

Air cleaners in energy-efficient buildings: performance, health evidence and implementation challenges

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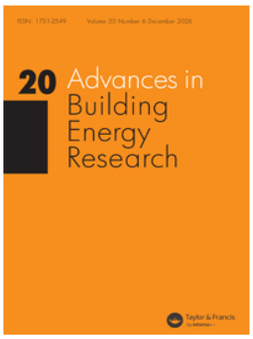

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Air cleaners in energy-efficient buildings: performance, health evidence and implementation challenges

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ABSTRACT

Indoor air quality (IAQ) plays a critical role in human health, yet indoor pollutants frequently accumulate despite improvements in ventilation and building design. Air cleaners are increasingly used as a complementary mitigation strategy, but their real-world effectiveness and clinical relevance remain heterogeneous. This review synthesizes evidence from 36 peer-reviewed studies to evaluate the pollutants targeted by air-cleaning technologies, their removal efficiency under realistic conditions, and their associations with respiratory, cardiovascular and other health outcomes. HEPA-based systems consistently reduce indoor particulate matter (PM), often by 20–80%, and show moderate evidence for short-term cardiopulmonary benefits, including reductions in blood pressure and inflammatory biomarkers. In contrast, evidence for gaseous pollutant removal, long-term health outcomes, cognitive effects and economic impacts remains limited, and some technologies may generate harmful byproducts such as ozone. The review also considers implications for vulnerable populations and energy-efficient buildings where ventilation may be constrained. By critically evaluating multidisciplinary evidence, this work bridges the gap between air-cleaning performance metrics and public-health relevance, supporting informed decision-making for practitioners, policymakers and building professionals.

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1. Introduction

Indoor air quality (IAQ) is an increasingly critical concern in the context of public health and well-being. With individuals spending a large proportion of their time indoors, human exposure to air pollutants is often dominated by indoor environments such as homes, schools, kindergartens, elderly care units, hospitals and workplaces (Klepeis et al., 2001). Despite improvements in building design and ventilation practice, indoor pollutants can still accumulate due to indoor emission sources, outdoor pollutant infiltration and occupant activities. Common indoor contaminants include particulate matter (PM), allergens and bioaerosols and gaseous pollutants such as volatile organic compounds (VOCs), nitrogen oxides and ozone-related byproducts (Nazaroff, 2016; Weschler, 2009). Poor IAQ has been associated with multiple adverse health outcomes, including respiratory morbidity and exacerbation of asthma, as well as cardiovascular effects linked to fine particulate exposure (Brook et al., 2010; Guarnieri & Balmes, 2014; Schraufnagel et al., 2019; World Health Organization [WHO], 2021). In addition to cardiopulmonary impacts, evidence is accumulating that indoor environmental conditions (including ventilation-related exposures, CO2 as a proxy for ventilation and VOC mixtures) may influence cognitive performance and decision-making, particularly in office-like environments (Allen et al., 2016). Air pollution exposure has also been linked to mental health outcomes through multiple biological pathways, and emerging indoor-focused literature suggests that indoor pollutant mixtures (e.g. VOCs and bioaerosols) may contribute to neurobehavioral and psychological effects, although causal attribution remains challenging (Block & Calderón-Garcidueñas, 2009; Braithwaite et al., 2019). The importance of IAQ is further emphasized by its implications for vulnerable populations, including children, older adults and individuals with pre-existing medical conditions (Jordan et al., 2020; Nazaroff, 2016; World Health Organization [WHO], 2021). This vulnerability was highlighted during the COVID-19 pandemic, where severe outcomes and mortality were strongly associated with underlying conditions such as cardiovascular disease and diabetes, reinforcing the public-health relevance of mitigating environmental stressors that interact with chronic disease risk (Jordan et al., 2020; Wortham et al., 2020).

Air cleaners (portable or integrated) have therefore been proposed as a complementary IAQ intervention, particularly when pollutant sources cannot be fully eliminated and when ventilation is constrained by climate, energy use, outdoor air quality, or building limitations (Azimi & Stephens, 2013; Cheek et al., 2021; Nazaroff, 2016). Evidence syntheses indicate that portable air purifiers can reduce indoor PM2.5 concentrations substantially in real settings, with the magnitude depending on device characteristics, room volume, air mixing, occupant behaviour and maintenance (Azimi & Stephens, 2013). Health-focused reviews and meta-analyses report short-term associations between air cleaning and selected outcomes (e.g. blood pressure and some respiratory endpoints), while also noting heterogeneity across studies and remaining uncertainty regarding long-term effects and pollutant classes beyond particles (Azimi & Stephens, 2013; Faridi et al., 2023). Practical guidance further emphasizes correct sizing (e.g. Clean Air Delivery Rate relative to room size), filter replacement and avoidance of technologies that may generate harmful byproducts such as ozone (Association of Home Appliance Manufacturers [AHAM], 2015).

Because existing evidence is distributed across engineering, exposure science and medical/public-health disciplines – and because study designs vary from laboratory performance tests to field interventions and clinical endpoints – there remains a need for an integrative synthesis that connects (i) pollutant types and sources, (ii) air-cleaning technologies and performance metrics and (iii) health outcomes and vulnerable-population considerations, while accounting for real-world constraints such as climate, building energy performance and policy context (Azimi & Stephens, 2013; Cheek et al., 2021; Nazaroff, 2016; Weschler, 2009).

