Aerosol Science and Engineering
https://doi.org/10.1007/s41810-023-00178-5

REVIEW

Air Pollution Control Technologies for Indoor Particulate Matter Pollution: A Review

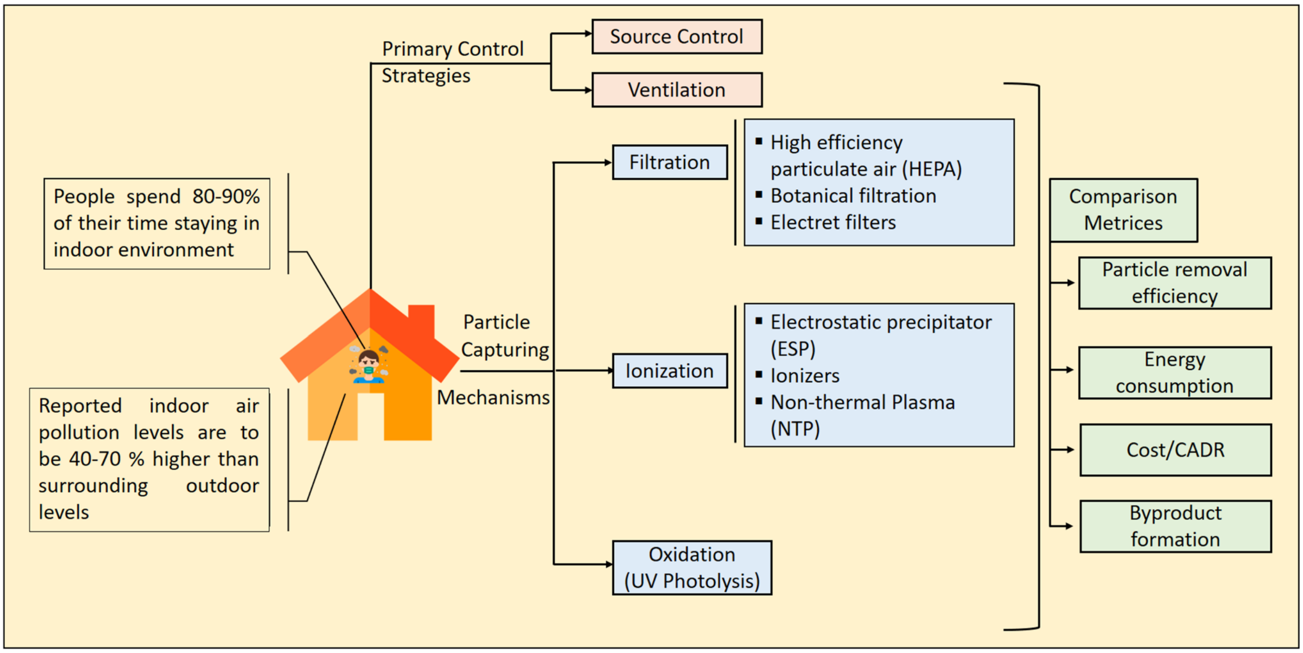
Aiswarya Kumar[1] · **Vasudev Malyan**[1] · **Manoranjan Sahu**[1,2,3]

Received: 31 October 2022 / Revised: 16 February 2023 / Accepted: 20 February 2023

Abstract

Indoor air quality is one of the major concerns in the modern environment since urban residents spend 80–90% of their time staying indoors. Pollutant exposure could be relatively higher indoors due to the increased number of sources along with activities that cause re-suspension of pollutants back into the air stream. Several existing and emerging technologies for indoor particulate matter (PM) control are available; however, there is a lack of a comprehensive review of these technologies for the end-users. Therefore, current study presents a techno-commercial comparison of the existing indoor air pollution control technologies based on several metrics such as particle removal efficiency, cost-commercialization, energy consumption, and by-product emission. Additionally, recent advancements and applications of the aforementioned technologies in real indoor environments have also been reviewed. The study suggests that for efficient particle removal, either high-efficiency particulate air (HEPA) filters or ESP should be preferred. Likewise, for the removal of multiple pollutants like particles, gases and volatile organic compounds simultaneously, emerging technologies can be integrated with pre- or post-stages of conventional technologies. The cost performance index is lowest for HEPA filters and ESP, indicating that they provide a better value for money in terms of performance. Ionization based and emerging PM control technologies should be avoided in case of sensitive populations due to health concern associated with emission of hazardous by-products.

