optimum due to the inert nature of their medium, and lack of living biological elements. In general, the issues surrounding biofilter design and operation revolve around the living biofilm on the surface of the medium, as well as microorganisms within the medium, which can range from bacteria and fungi to more complex organisms such as nematodes and even arthropods such as spiders. Most importantly, conditions such as pollutant intake concentration (which the organisms catabolise) and nutrient flow need to be kept constant, which is the largest hurdle in filtration application. In addition, biofilters are generally limited to only very specific pollutants, since the organisms which the filter is inoculated with or which subsequently develop, tend to only work efficiently with one or a few similar pollutants, and filtration efficiency decreases if others are introduced. Therefore, common practices such as not using a filter during the night or over the weekend (in industrial applications) somewhat void the use of biofilters. Similarly to nano coatings in nano filters, there is a question of leaching, especially since organisms which are classed as a biohazard are used. If a biofilter is not used over an extended period (e.g. a week), negative changes can occur in the medium, leading to potentially harmful emissions upon restarting. While this can be mitigated through regular artificial injection of pollutants or pollutant analogues over the period of rest, this would ideally not occur in the first place. Similar drawbacks can also be seen among simpler biofilters, such as houseplant-based systems – for example the release of metabolic VOCs. Overall, the largest drawbacks of biofilters are the consistent conditions needed for the microorganisms present to function and degrade pollutants without side effects, as well as the lack of data – as is the case with many other bio-applications such as hydroponics farms. The reality of production, or in this case filtration, is that the research needed to fully understand the effects of each constant being changed in biofilters is inaccessible, due to both time and resource limits. Especially for biofilters, results in real biofilters can vary largely in comparison to lab-based biofilters, and this means that the full potential of biofilters is currently unattainable for commercial operators. Biofilters show the most promise for application in industrial filtration, where a constant concentration and volume of a known pollutant is emitted. This could include chemicals such as toluene, one of the most widely studied pollutants for biofiltration. It has extensive use in fuel and solvents facilities as it is used to produce a wide range of chemicals and is a characteristic VOC (Maestre, 2006)[138]. It is proven to be very effective for such scenarios and strongly contends with conventional filtration systems, not least since most mechanical filters are unable to filter gases such as toluene.

Nanotechnology has enabled significant advances in mainstream filters, is already employed in many high-end respirator filters such as 3M FFP3 masks and additionally offers much promise for integration into portable air cleaners. In many ways, nano-based mediums are *the* most promising ready to integrate technology, due to their structure – smaller (and tuneable) pore sizes, and larger surface areas, allowing the most harmful PM2.5 and UFP to be captured with high efficiency. In addition, they are generally highly energy efficient due to low pressure drop, high porosity and low propensity of clogging. Scalable manufacturing already exists for such structures at market prices, although steeper prices than conventional filters are unavoidable. While nano coatings such as TiO2 offer promising antimicrobial advantages, these need

[138] This source is reliable since it is published in a respected peer-reviewed journal, Chemosphere.

further development and at present risk leaching into the environment. Nanofiltration systems are ready for implementation in a wide variety of applications, with a focus on particulate filtration, and with small improvements in germicidal filtration gained from nano-surface coatings.

When evaluated using the Quality Factor (QF), nano-engineered filters emerge as the likeliest candidates for replacing conventional HEPA systems, with achieved performance equating to several times the performance of HEPA systems per unit pressure drop. While HEPA filters typically have a QF of 0.01 to 0.015 P/a (Kim H.-J. , 2021), a PVDF (a thermoplastic) electret nanofiber multilayer membrane – a great example of a nano-engineered filter, achieved a QF an order of magnitude greater, at around 0.109 P/a (Leung, 2020). This was similarly observed in a cellulose hybrid composite, which achieved a QF of 0.10-0.15 P/a, again outclassing HEPA filters by tenfold. This example shows the potential of biotechnologies for integration into filters, especially when combined with nanotechnologies. Carbon nano-tube filters also show incredible promise, with a Cambridge study demonstrating a constant filtration efficiency of >99.95%, which could be comparable to ULPA filters, a conventional filter with an incredibly high filtration efficiency and a very high pressure drop, leading it to be used only in applications such as clean rooms, where a large energy expenditure is seen as a necessary evil. Unlike ULPA filters, a low-pressure drop can be inferred from the study, since the filtration efficiency was unchanged by a greater than ten-fold thinning of the filter thickness (Issman, Filtration of Viral Aerosols via a Hybrid Carbon). When combined with other more specialised attributes such as electrical conductivity and high structural integrity of carbon nanotubes, such technologies seem on trac to replace HEPA filters, if they can be commercialised. The proven ability for resistive heating to occur throughout a carbon nanotube structure, removing pollutants, while keeping its structural integrity, would create as great of a paradigm shift as the concept of biofilters. This leads nanofilters to have a very strong replacement potential.