Accordingly, this article is structured as a comparative review of air-cleaning approaches in energy-efficient buildings, synthesizing evidence on (1) the indoor pollutants targeted by air cleaners (particles, gases and biological contaminants), (2) the reported removal performance and key determinants of effectiveness under realistic use conditions and (3) the strength and limitations of evidence linking air cleaning to health outcomes (respiratory, cardiovascular, cognitive and other endpoints). The review also discusses implementation considerations relevant to energy-efficient buildings (e.g. ventilation interactions, climate constraints, maintenance and potential byproducts), and summarizes how guideline frameworks and risk-based thinking can inform practical IAQ targets and air-cleaner selection (Association of Home Appliance Manufacturers [AHAM], 2015; Nazaroff, 2016).

2. Methodology

A systematic literature review was conducted to assess the scientific evidence linking indoor air cleaning technologies with human health outcomes. Peer-reviewed studies published between 2000 and 2024 were identified through comprehensive searches of Scopus, Web of Science, PubMed and ScienceDirect. The search strategy employed Boolean combinations of key terms related to indoor air treatment and health effects, including ‘air cleaners’, ‘air purifiers’, ‘indoor air quality’, ‘HEPA’, ‘particulate matter’, ‘volatile organic compounds’, ‘ozone’, ‘asthma’, ‘respiratory’, ‘cardiovascular’, ‘blood pressure’, ‘allergy’, and ‘oxidative stress’. All records retrieved through database searches were screened according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021).

Figure 1 shows a PRISMA flow diagram that outlines the study selection process for the review. A total of 150 records were identified through database searches, of which 75 were excluded after title and abstract screening due to animal studies, laboratory-only experiments, non-relevant topics, or reviews without original data. The remaining 75 full-text articles were assessed for eligibility, and 39 were excluded because they lacked measurable human health outcomes, did not evaluate air cleaning technologies, or had insufficient methods or data. Ultimately, 36 studies met all inclusion criteria and were incorporated into the final analysis, with data categorized by air cleaner type, health outcome, participant demographics and exposure context.

For each study, data were extracted on air cleaner type, pollutant removal performance, exposure environment, participant characteristics and measured health outcomes, see Figure 2. Quantitative results were standardized, when possible, to support cross-study comparability. Due to substantial heterogeneity in study designs and outcome metrics, a narrative synthesis approach was used rather than meta-

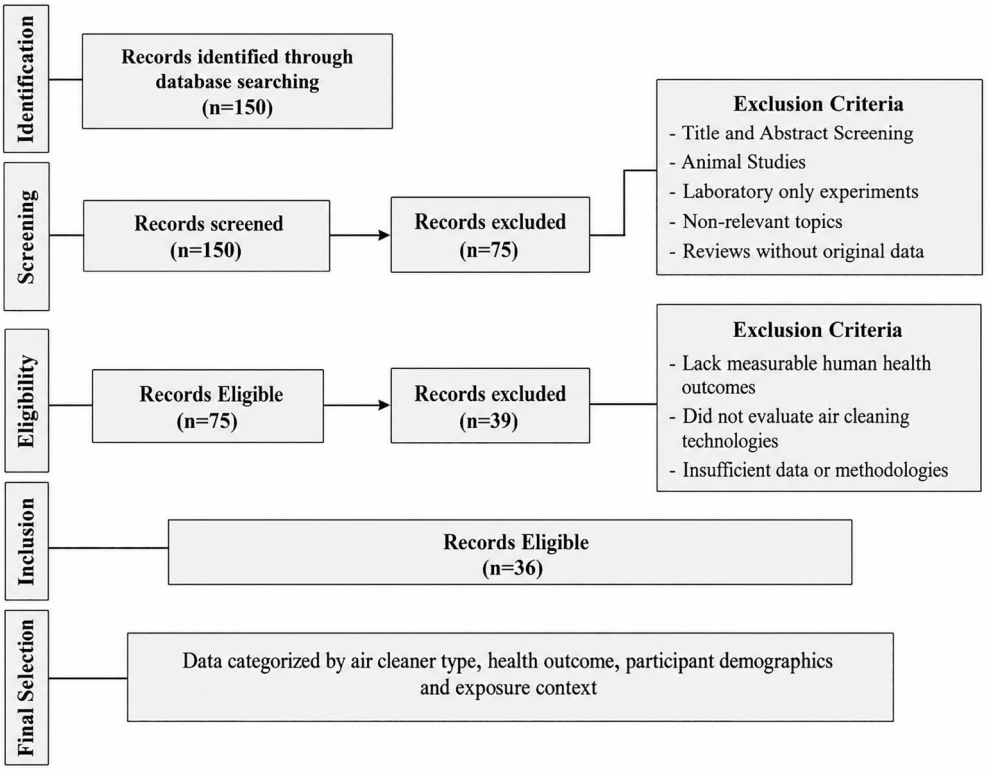

Figure 1. Screening of database through PRISMA.

analysis, allowing identification of recurring patterns, inconsistent findings and key evidence gaps regarding the health impacts of indoor air cleaning technologies. Further assessment resulted in the types of air cleaning technology and the health outcomes, as shown in Figure 3.

Health outcomes were grouped into major categories – respiratory and asthma-related measures (e.g. lung function, FeNO), cardiovascular responses (e.g. blood pressure, heart rate variability, oxidative stress), allergic and immune reactions, irritation symptoms, adverse by-products (such as ozone generation), mixed outcome sets and general well-being or cognitive effects. Air cleaning technologies represented in the selected studies included HEPA filters, portable HEPA devices, electrostatic precipitators, ionizers, photocatalytic oxidation systems, cold plasma devices, carbon and hybrid filters and conventional mechanical filtration. HEPA-based systems were most frequently studied and generally showed substantial reductions in indoor particulate matter (PM and PM), although corresponding health effects ranged from measurable improvements (e.g. reduced airway irritation, lower blood pressure, decreased oxidative stress) to minimal or no change. Variability in results was often linked to differences in baseline pollution levels, exposure duration, building conditions and device maintenance. Some technologies produced ozone or secondary pollutants, which in certain cases offset potential health benefits.