Graphical Abstract



Extended author information available on the last page of the article

Keywords Particulate matter control technology · Performance comparison · Cost/cadr · By-product · Indoor real environment

1 Introduction

Over the past few decades, increased urbanization and industrialization have drastically upgraded people's lifestyles in developing countries (Tofful et al. 2021). While many may have benefited economically due to the increase in employment opportunities and technology-assisted operations, it has also increased the risk of exposure of the masses to poor-quality air (Afshari et al. 2020; Mannan and Al-Ghamdi 2021). Indoor air quality is of major concern in the modern environment among various aspects of air pollution. Most of the population living in urban areas spend 80–90% of their time in homes, workspaces and different conveyance means such as cars, buses trains etc. (Afshari et al. 2020, Pei et al. 2019., US EPA 2018). As these structures are generally congested, free air circulation is restricted due to space constraints in developing and populated countries (Guo et al. 2019; Khandare et al. 2019; Pettit et al. 2017). Several air pollution exposure studies have reported two to five times higher concentrations of pollutants in the indoor environment and about twice as toxic as that of the typical outdoor pollutant concentration (US EPA 2018; Macintosh et al. 2008; Wallace 2004).

Different indoor pollutants result in uncomfortable and unhealthy living conditions (Afshari et al. 2020; Altun and Kilic 2019; Chen et al. 2005; Tofful et al. 2021; Zhang et al. 2011). Exposure to indoor pollutants may result in sick building syndrome (SBS) which consists of several health problems such as headache, nausea, dizziness, irritation of the eyes and mucous membrane. (Aydogan and Montoya 2011; Cheek et al. 2020; Guieysse et al. 2008). Moreover, they may cause building related illness (BRI) and multiple chemical sensitivity (MCS) (Luengas et al. 2015; Tran et al. 2020). Among different indoor pollutants, particulate matter (PM) is of special concern. Smaller size in the atmosphere and greater penetration capacity of PM make it more harmful and toxic than gases (Manisalidis et al. 2020; Zhu et al. 2021). Particles of very small and variable diameters can penetrate through the respiratory tract resulting in cardiovascular diseases, reproductive, central nervous system dysfunctions and respiratory diseases like pneumonia, chronic obstructive pulmonary disease (COPD) and lung cancer (Gawronska and Bakera 2014; Liu et al. 2022; Manisalidis et al. 2020; Tran et al. 2020; Wheeler et al. 2014). Therefore, poor indoor air quality (IAQ) is ranked among the top five risks to human health by the US Environmental Protection Agency (EPA) (Gawronska and Bakera 2014; Guieysse et al. 2008). Source-apportionment studies have discovered that household biomass burning is the largest contributor to outdoor $PM_{2.5}$ concentration in India (Venkataraman et al. 2018).

Although PM concentration in both outdoor and indoor environments can be correlated most of the time, exposure will be higher indoors due to more number of indoor particle sources such as smoking, cooking, heating, candle and incense burning, use of electrical equipment like cloth dryers, printers and electric ovens. In addition to that, human activities such as cleaning and movement cause re-suspension of particles back into the air stream that significantly increasing the exposure (Boedicker et al. 2021; Ibrahim et al. 2021; Jeong et al. 2021; Molgaard et al. 2014; Tofful et al. 2021; WHO 1998). Closed buildings provide some protection from outdoor coarse particles; however fine particles still enter through open doors and windows even when efficient mechanical air conditioning systems are provided (Irga et al. 2017).

Indoor air quality can be improved by three approaches, namely source control, ventilation and control technologies. Source control is the most economical strategy; however, it is not always practicable due to several technical and financial constraints (Siegel 2015). Under such circumstances, ventilation that removes contaminated air away from occupants is employed (Luengas et al. 2015; Wang et al. 2004). Nevertheless, ventilation is not suitable in situations where the outdoor particle concentration is higher and is usually costly due to heating or cooling requirements (Molgaard et al. 2014; Brager et al. 2011). Indoor control technologies operate by cleaning the contaminated indoor air either by physical means or by chemically converting contaminants into harmless byproducts (US EPA 2018). All of the aforementioned approaches can be effectively inducted by integrating them into air handling systems and can be used as portable units in specific indoor spaces having flexible times of operation (Chen et al. 2005; Hart et al. 2011).