Biofilters cannot be meaningfully compared using QF, as their mechanism relies on biological degradation rather than mechanical capture. Biofilters (distinctly different from filters with biotechnologies integrated into them, e.g. hybrid bio-nano filters) have relatively low operating and capital costs, effectively remove specific gases when properly operated, and have a low pressure drop, all while not creating any further waste streams, but fall short in terms of the large footprint required, deterioration of the medium, and inability to filter particulate matter efficiently. Overall, biofilters cannot realistically replace HEPA filters, since unlike nano-based filters which have a strong potential to displace HEPA in particulate removal, biofilters are more suited to VOC and chemical gas removal in industrial settings, and therefore strongly diverge from biotechnology based mechanical filters, nano-based filters, or bio-nano based filters. This explains why nano-based filters are already appearing in consumer-grade respirators, whereas biofilters are mainly confined to industrial treatment.

Further examples of bio and nano-technology-based filters include a zein biopolymer-based filter (a biotechnology based filter), which despite a significantly lower filtration efficiency (91-95%) compared to HEPA, still achieved a QF several times larger than that of HEPA, at around 0.04 P/a, and had excellent biodegradability (Wu, 2023). This is an interesting factor which needs to be carefully considered – filtration systems with biotechnologies and nanotechnologies integrated into them have a propensity to lean heavily towards certain characteristics and less so towards others, which can lead to certain desirable characteristics being lower than conventional filters, but metrics such as QF demonstrating that they still come out on top overall. This can be seen as an advantage for innovative technologies such as these, as it optimises them for specific applications. In another example, a hybrid nano-bio filter which was also synthesised from zein, which when combined with a cellulose derivative, led to filtration efficiencies of above 99% (99.25%). Similar results were achieved when combining zein into a nanofiber composite (99.35% for PM0.3). This shows a high replacement potential for both pure bio-based filters, and bio-nano hybrid filters. Limitations must be considered, which include relatively poor stability under humidity, but this can be countered with the addition of reinforcers such as cellulose (Surat'man, 2025).

In terms of contextual applications, many are unchanged from conventional filters. Most bio and nano-based filters, or hybrid filters, will be implemented in the same way. However, the customisable and specialist nature of some of these filters will lead certain innovative filters, for example those which harness bio- or nano- based coatings to deactivate microbes, to be applied where the greatest benefit will be gained, such as in hospitals.

Despite the apparent shortcomings of pure biofilters, they have intriguing potential applications, capitalising on their divergence from other innovative filters. Open bed biofilters are a low-tech biofilter configuration, where the compost or soil media is placed directly on top of the contaminated air distribution system, in or on a supporting structure. The top layer is open to the normal atmosphere and can be at ground level if a pit is dug for the medium. It can be protected with an inexpensive cover to counter heavy rainfall which could saturate the media and cause airflow problems. Due to the overall low cost (and notably, low performance), this configuration can be successfully applied in both LEDCs and MEDCs, or developed economies. In LEDCs, where the main constraint is cost, I believe open bed biofilters could be successfully integrated into systems where odorous gas is produced, for example, in sewer systems. In MEDCs, I believe this model could be applied in the same way, and additionally, for livestock farms, where some amount of greenhouse gas emissions could be captured and sequestered into the soil, for example, for gases from enclosed manure storage, covered slurry pits, and anaerobic digesters, which all create constant emission of gases. These are striking applications, since in these systems, degradation or sequestration of pollutants is equally as important as capture. A potential application of (not exclusively open bed) biofilters exists, for canals and other microclimates of high relative humidity. Humidity is required for biofiltration, otherwise pollutants are unlikely to transfer to the medium which will degrade them. Often, pollutant streams are humidified before filtration, however for application in a humid microclimate the need for this may be reduced, simplifying the process. In addition, the microclimate of a canal with living organisms could introduce a wide range of microbes into the biofilter, which could augment its operation. If nothing else, this could be an interesting research application but also has the potential to optimally remove harmful gases, e.g. from barges along canals and similar spaces.

Lastly, through market research I have conducted at See Research on the future of the restaurant experience, wellness orientated dining, and how biophilic[139] design can positively alter mental, emotional, and physical states, for example even potentially

[139] "In a design context, the concept of biophilia refers to architecture and urban planning that mimics natural environments to enhance and improve well-being." – University of the Built Environment

lowering blood pressure, I believe that biofilters could be successfully applied in this sector (See Research, 2025). Although biofilters would struggle to degrade kitchen fumes, as oil aerosols and smoke particulates create biomass clogging and starve microbes of the oxygen required for biofiltration (Devinny, 2020), biofilters are perfectly suited to degrade pollutants commonly found in other restaurant areas. Aldehydes, terpenes, ethanol, VOCs, and odours are commonly found in restaurants, with a wide range of sources ranging from cleaning agents, bathrooms, and body odour to food waste bins, dishwashing areas, and perfumes (OpenAI, 2025). Biofilters are excellent at degrading alcohols, terpenes, aldehydes, and organic acids, and could therefore significantly improve air quality in restaurants, and do so far more efficiently than most other filtration systems at a similar price point. In this biofiltration for restaurants concept, I am therefore excluding emissions originating explicitly from cooking, since aside from being unable to be filtered through biofilters, they are a very large issue by themselves. Most restaurants have a kitchen extraction system without any significant filtration capability, so PM and other harmful pollutants are released straight onto street level. As discussed previously, cooking creates a great amount of pollution, and regardless of whether the person cooking is exposed or the pollutants are extracted before, it can have large impact on the pollution microclimate near the exhaust. (ElSharkawy, 2022)[140]. According to research by the City of London Corporation, restaurants make up a large proportion of PM emissions originating from within the City of London (McAleavey, 2025)[141]. Indoor restaurant ventilation systems are typically standard HVAC systems employing insufficient, low quality, pleated filters, and HEPA