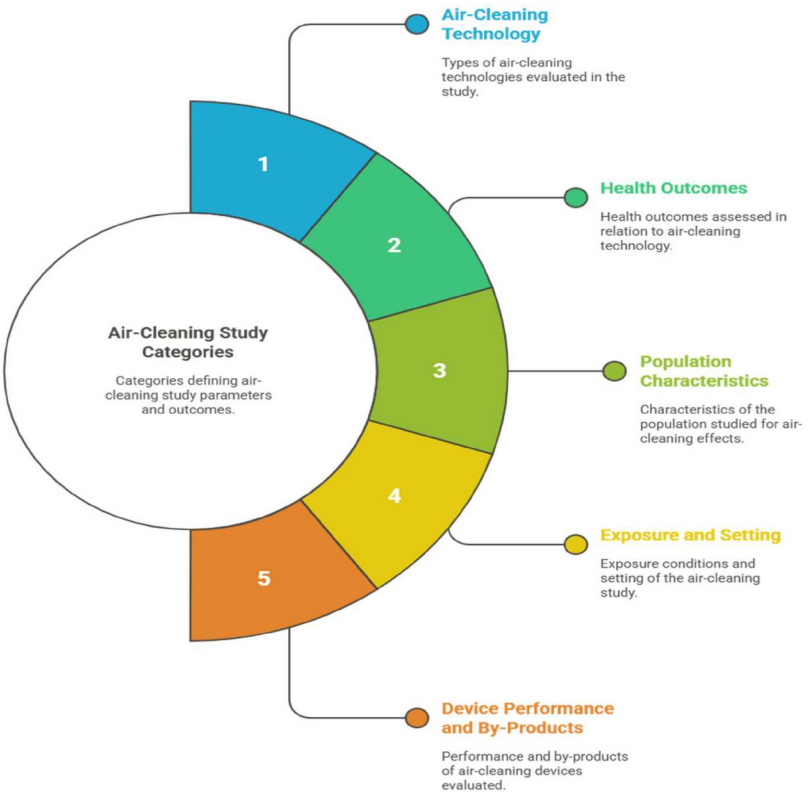

Figure 2. Dimensions of air-cleaning studies.

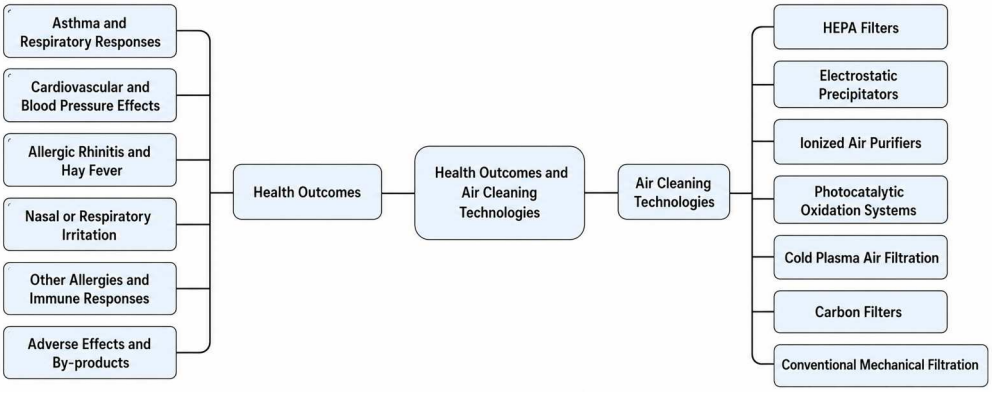

Figure 3. Classification of air-cleaning technologies and health outcomes.

3. Results

The results presented in the following section are derived exclusively from the 36 studies that met the predefined inclusion criteria of this systematic review. All findings are based on structured database searches, PRISMA-guided screening and standardized data

extraction procedures described above. The synthesis reflects only the eligible peer-reviewed evidence identified through the specified search strategy and methodological framework. To provide clarity and coherence, the findings are organized into nine key thematic statements addressing crucial aspects of air-cleaning technologies and associated health outcomes.

3.1. Pollutants targeted by air-cleaning technologies

Air cleaners have become increasingly utilized tools in managing indoor air quality, particularly in densely populated urban settings where exposure to fine particulate matter (PM) is of concern (Cheek et al., 2021). These devices are designed to reduce concentrations of airborne particles and other pollutants associated with adverse respiratory and cardiovascular outcomes (Brook et al., 2010; Guarnieri & Balmes, 2014). Negative ion air purifiers (ionizers) have been shown to reduce airborne particle concentrations by promoting particle agglomeration and surface deposition; however, certain devices may generate ozone or reactive byproducts, raising concerns about unintended health risks (Destaillats et al., 2006; Weschler, 2000). Reviews have therefore cautioned that potential benefits of particle reduction must be balanced against possible adverse chemical byproducts (Cheek et al., 2021; Weschler, 2000).