Multiple reviews have already been done on indoor air quality for specific environments mainly focusing on the associated health effects and different monitoring methods. On the other hand, no significant reviews were focused on particularly indoor pollution control technologies (Saini et al. 2020a, b, 2021; Van Tran et al. 2020; Ye et al. 2017; Zhang et al. 2021; Zhuang et al. 2000). After a comprehensive review done by Zhang et al. (2011) on different indoor control technologies, to date there was no critical comparison of different indoor pollution control technologies; thus information seems widely scattered (Zhang et al. 2011). Amid this, since 2017, multiple review articles were concentrated on technologies like filtration, photocatalysis or botanical filtration (Bandehali et al. 2021; Beckman et al. 2022; Martin et al. 2021; Han and Ruan 2020; Irga et al. 2018; Kraakman et al. 2021; Li and Ma 2021; Liu et al. 2017a, b; Tran et al. 2020). As multiple pollutants of different characteristics coexist in indoor environments, there is a need to study each of the pollutants independently to gain a better understanding. Therefore, current review article focused on mechanism of PM removal, factors influencing the removal mechanism and recent advancements as well as possible applications of different PM control technologies in real indoor environments. In addition, this article critically compares different indoor particle technologies like filtration, ESP, ionization, botanical filtration, non-thermal plasma, and photolysis based on their particle removal efficiency, cost-commercialization, energy consumption and by-product formation. This will enable readers and users to select suitable technology for indoor applications. Relevant research papers on the domain of indoor PM pollution control were searched on Scopus, web of science, IEEE and google scholar based on related keywords. Contents were then integrated, and comparison of different technologies was done with help of analysis of previous experimental results and further calculations.

2 Classification of Indoor Control Technologies

Irrespective of the origin of pollutants, it is required to mitigate and reduce air pollutants to achieve a healthier indoor environment (Irga et al. 2017). Indoor air pollution control is a hierarchy of three approaches, namely universally preferred source control, ventilation which dilutes pollutant concentration and indoor pollution control technologies to purify polluted air (Huang et al. 2016; Lee et al. 2020; Siegel 2015).

2.1 Source Control

Source control is the most economical and effective method to control PM emissions and involves elimination or reduction of various indoor pollution sources (Cheek et al. 2020; Tan and Zhang 2004). Source control includes judicious product selection, modification or implementation of restrictions that eliminate or reduce emissions of harmful substances into indoor air (Levin 1992). Source control in indoor environments is usually achieved by the elimination of sources of pollution such as avoiding smoking, reducing high-strength activities in room and use of low emitting products. Different emission reduction strategies like maintaining sanitation, reducing usage of solid fuels, sealing or encasement of sources, construction of buildings away from busy roads and periodic monitoring and control over different combustion devices like gas stoves can also be adopted (Bennett 2009; Pettit et al. 2017; Yu et al. 2009). Efficient source control requires a good understanding of emission processes, secondary reactions and availability of other useful data if any (such as manufacturer's innovative product development and architect's building designs with least emitting products) (Levin 1992). Over the years modern sensors and monitors were developed and employed for automated indoor environment monitoring (Carminati et al. 2021; Demanega et al. 2021). However, sometimes to adapt source control, raw materials need to be altered and processes need to be modified. This can result in additional costs and other associated issues (Siegel 2015). Additionally, whatever optimization one does at the sources, one or other air contaminants will be produced at the exhaust due to different pathways of their formation.

2.2 Ventilation

Under circumstances when source control is not practicable due to technical and financial constraints, ventilation or control technologies that tend to divert the contaminated air away from occupants are adapted (Luengas et al. 2015; Wang et al. 2004). Ventilation can supply clean air or remove PM-laden air from an indoor environment (ANSI 2019). Based on the force that initiates the flow of air, ventilation can be classified as either natural or mechanical. Natural ventilation, such as airflow through vents, window openings, hoods and wind towers is caused by pressure differences due to temperature gradient and wind flow (Mukhopadhyay et al. 2014; Russell et al. 2007). As the dependency on local meteorological and environmental conditions makes natural ventilation unpredictable and uncontrollable, mechanical ventilation provided by exhaust fans and ducts is usually preferred (Barger et al. 2011).

Particle removal efficiency in a ventilation system that depends on various factors such as the strategy of ventilation, number of occupants, floor size, outdoor particle concentration, distribution in room, location as well as emission strength of source, integration with different systems like hoods and filtration, environmental factors like humidity and temperature in the indoor environment (ANSI 2019; Lu et al. 2011; Nagy et al. 2019; Zhong et al. 2010). Ventilation was found effective in different real indoor environments like residences, classrooms, dental clinics, kitchens, historical buildings and offices (Bohanon and Zaatari 2020; Guo et al. 2008; Kang et al. 2019; Nagy et al. 2019; Park et al. 2014; Ren et al. 2021; Singer et al. 2017). However, ventilation can increase energy usage in building and allows entry of pollutants from outdoors (Siegel 2015).