[140] This source is reliable – it is published in Atmospheres, a peer-reviewed journal.
[141] This source is reliable since it is primary data from the City of London Corporation air pollution team.

filters are few and far between. Therefore, PM from the kitchen does inevitably drift, e.g. into dining spaces, but again, this is a separate issue, which could be remedied simply, through education and greater regulatory requirements.

In any case, even modern HVAC systems equipped with HEPA filters are unable to deal with the aforementioned subtle odorous compounds which can originate from a multitude of non-cooking sources, and biofilters are therefore a prime functional candidate for this application. In addition to filtration functionality, there are aesthetic and atmospheric arguments based on biophilic concepts, which are perhaps even more compelling. Since the biofilter medium is typically composed out of organic material and supports living organisms, it has a unique smell often likened to the pleasant odour of a forest after a rainy day. While biofiltration is therefore not typically recommended for the treatment of indoor air in closed loop (Devinny, 2020), I believe a small biofilter, which is well maintained and managed, and only handles relatively inoffensive odours and compounds, could be used to the restaurant's advantage in terms of mild, pleasant, forest-like scent. This ties into the concept of biophilic design and could provoke the same physiological and psychological responses as natural wood elements do visually. Natural aromas are proven to enhance perceived air quality and cleanliness, as well as a host of other attributes shared with biophilic visual design (Bentley, 2022)[142]. The medium could be carefully chosen to optimise the scent, to ensure it is not so strong that it detracts from the scent of the food, and to align with the restaurant's area of focus and professional brand. For example, wood chips have been successfully used in biofilters (Devinny, 2020), and varying woods such as pine and cedar will create

[142] This source is reliable – it is published in Ambio, which is a part of Springer. Its authors were in specialised ecology and sustainability academic departments.

varying atmospheres (Ikei, 2016)[143], with hardwood compost offering a more neutral choice (OpenAI, 2025) should this be desired, e.g. in restaurants where the food scent is especially important[144]. In addition to this, since the biofilter need not have a large volume, it could be designed in the form of transparent piping or components tastefully recessed into walls with ambient lighting. This has the potential to additionally evoke visual biophilic cues and reinforce a "premium dining" brand identity of wellness, sustainability, and connection to nature. Therefore, I believe that using specifically designed biofilters in restaurant dining areas is not only advisable, but strategically advantageous, and this concept could also be applied in other hospitality spaces.

Sukiyabashi Jiro, the first sushi restaurant to receive 3 Michelin Stars.

[143] This source is reliable – it is published in the Journal of Wood Science, through Springer Nature.
[144] For example, at some of the best restaurants in the world serving subtly dishes, such as Sukiyabashi Jiro, even wearing perfume is strictly prohibited.

Conclusion

This review focuses on the significance of air pollution for humans, and innovative methods of mitigation. The intention is that it synthesises a large amount of relevant information in this sphere into one coherent source, so that people are better informed, not only with technical filter-related knowledge, but also a holistic overview of the industry.

To carry out these objectives, this paper analysed studies, mini-reviews, reviews, and industry-related websites, as well as primary research – created through a previous internship and contact with experts in this field. The evidence suggests that innovative filtration technologies will complement rather than universally replace conventional technologies, with nanofiltration accounting for the majority of near-term uptake, and biofiltration satisfying specialised sustainability-driven niches. While traditional biofilters which rely purely on microbial degradation have had success in certain industrial and commercial settings, their inherently narrow filtration scope limits make a significant rise in demand unlikely. Additionally, there is a lack of conclusive, actionable data on how varying conditions affect different performance metrics of biofilters, due to their innate biological complexity, and the resource intensity of running such trials. Research suggests that biofilters may see a small but marked increase in demand in consumer settings due to their biophilic characteristics.

On the other hand, bio-engineered components have shown excellent characteristics and therefore a high replacement potential, when combined with traditional or nano-engineered elements, with hybrid bio- and nano-engineered filters showing the most promise overall, in terms of both performance and sustainability. A convergence between these technologies is likely, with an increasing number of filters adopting biopolymer-based structures integrated with nanoengineering methods such as electrospinning. Fewer limitations are likely to arise with such designs, since biopolymers and nano-engineered structures are usually inert, leading to faster uptake and commercialisation. Altogether, these findings suggest that growing scrutiny of air pollution will require policymakers and industry leaders to adopt a stronger sense of agency in tackling this environmental health challenge. Air pollution's transboundary nature makes it an indiscriminate threat, reinforcing the need for coordinated scientific progress, policy change, and investment.

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