Portable air filtration systems, particularly HEPA-based devices, have demonstrated substantial reductions in indoor PM2.5 concentrations under real-world conditions, with reductions often ranging between approximately 20% and 80% depending on device size, room volume, baseline pollution and operating conditions (Azimi & Stephens, 2013; Cheek et al., 2021). However, systematic reviews note considerable heterogeneity across studies and generally classify the certainty of health evidence as moderate to low for many endpoints (Cheek et al., 2021; Fisk, 2013). Air cleaners are particularly discussed in the context of mitigating cardiovascular risks associated with fine particulate exposure, as PM. has been strongly linked to hypertension, vascular dysfunction and systemic inflammation (Brook et al., 2010; Schraufnagel et al., 2019). Intervention studies have reported reductions in blood pressure and markers of oxidative stress following the use of portable HEPA filtration in residential settings (Fisk, 2013). Air-purifier intervention studies have reported short-term cardiopulmonary benefits following reductions in indoor particles, although findings are not uniform across all outcomes (Chen et al., 2015).

Hybrid systems combining HEPA filtration with electrostatic or sorptive technologies have been proposed to broaden pollutant removal, although careful evaluation of byproduct formation remains essential (Destaillats et al., 2006; Weschler, 2000). HEPA filtration has also been shown to reduce indoor black carbon and fungal spores in urban residences, contributing to lower exposure levels in susceptible populations (Azimi & Stephens, 2013; Reisman et al., 1990). The use of ionization-based technologies warrants caution due to the documented potential for ozone generation and secondary pollutant formation, particularly in poorly ventilated environments (Destaillats et al., 2006; Weschler, 2000). (Batterman et al., 2012). Reviews consistently emphasize that continued development and rigorous evaluation of air-cleaning technologies are needed to improve effectiveness, reduce unintended emissions and address operational factors such as noise, energy use and maintenance burden (Cheek et al., 2021; Fisk, 2013). Reducing indoor particle exposure is broadly considered beneficial, yet effectiveness depends on

correct sizing, placement, airflow patterns and sustained maintenance (Azimi & Stephens, 2013; Cheek et al., 2021). Air cleaners have also demonstrated reductions in indoor allergens such as pet dander and mold spores, which are relevant for asthma management, although results vary across settings and populations (Guarnieri & Balmes, 2014; Reisman et al., 1990). HEPA-based systems generally show consistent effectiveness against traffic-related particles and combustion-derived pollutants in residential environments (Azimi & Stephens, 2013; Reisman et al., 1990). Overall, while air cleaners can substantially reduce indoor particulate matter and selected pollutants, their health impacts depend on pollutant type, baseline exposure, device characteristics and proper use. Continued research is necessary to clarify long-term health outcomes and optimize implementation strategies in different building and climatic contexts (Cheek et al., 2021; Fisk, 2013).

3.2. Sufficiency of current evidence linking indoor air pollution levels and composition to health effects

The discussion of indoor air pollution and its chemical composition alongside related health effects is in the literature, highlighting a broad spectrum of diseases and symptoms connected to various indoor contaminants (Fisk, 2013). One article extensively discusses how environmental tobacco smoke (ETS), nitrogen dioxide, carbon monoxide, volatile organic compounds (VOCs), phthalates, pesticides and allergens from house dust mites, molds, rodents, cockroaches and animal dander can lead to a myriad of health issues including allergies, asthma, infections, hypersensitivity pneumonitis, mucosal irritation, central nervous system effects, psychological effects including depression, dermatitis and even some forms of cancer (Brook et al., 2010; Guarnieri & Balmes, 2014; Schraufnagel et al., 2019).

In contrast, another study focuses on a specific intervention programme to reduce indoor allergens and ETS exposure in homes of children with asthma, yet it falls short of exploring the broader correlation between indoor air pollution levels, their chemical composition, and related health effects (Reisman et al., 1990). Similarly, another article evaluates the effectiveness of stand-alone room air filters in reducing particulate matter concentrations, such as tobacco smoke, pollen, dust mites, animal allergens and diesel exhaust particles. The study found that filters decreased PM concentrations by 30–70%, depending on the size fraction and occupant activities, and significantly reduced the half-life of PM0.3–1.0. However, it does not provide information on the chemical composition of the pollution or the related health effects (Batterman et al., 2012).

Another study delves into the effectiveness of a portable indoor air cleaner equipped with HEPA systems in removing large pollen and spores from indoor environments, discussing factors that affect the performance of air cleaners, such as the air exchange rate and the size of the particles being filtered. Despite these insights, the study does not provide information on the chemical composition of indoor air pollution or its related health effects (Fisk, 2013). Yet another research discusses the measurement and simulation of the IAQ impact of particle air cleaners in a single-zone building. However, the article does not discuss the chemical composition of the pollution or its related health effects, therefore, it does not provide sufficient information on the topic (Batterman et al., 2012).

Further research focuses on the effects of air cleaners on children with perennial allergic rhinitis (PAR), which is primarily due to mold allergy. It suggests that reducing exposure to mold allergens, such as the use of air cleaners in the home, may be a valuable adjunct to conventional therapy (Reisman et al., 1990). Additional studies address interventions using air cleaners and measuring allergen levels, often without detailed analysis of chemical composition or broader health implications (Batterman et al., 2012; Brook et al., 2010; Fisk, 2013; Guarnieri & Balmes, 2014; Reisman et al., 1990; Schraufnagel et al., 2019).

While the literature provides insights into specific pollutants and interventions, it presents a fragmented view of the link between indoor air pollution's chemical composition and health impacts. The comprehensive understanding of chemical compositions and the full health effects spectrum remains underexplored.