It is important to understand the ventilation type and rate suitable for an application. For example, a ventilation rate above 4 air changes per hour would not be preferred in heating, ventilation and air conditioning (HVAC) applications as it adds energy requirements owing to heating and cooling (Lu et al. 2011; Molgaard et al. 2014). Ventilation can be made energy efficient by optimizing parameters like airflow, recirculation rate, fan power and heat recovery rate (Godish 1996; Nagy et al. 2019). Mechanical ventilation could also generate noise and secondary pollutants (Lai et al. 2018). In summary, it can be seen that ventilation is difficult to exist as a single stand-alone unit and therefore, requires to be integrated with PM control technologies to achieve desired benefits. The third method, indoor air cleaning, is employing different physical and chemical technologies which are explained in detail along with their removal mechanism, factors impacting removal, application in different indoor environments as well along with their possible advantages and disadvantages in Sect. 3.

3 Indoor Particulate Matter Control Technologies

Indoor pollution control technologies are methods that clean contaminated air by either physical means or chemically converting contaminants into harmless byproducts (US EPA 2018). Indoor air cleaners can be portable and inductive devices; the former is preferred in specific spaces having flexible time of operation like kitchen or fire space (Hart et al. 2011). On the other hand, inductive devices work for entire buildings and, therefore, are usually installed with an air handling system (Chen et al. 2005). Portable air purifiers have reduced risk of cross contamination between different rooms whereas inductive ones produce no noise (Afshari et al. 2020)**.** Indoor control technology is broadly classified as existing and emerging control technologies based on its commercialization in the consumer market. Technologies such as photocatalysis and ozonation are not included in this review article as they are not very effective for removing particle pollutants.

3.1 Existing Indoor Particle Control Technologies

Existing or conventional indoor air pollution control methods include mechanical filters, ionizers and electrostatic precipitators.

3.1.1 Mechanical Filtration

Filtration involves the separation and removal of suspended particles from the indoor air stream utilizing a porous medium. Filtration can work by the following two principles: surface filtration and depth filtration. In the former method, particles of sizes greater than 10 μm are collected by trapping them on the surface of the filter. In case of depth filtration, collected deposits of particles having sizes lesser than 0.01 μm form a cake and that eventually starts trapping more particles, thereby collecting particles through the surface as well as through the entire depth of the filter (Luengas et al. 2015). According to basic filtration theory, five mechanisms like inertial effect, interception, diffusion, electrostatic forces and gravitational settling are responsible for the removal of particles (Hinds 1998; Hung et al. 2007; Liu et al. 2017a, b). The first two mechanisms, inertial impaction and particle interception remove particles larger than 1 μm, whereas smaller particles less than 0.1 μm are usually removed by diffusion. Due to higher mobility for intermediately sized particles between 0.1 and 1 μm they are not efficiently removed by any of the aforementioned mechanisms (Offermann et al. 1985). Charged filters called electret filters can trap particles using mechanisms like electrostatic attraction and polarization. Particles can be captured effectively using gravitational settling if their settling velocity is larger than the convective velocity of the flow through the filter, thus limited to large-sized or heavy particles (Colbeck and Lazaridis 2009).

Filtration is widely used in indoor environments due to its low cost, easy installation, and simplicity in operation (Komaladewi et al. 2018). Removal efficiency depends on factors like flow rate, particle characteristics, fiber characteristics, and air flow pattern within the room (Bian et al. 2019; Chen et al. 2019; Irga et al. 2017; Ji et al. 2020; Ruan and Rim 2019). HEPA filters with removal efficiency of 99.99% for 0.3 μm size particles are widely preferred in many indoor spaces like theatres and hospitals (Liu et al. 2017a, b). As filtration efficiency is dependent on particle size, nano fibers in cabins were shown to be capable of reducing concentrations of ultra-fine particles and black carbon from vehicular emission at relatively higher rates of removal of 88% and 84%, respectively (Lee et al. 2015). Although there was a reduction in $PM_{2.5}$ by about 70% with HEPA filtration unit, CO_2 concentration was increased by 6 times due to inadequate air change rate in a classroom (Tong et al. 2020). Applicability of low-cost and low-efficiency filters in rural kitchens has been discussed in many research articles (MacIntosh et al. 2009; Namara et al. 2017; Still et al. 2018; Ward et al. 2017). However, adoption of those filters on a broader scale requires considerations for cost, replacement, energy usage and provisions to maintain adequate air exchange rates capable of maintaining CO_2 concentration within desirable limits. More details on applications of filtration and corresponding removal efficiency in different environments are shown in Table 1.

Despite these advantages, mechanical filters get clogged resulting in increased pressure drop which incurs increased

Table 1 Application of filtration in indoor environment

Filter	Airflow ($m^3\ hr^{-1}$)	Single pass efficiency	Application	Summary	References
High efficiency particulate air (HEPA) Ultra –low penetration air (ULPA)	NA	99.97% for 0.3 µm 95% for 1 µm 99.99% for 0.12 µm	Living and dining room	Efficient in capturing particulate matter and allergens while tested over 6 months	Vijayan et al. (2015)
Nano fibers	1160–1360	UFP—88 ± 6% BC—84 ± 5% $PM_{2.5}$—55 ± 22%	School bus	Nanofibers are advantageous as they provide high efficiency with quiet low pressure drop	Lee et al. (2015)
Two filtration systems – one at air handling unit filter and outdoor air filter	30.6–122.4	28% effective than single filter	Office building in megacities	Two filters are favorable when outdoor airflow rate by ventilation is higher	Ruan and Rim (2019)
HEPA furnace filters	NA	$PM_{2.5}$emissionrate-1.5 mg min^{-1}	Rural kitchen	Application of high rated filter and box fan can reduce particle emission	Still et al. (2018)
High efficiency (99% at 2 µm) Low efficiency (99.7% at 0.3 µm)	NA	$PM_{2.5}$ exposure reduction—53% $PM_{2.5}$ exposure reduction—31%	Bedroom, living room	Reduce exposure to particles in sensitive population in urban areas	Morishita et al. (2018)
High efficiency (active) Low efficiency (placebo)	0.12	$PM_{2.5}$ – 63.3%; endotoxin-91.8% $PM_{2.5}$—40.6%; endotoxin—80.4%	Residences with wood stove homes	Even low-cost low efficiency filter is efficacious in wood stove homes	McNamara et al. (2017)
Highly efficient in-duct filtration	NA	Reduction in hospital visits by 700 premature death, 940 hospital visits and 130,000 asthma attack	Residential building in metropolitan cities	Duct cleaning is preferred to portable air cleaning when ventilation rate in room higher	MacIntosh et al. (2010)
Highly efficient filters (85% for 0.2 µm; 95% 0.3 µm)	NA	$PM_{2.5}$—63% Particle count (0.3–0.49 µm)—75%	Residential space heating	Filtration was found more efficacious and less expensive compared to stove change out	Ward et al. (2017)
HEPA filters (99.97% for 0.3 µm)	70–150	$PM_{2.5}$—70%	Classroom	Even though particle concentration reduced CO_2 concentration increased 6 times due to inadequate air change rate	Tong et al. (2020)

NA not available, *UFP* ultrafine particles, *BC* black carbon energy consumption and thus needs to be replaced regularly in long run (Chen et al. 2020; Liu et al. 2017a, b; Zhao et al. 2013). As filtration needs regular maintenance and replacement, it is not applicable in high dust environments like railroads, tunnels, and also should be avoided in high temperature indoor applications due to chance of fire hazards (Wen et al. 2015). Higher maintenance, reduced sustainability and inefficiency in capturing gaseous pollutants are some other disadvantages of filtration (Pettit et al. 2017). Different structure-based and interaction-based approaches can be adopted to improve the performance of conventional filters. Structure-based modifications are done by varying morphology, hybridization techniques and stacking multiple layers on the surface. Interaction-based approach includes either providing charges to the filters as in electret filters or providing separate energy sources such as in ESP (Chen et al. 2020; Colbeck and Lazaridis 2009; Han et al. 2021). In summary, particle removal by filtration depends on several factors such as particle characteristics in an air stream, filter properties, source strength, duration of operation and attributes of accessories like fan.