3.3. Evaluation of the medical evidence establishing quantified correlations between air cleaner use and specific health outcomes

Research examining the efficacy of air cleaners on various health outcomes presents a multifaceted landscape, suggesting some potential health benefits but often lacking in robust, quantified correlations necessary for conclusive results. Studies have shown promising signs that air cleaners might mitigate respiratory issues in children, evidenced by reductions in inflammation biomarkers such as FeNO, EBC IL-1β and IL-6. These findings imply that air cleaners can potentially protect children's respiratory health, though the specific quantification of these benefits directly attributable to air cleaner use remains unestablished (McCreanor et al., 2007). Additionally, the integration of HEPA vacuum cleaners along with other interventions like dust mite-impermeable covers and enhanced cleaning practices have demonstrated asthma trigger reduction and improved respiratory health outcomes. Yet, these studies have not provided precise quantified correlations that can be solely attributed to the air cleaners themselves (Eggleston et al., 2005).

Cardiovascular health and blood pressure also appear to be influenced by air cleaner use, with some studies noting benefits such as reductions in systolic and diastolic blood pressure and improvements in cardiovascular risk markers such as plasma-soluble P-selectin, especially following the removal of ESPs (Delfino et al., 2008). These observations suggest that air cleaners might play a protective role in cardiovascular health. However, the lack of direct, quantified correlations makes it difficult to definitively link these improvements directly to the use of air cleaners. In terms of lung function, while some studies have shown that air purification can lead to decreased diastolic blood pressure and improvements in lung function indicators like FEV1 and PEF in young adults (Brauner et al., 2008), these outcomes are not quantitatively linked directly to air cleaner usage.

The impact of air cleaners on oxidative stress and pregnancy outcomes remains underexplored and complex. Ionization-based devices require caution because ozone and other reactive by-products may be generated under some conditions. Regarding pregnancy outcomes, limited research, like the studies on HEPA filter use in high-pollution areas, suggested an increase in birth weight among term babies. However, these studies lacked broad, quantified correlations, underscoring the need for further investigation to

establish any definitive links between air cleaners and these specific health outcomes (Eggleston et al., 2005). Overall, the existing literature calls for more comprehensive and detailed research due to the currently insufficient medical evidence needed to establish clear, quantified correlations between air cleaners and various health outcomes (Brauner et al., 2008; Eggleston et al., 2005; McCreanor et al., 2007).

3.4. Assessment of the evidence linking air cleaner use to long-term health outcomes and economic impacts

Current research provides limited evidence to establish clear correlations between the use of air cleaners and their long-term health and economic impacts. Various studies indicate that while some air cleaners, such as negative ion air purifiers (NIAPs), effectively reduce indoor PM2.5 concentrations, they also elevate negative ion levels. Although systematic analyses demonstrate that air filtration significantly lowers PM2.5 levels, these findings have not successfully addressed the long-term health or economic outcomes, revealing a significant gap in the research (Hänninen et al., 2005). Evaluations of different air filtration methods have shown improvements in air quality and filter effectiveness. Despite these advances, the research has yet to provide substantial data to correlate these benefits with long-term health or economic impacts, highlighting a critical area for future investigation (Stephens & Siegel, 2013). Short-term studies in environments like schools have shown that air cleaners can reduce FeNO, EBC IL-1β and IL-6 biomarkers along with PM concentrations, yet these interventions have not conclusively demonstrated long-term health or economic benefits (Chen et al., 2015; Karottki et al., 2013).

Strong evidence connects PM2.5 exposure to cardiovascular disease, yet studies focusing on air cleaners have primarily examined short-term reductions in PM2.5 without addressing the prolonged health or economic effects (Pope & Dockery, 2006). For instance, a study found that air cleaners reduced mean systolic blood pressure over a median of 13.5 days but did not impact diastolic blood pressure, failing to conclude long-term health impacts (Hänninen et al., 2005). In residential settings, HEPA air purification reduced traffic-related and other aerosols, though these investigations stopped short of exploring long-term health or economic impacts (Stephens & Siegel, 2013). During pregnancy, using portable HEPA filters was linked with a slight increase in birth weights, yet the long-term health or economic outcomes were not further explored (Karottki et al., 2013). Additional insights on the cardiovascular effects of PM2.5 were noted, but these did not establish long-term health or economic correlations (Pope & Dockery, 2006). The existing literature also includes various limited-scope studies, often focused on short-term interventions or specific settings without considering long-term outcomes (Chen et al., 2015; Hänninen et al., 2005; Karottki et al., 2013; Pope & Dockery, 2006; Stephens & Siegel, 2013).

3.5. Evaluation of the sufficiency of medical evidence regarding the impact of indoor air pollution on health-related symptoms

The review of the studies emphasizes that while there are indications that indoor air pollution may affect health symptoms, the current medical evidence is insufficient to

definitively evaluate the impact, particularly regarding specific health symptoms related to indoor air quality. Numerous studies focus on various aspects of indoor air pollution, such as particulate matter (PM), negative ion air purifiers (NIAPs) and the use of HEPA filters, presenting mixed findings that underscore the necessity for more rigorous and targeted research. Studies that utilize NIAPs and other personal-level air filtration equipment primarily assess the efficacy of reducing indoor PM concentrations but do not thoroughly investigate the direct health implications of these reductions. Although some results show moderate-to-large decreases in PM2.5 levels, specifically reducing concentrations from levels around 35 μg/m^3 to approximately 15 μg/m^3, they lack a direct correlation with health symptoms or outcomes (Barn et al., 2008). The effects of indoor air pollution on specific health symptoms are acknowledged, yet the research often focuses more on air filtration technology and its potential to improve indoor air quality rather than on direct health outcomes, leading to calls for more in-depth studies to establish a quantifiable relationship between indoor air pollution and its health effects (Mendell & Heath, 2005). Some studies suggest that indoor air pollution, particularly from particulate matter, could influence health symptoms, citing associations between PM exposure and various biomarkers of health issues such as oxidative stress and respiratory inflammation (Mustafic et al., 2012; Strak et al., 2012). However, these studies typically examine indirect markers rather than direct symptoms, indicating a potential impact but not providing conclusive evidence. Research linking cardiovascular disease to PM2.5 highlights the need for further investigation into how indoor air pollutants directly affect other health symptoms (Hoek et al., 2013).