3.1.2 Ionizers

Ionizers trap particulate matter by introducing differently charged ions into an indoor environment (Shiue et al. 2011; Zhang et al. 2020). Mechanism of PM capture by ionizer is illustrated in Fig. 1. Particles start acquiring these diffused charges by ion–particle attachment mechanisms and get attracted to neutral particles thereby forming aggregates which get settled (Guo et al. 2019; Pushpawela et al. 2017). Additionally, electrostatic repelling forces and attraction between charged particles with different surfaces at ground potential like walls, furniture, tables, occupants, etc. cause particles to move towards them and eventually get deposited by either static electrification or image forces (Chen et al. 2020; Grinshpun et al. 2005; Luengas et al. 2015; Pushpawela et al. 2017; Shaughnessy et al. 1994). Ionizers can be classified as unipolar ionizers and bipolar ionizers based on polarity of emitted ions (Zeng et al. 2022).

Lee et al. (2004) obtained an increase in particle removal efficiency for three tested ionizers with increased ion emission rate as well as with emission duration while insignificant influence was found with particle size (Lee et al. 2004). Particle removal by ionizer was found to be independent of polarity, dependent on ion emission rate and showed nearly insignificant influence with other parameters like particle size within a particular size range of 0.3–3 µm, particle characteristics and human body temperature (Grinshpun et al. 2005). Shiue et al. (2011) observed increased removal of PM when ionizer was placed near PM source and the highest removal efficiency was obtained at a height of about 60 cm from floor level (Shiue et al. 2011). Portable ionizers are usually preferred in confined areas with a high surface-to-volume ratio like automobile cabins, flights, bathrooms, cellular offices, animal sheds and small residential areas as well as in applications where reduced noise nuisance is preferred (Agarwal et al. 2021; Grinshpun et al. 2005; Grabarczyk 2001; Lee et al. 2004; Shiue et al. 2011., Zhao et al. 2005). As flow rate is lower for ionizers due to the absence of fans, they are preferred in rooms where little mixing is required (Molgaard et al. 2014). Application of an ionizer reduced particle concentration of size range 0.3–2.5 µm by two orders of magnitude in an office building (Grabarczyk 2001). Continuous operation of negative ion air purifier removed ultrafine particle concentration in clean room (Shiue et al. 2011). Vortex desktop stationary ionizer with ion production rate of $30*10^5$ negative ions provided efficiency of about 90% in 5–6 min and 100% in 10–12 min for PM sizes 0.3–3 µm (Grinshpun et al. 2005). Negative ionizer installed in ventilation duct provided capture efficiencies of 31.53% and 12.17% for bacterial species *Serratia marcescens*, and *Staphylococcus epidermidis,* respectively (Zhou et al. 2018). Despite being widely used in indoor environments it has drawbacks such as charging of materials in the room, high ozone concentration, and soiling of different surfaces like tables, furniture and the human body (Offermann et al. 1985). In the worst case, this contamination can result in black wall effect (Grabarczyk 2001).

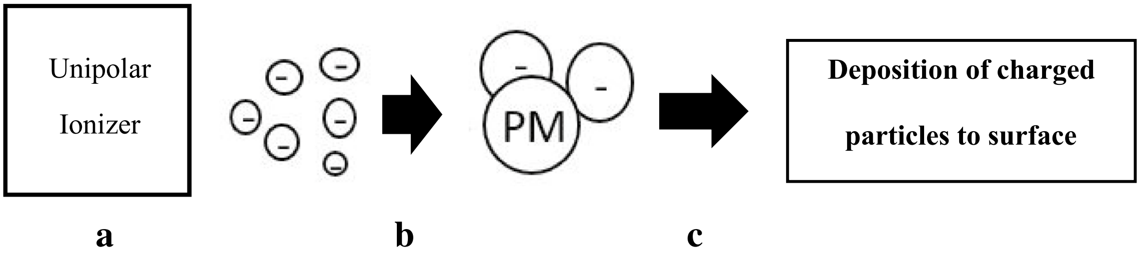


Fig. 1 Mechanism of PM capture by ioniser; **a** Diffusion of ions from ionizer to space, **b** PM-ion attachment, and **c** Deposition of charged particles to different surfaces