Other studies investigate specific outcomes, such as changes in birth weight or cardiovascular risk biomarkers associated with the use of air filtration systems (Barn et al., 2008). Despite various studies indicating potential health benefits from reducing indoor air pollutants through air purification technologies, there remains a significant gap in medical evidence directly linking these interventions to improving health-related symptoms (Mendell & Heath, 2005; Strak et al., 2012). In conclusion, while some individual studies suggest beneficial effects of reducing indoor air pollution on health, the overall body of medical evidence remains inconclusive (Hoek et al., 2013; Mustafic et al., 2012).

3.6. Evaluation of the available medical evidence on the health effects of different sources of indoor air pollution

Numerous studies provide robust quantitative data on the health impacts of indoor air pollution. Research indicates that the use of negative ion air purification systems (NIAPs) can significantly reduce indoor concentrations of particulate matter (PM2.5). Measurements show reductions to as low as 10 micrograms per cubic metre (μg/m^3), down from baseline values often exceeding 35 μg/m^3 in typical urban settings (Grabarczyk, 2001). Furthermore, another study assesses the impact of air cleaner interventions on biomarker levels, essential for understanding health effects. This investigation recorded a decrease in fractional exhaled nitric oxide (FeNO) levels, with averages falling from 25 parts per billion (ppb) to 15 ppb, suggesting a potential reduction in airway inflammation. (Karottki et al., 2014).

Other studies explore the efficacy of HEPA filters in reducing indoor black carbon levels, which primarily stem from traffic emissions. These filters were shown to decrease

concentrations by up to 60%, achieving levels around 2 μg/m^3 from initial readings close to 5 μg/m^3. This significant reduction in PM2.5 and black carbon was linked to improvements in cardiovascular health markers, although variability in health outcomes was noted across different populations and environments (Janssen et al., 2011; Mills et al., 2009).

The research also underscores the complexity and necessity of differentiating between sources of particulate pollution, such as traffic, tobacco smoke, or woodsmoke, as these sources significantly influence the health benefits observed (Cao et al., 2014; Klepeis et al., 1996; Logue et al., 2011). In summary, integrating specific concentration measurements and health impact data enhances the scientific understanding of how various indoor air pollution sources impact human health. This comprehensive approach highlights the urgent need for targeted research to further clarify these relationships and to develop effective public health interventions.

3.7. Understanding the impact of indoor air pollution on the health of different population groups

Studies frequently measure concentrations of particulate matter, specifically PM2.5 and PM10 (particulate matter with diameters less than 2.5 and 10 micrometers, respectively). Concentrations are typically reported in micrograms per cubic metre (μg/m^3). For example, a study might report finding reductions in PM2.5 concentrations in homes using HEPA filters, with levels decreasing from an average of 35 μg/m^3 to 20 μg/m^3 over a certain period (Chen et al., 2015). Research often measures biomarkers in exhaled breath condensate (EBC), blood, or urine to assess inflammation or oxidative stress caused by air pollution exposure. (Zhang et al., 2011). Studies evaluating air cleaners often report efficiency as a percentage that describes how much particulate matter or gaseous pollutants the device removes from the air. For instance, a HEPA air purifier might be reported as removing 99.97% of particles larger than 0.3 microns (Chen et al., 2015). Health impacts are often measured by changes in blood pressure, respiratory function tests, or incidence of respiratory symptoms. For example, reductions in systolic blood pressure might be reported as a decrease from an average of 120 mmHg to 116 mmHg following the use of air purifiers in a participant's home (Brauner et al., 2008). Studies also detail the exposure duration (e.g. 24-hour exposure, several weeks, or long-term exposure) and the settings (e.g. residential homes, schools, or workplaces), which help contextualize the concentration levels and health impact results (Barn et al., 2008; Sublett, 2011).

While several studies provide insights into the benefits and potential risks associated with various air cleaning technologies, the overall understanding of indoor air pollution impacts remains segmented by specific demographic and health condition variables. This highlights a critical need for broader, more inclusive research to develop effective public health responses and guidelines tailored to diverse populations (World Health Organization [WHO], 2010). Additional reference numbers that discuss related topics include studies on the influence of air quality on elderly individuals and their cardiovascular health (Institute of Medicine [IOM], 2000), and the specific effects of air cleaners on children with perennial allergic rhinitis due primarily to mold allergy (Reisman et al., 1990).

3.8. Assessment of concentration levels of indoor air pollution associated with adverse health effects

The summary concerning the concentration levels of indoor air pollution that may have adverse health effects, as derived from various studies, reveals that specific threshold levels are often not explicitly mentioned. However, significant insights can be gleaned regarding the relationship between indoor air pollution and health: The studies generally acknowledge the adverse effects of indoor air pollution but do not specify exact harmful concentration levels. They emphasize the need for further research to establish these levels across different settings and pollutants (Mendell, 2007; U.S. Environmental Protection Agency [EPA], 2019; Weschler, 2006; World Health Organization [WHO], 2021).

There is a focus on the efficiency of air purifiers in reducing particulate matter (PM) concentrations. While specific thresholds for PM that may cause health problems aren't detailed, the reductions achieved (ranging from 11% to 82%) underline the importance of efficient filtration systems (Chen et al., 2015; Zhang et al., 2011). Various studies hint at the negative health impacts linked to specific pollutants or technologies, such as electrostatic precipitators and HEPA filters. The association between these technologies and health indicators like cardiovascular biomarkers is noted, although without defining harmful concentration levels (Brauner et al., 2008; Janssen et al., 2011; Weschler, 2006). Discussions about the broader impact of indoor air pollution on health, particularly concerning asthma and cardiovascular diseases, are common. The need to reduce exposure to various indoor allergens and pollutants is consistently highlighted as crucial for improving health outcomes (Institute of Medicine [IOM], 2000; Mendell, 2007; Reisman et al., 1990). The research acknowledges the complex interplay of factors that influence indoor air quality and health impacts, stressing the necessity for further studies to identify hazardous concentration levels and effective mitigation strategies (ASHRAE, 2022; European Commission [EC], 2022; U.S. Environmental Protection Agency [EPA], 2019). In summary, while specific concentration levels of indoor air pollutants that harm health are rarely pinpointed, the existing literature emphasizes the importance of reducing indoor air pollution through various means and continuing research to better understand its health impacts. The consensus across studies is that there is a critical need for efficient air filtration and the reduction of pollution sources to mitigate health risks associated with indoor air quality.

3.9. Criteria for selecting IAQ limits in built environments to minimize health impacts

In the quest to establish IAQ limits conducive to minimal health impact within built environments, a multifaceted approach emerges from a synthesis of diverse research findings: Negative Ion Air Purifiers (NIAPs), despite their efficacy in reducing PM2.5 concentrations, may introduce adverse health effects due to elevated negative ion levels and ensuing reactions with room air constituents (Laurent et al., 2013). Consequently, when formulating IAQ limits, it becomes imperative to scrutinize the potential health risks associated with NIAPs alongside the imperative to reduce PM2.5 concentrations.

A thorough examination of filtration technology reveals additional dimensions for IAQ limit selection, encompassing factors such as air quality enhancement, filtering efficiency,

energy and economic efficacy, thermal comfort and auditory impact (Fisk & Chan, 2017). These parameters serve as critical benchmarks for assessing the effectiveness of filtration systems and inform the establishment of IAQ limits that prioritize both health and environmental sustainability. Acknowledging the variability in air filtration efficacy across different geographic regions and technological implementations is paramount (Chen et al., 2015). This variability underscores the need for tailored IAQ limit criteria that account for regional disparities in pollutant levels, filtering technologies and socio-economic factors.

Studies highlighting the potential benefits of interventions, such as portable air cleaners with HEPA filters, for vulnerable populations, especially pregnant women and infants, underscore the importance of incorporating targeted measures into IAQ limit criteria. Criteria should prioritize interventions that safeguard the health and well-being of vulnerable groups, thereby ensuring equitable access to clean indoor air. Given the significant health risks posed by specific pollutants, particularly in urban settings with high traffic-related contamination, IAQ limit criteria must focus on mitigating the adverse health effects of these pollutants (Dimitroulopoulou, 2023; Fisk, 2013; Pope & Dockery, 2006; U.S. Environmental Protection Agency [EPA], 2018). Understanding the complex interplay between pollutants, such as PM2.5, and their impact on cardiovascular health is essential for formulating effective IAQ limits. Expert consensus and practical approaches offer invaluable insights into IAQ limit selection, guiding the adoption of evidence-based strategies to protect public health (World Health Organization [WHO], 2021). By aligning IAQ limit criteria with expert recommendations, policymakers can ensure that indoor environments prioritize health outcomes while optimizing resource allocation and implementation strategies. Adopting a hypothesis-driven approach facilitates the identification of IAQ limit criteria that target specific airborne pollutants contributing to negative health impacts (ASHRAE, 2022). By formulating hypotheses regarding alleviating exposure-related illnesses and symptoms, researchers can guide the development of IAQ limits that effectively address the root causes of indoor air pollution. In conclusion, synthesizing these diverse perspectives underscores the need for a holistic and nuanced approach to IAQ limit selection. By integrating considerations such as technological variability, targeted interventions for vulnerable populations and expert consensus, policymakers can formulate IAQ limits that prioritize health outcomes and promote equitable access to clean indoor air.

4. Discussion

This comparative review of 36 peer-reviewed studies demonstrates that indoor air cleaning technologies – particularly HEPA-based filtration systems – consistently reduce indoor particulate matter concentrations under real-world conditions, with reported PM. reductions typically ranging from approximately 20% to 80% depending on baseline pollution levels, room volume, device capacity, airflow patterns and maintenance practices. The strongest and most reproducible evidence concerns particulate removal and short-term cardiopulmonary responses, including modest reductions in systolic blood pressure, improvements in endothelial function and decreases in inflammatory biomarkers such as FeNO and circulating cytokines. In children, reductions in airway inflammation markers suggest potential respiratory benefits, although quantified dose–response relationships