3.1.3 Electrostatic Precipitator (ESP)

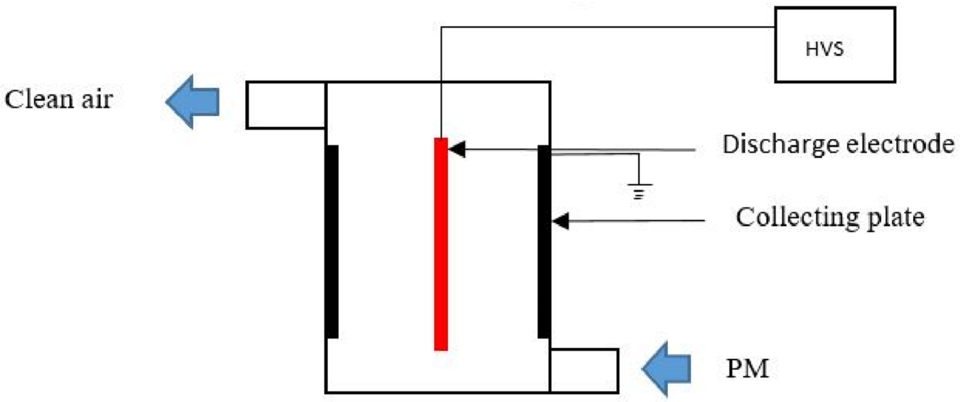
Electrostatic precipitator (ESP) is a type of ionizer where ions are produced on application of high-voltage current at corona point. Although different designs of ESP are available, the simplest one is wire and plate ESP. Figure 2 shows the schematic diagram of a typical wire and plate ESP. It consists of a discharge electrode which is connected to high voltage power supply and the grounded collection plates.

Detailed mechanism of PM capture in an ESP is illustrated in Fig. 3. With an increase in applied voltage above a threshold value, electrons get excited and ionize gas molecules in region of nonuniform electric field. Ionization of gas molecules produce a positive as well as negative ion which is indicated by (a) part of Fig. 3. Generated ions charge particles by either diffusion or field charging and will get attracted to grounded collection electrode by Coulomb force as indicated by (b) and (c) parts of Fig. 3, respectively (He and Wang 2018). ESPs is an in-situ device having higher flow rates compared to ex-situ conventional ionizers due to the fans and collection plates in their design (Waring et al. 2008).

ESP is an effective technology as it provides higher particle removal efficiency with low power consumption (Altun and Kilic 2019). High collection efficiency of particles is due to low drag force and high electric force exerted on them (Wen et al. 2015). Low power consumption of ESP is attributed to low-pressure drop and current density (Altun and Kilic 2019; Parker 2016). Another advantage of ESP compared to filters is that plates of ESP could be cleaned by users themselves compared to filters which may require trained technicians (Chen et al. 2020).

Wallace (2004) obtained particle removal efficiency above 50% in all size ranges from an ESP installed in duct system. However, there was a reduction in efficiency after a few weeks of operation, which necessitated regular cleaning for effective removal of particles (Wallace 2004). ESP was looked at as a promising technology to reduce dust from swine farms, where there was an increased removal in farrow environment compared to a nursery environment owing to the differences in ventilation rate (Rosentrater 2003). Results from computational fluid dynamics (CFD) models suggested that the performance of ESP increased with increasing voltage and decreased with air velocity and these two parameters were not sensitive to each other (Manuzon 2012). More

Fig. 2 Schematic diagram of wire and plate electrostatic precipitator (ESP)



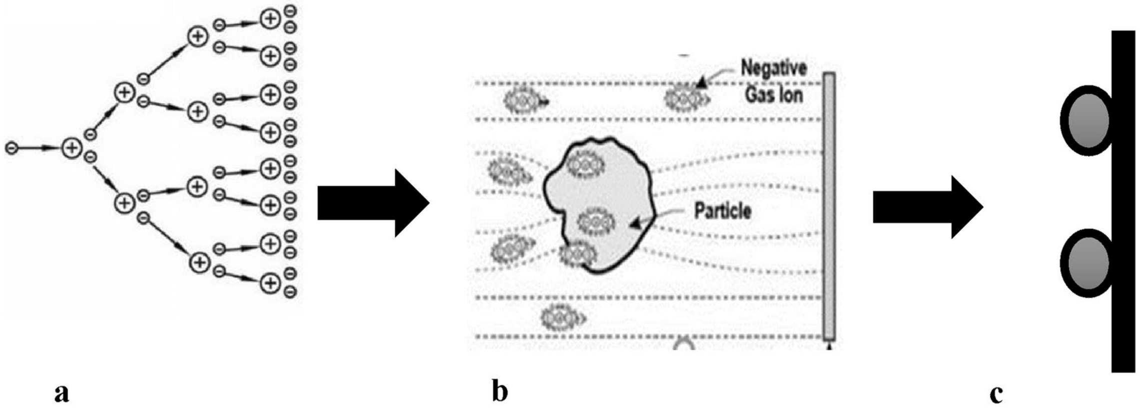


Fig. 3 Different steps involved in PM capture by an ESP; **a** Ionisation, **b** particle charging, and **c** collection to grounded collecting plate

details on the application of ESP in different indoor environments, corresponding efficiency of removal and major influencing factors of removal are tabulated in Table 2.