remain insufficiently established. In contrast, evidence regarding gaseous pollutant removal remains fragmented, with activated carbon, photocatalytic oxidation, plasma systems and ionization technologies demonstrating laboratory efficacy but limited real-world clinical validation; moreover, ionization-based devices and some electrostatic systems may generate ozone or reactive secondary byproducts, raising concerns that pollutant transformation may offset removal benefits. Across technologies, HEPA filtration shows the most consistent performance for particles, including traffic-related black carbon, fungal spores and allergens relevant to asthma management, whereas hybrid systems combining filtration with sorptive or electrostatic mechanisms offer broader removal potential but require careful evaluation of byproduct formation and long-term performance stability. Despite documented exposure reductions, translation into sustained long-term health outcomes remains uncertain, as most intervention studies are short in duration, involve relatively small cohorts and rarely assess chronic disease progression, hospitalization rates, or mortality endpoints. Evidence for benefits among vulnerable populations, children, elderly individuals, pregnant women and those with cardiometabolic disease suggests potential disproportionate gains, yet stratified analyses are limited and economic evaluations are scarce. In energy-efficient buildings, where ventilation rates may be constrained due to thermal or energy considerations, air cleaners may function as supplementary mitigation tools; however, effectiveness depends critically on correct sizing (e.g. Clean Air Delivery Rate relative to space volume), airflow distribution, sustained maintenance and avoidance of ozone-generating technologies. Table 1 summarizes the comparative performance, strength of health evidence, cost implications and key implementation considerations across major air-cleaning technologies.

Overall, the literature indicates moderate evidence for short-term cardiovascular and respiratory improvements associated with HEPA-based particle reduction, low-to-moderate evidence for gaseous pollutant mitigation benefits and insufficient evidence for long-term clinical and economic impacts. Major research gaps include the absence of long-duration intervention trials, limited cost–benefit analyses, insufficient characterization of pollutant mixtures and chemical composition changes and lack of standardized outcome reporting frameworks. Consequently, while air cleaners – particularly mechanical filtration systems – can substantially reduce indoor particulate exposure and may contribute to measurable short-term physiological improvements, their role should be considered complementary to source control and adequate ventilation within risk-based IAQ management strategies, especially in densely populated or energy-constrained built environments. Importantly, implementation and effectiveness vary considerably across climatic regions and socioeconomic contexts: cold Nordic climates with energy-constrained ventilation, wildfire-prone regions with episodic extreme PM exposure and highly urbanized high-pollution settings present distinct operational challenges and exposure profiles. Socioeconomic disparities influence access to portable air cleaners, maintenance quality and electricity affordability, while policy frameworks and guideline values differ across WHO, EPA, European Commission and ASHRAE recommendations, shaping adoption strategies and IAQ targets. Practical constraints – including filter replacement costs, electricity consumption, acoustic comfort and user behaviour – further determine real-world performance, underscoring the need for context-sensitive, policy-aligned implementation strategies.

Table 1. Comparative overview of air-cleaning technologies: effectiveness, health evidence and practical consideration.

Technology type	Primary pollutants targeted	Typical removal effectiveness (real-world)	Strength of health evidence	Relative cost (device + O&M)	Energy use	Key advantages	Key limitations / risks
HEPA filtration (portable)	$PM_{2.5}$, PM_{10}, black carbon, allergens, bioaerosols	20–80% $PM_{2.5}$ reduction (context-dependent)	Moderate (short-term cardiovascular & respiratory biomarkers)	Moderate	Low–Moderate	Consistent particulate removal; well-documented	Filter replacement cost; noise; limited gas removal
HEPA (central HVAC)	$PM_{2.5}$, PM_{10}, infectious aerosols	40–90% depending on MERV/HEPA grade & airflow	Moderate (indirect health benefit evidence)	Moderate–High (retrofit dependent)	Moderate	Building-wide coverage; integrated solution	Pressure drop; fan energy penalty; retrofit complexity
Activated carbon filtration	VOCs, ozone, odors, some gases	Variable (strongly dependent on media mass & contact time)	Low–Moderate (limited clinical studies)	Moderate	Low	Gas-phase pollutant removal	Media saturation; limited evidence of health outcomes
Electrostatic precipitators (ESP)	Fine particles	30–70% PM reduction	Low–Moderate	Moderate	Low	Low pressure drop	Potential ozone generation; maintenance sensitive
Ionizers / Negative ion devices	Fine particles (via agglomeration)	20–60% (surface deposition dependent)	Low / Inconsistent	Low–Moderate	Very Low	Low energy demand	Ozone/byproduct formation risk; limited clinical evidence
Photocatalytic oxidation (PCO)	VOCs, some microorganisms	Variable; strong lab results, limited field validation	Low	Moderate–High	Moderate	Potential gas-phase removal	Secondary pollutant formation; limited long-term data
Cold plasma systems	VOCs, particles, microorganisms	Variable; limited real-world data	Low	Moderate–High	Moderate	Multi-pollutant targeting	Byproduct uncertainty; limited health validation
Hybrid systems (HEPA + carbon/ ESP)	Particles + selected gases	Broad removal; performance technology-dependent	Moderate (particles) / Low (gases)	Moderate–High	Moderate	Multi-pollutant control	Cost; maintenance complexity

5. Conclusion

This review demonstrates that air-cleaning technologies – particularly HEPA-based filtration systems – consistently reduce indoor particulate matter concentrations and may provide short-term cardiopulmonary benefits, including modest improvements in blood pressure and inflammatory biomarkers. However, evidence linking air cleaner use to long-term health outcomes, economic benefits and comprehensive removal of gaseous pollutants remains limited and heterogeneous. While air cleaners can serve as valuable complementary measures – especially in energy-efficient or ventilation-constrained buildings – their effectiveness depends on correct sizing, maintenance and avoidance of byproduct-generating technologies. Future research should prioritize long-duration intervention studies, standardized health outcome reporting and integrated evaluations that connect pollutant reduction, exposure chemistry and clinical relevance.

Disclosure statement

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