Designed positive polarity two-stage ESP with 16 carbon fiber filter provided high CADR (> 12 m^3 min^{-1}) and lesser pressure drop for ultrafine particles suggesting its possible application in air conditioning devices which require higher volumetric air flow rate (Kim et al. 2013). ESPs can be used as either induct or stand-alone devices in mechanical ventilation systems in residential buildings due to their high efficiencies and low pressure drop (Afshari et al. 2020; Hao et al. 2022). However, it is preferred more in large-scale applications than small-scale ones because of high flow rate in former (Oliveira and Guerra 2021). Usually, positive polarity and two-staged ESPs are preferred for indoor environments due to lower emission of ozone, larger area of collected electrode, quiet operation and application of low voltages (Afshari et al. 2020; Kim et al. 2013; Parker 2016). An electrostatic precipitator is used when particles are to be cleaned by deposition such as in the smokestacks (Liu et al. 2017a, b; Zhuang et al. 2000). ESPs can be safely operated in high-temperature environment (Molgaard et al. 2014). The collection efficiency of electrostatic precipitators depends on several parameters like charging efficiency, flow rate of air, collecting mechanisms, electrode geometries and particle properties (Chen et al. 2020; Offermann et al. 1985; Parker 2016; Sung et al. 2020; Zhuang et al. 2000; Wen et al. 2015). Different aerosol properties such as concentration, size, morphology, particle density, resistivity and elemental composition should be considered while selecting ESP for a particular application (Manuzon 2012). Formation of ultrafine particles from ESP was reported due to sparking between corona wire and plate (Offermann et al. 1985). Lin et al. (2012) reported nanoparticle generation when operating temperature was increased above 37 °C and flow rate was maintained below 9 L min^{-1}. Increasing voltage to improve removal of particles below 20 nm was found to increase emission rate of ozone (Lin et al. 2012). Therefore, particle properties, design, geometric parameters and operating conditions of ESP influence its efficiency of PM capture.

Major drawbacks of ESP include back corona, particle re-entrainment and less efficient removal of particles in the submicron range. Pre- or post-filters are usually employed in commercial ESPs due to their inefficiency to remove particles in all size ranges (Altun and Kilic 2019; Parker 2016; Wen et al. 2015). Proper measures should be taken to avoid sparks due to high voltage supply (Afshari et al. 2020; Zhu et al. 2021). Requirements for frequent cleaning, production of charged ions, ozone, oxides and secondary aerosol as by-products are major disadvantages of using ESP in indoor environment (Afshari et al. 2020; Lee et al. 2020; Tan and Zhang 2004). Additionally, initial cost is very high due to usage of high-voltage supplies (Parker 2016). Recent advancements such as ion spray ESP, guidance plated covered ESP and foam-covered ESP have helped in reducing drawbacks of conventional indoor ESP. Ion spray ESP with diffusion charging removes particles at a higher rate without any emission of ozone. Holes in the guidance plate collect particles at 20% higher efficiency than conventional ones for $PM_{0.1}$. Foam-covered ESP reduces re-entrainment of particles, thereby providing collection efficiency of 99% for $PM_{0.3}$, $PM_{0.5}$and$PM_{0.7}$ (Parker 2016; Sung et al. 2020; Kim et al. 2013; Wen et al. 2015). There is a scope for development of air cleaners with high residence time and low gas velocity compared to industrial ones due to lesser area requirement in former which benefits from an economic perspective (Oliveira and Guerra 2021).

3.2 Emerging Indoor Particle Control Technologies

Existing indoor control technologies have a lot of drawbacks such as regular mandatory replacements for mechanical

Table 2 Application of ESP in indoor environment

ESP	Flow rate (m^3 h^{-1})	Efficiency of Particle removal	Application	Conclusion	References
Two stages flat plate with positive voltage	200–434	57–58%	Reduction of particle concentration from cigarette smoke in residences	Sharp increase in total particle concentration during start of operation	Offermann et al. (1985)
Commercial ESP	NA	Total PM—89.4 ± 7.3%	Poultry farm	Promising technology	Manuzon (2012)
ESP	NA	Nursery PM_3—36% Farrow PM_3—50%	Swine farms	Difference in both rooms attributed to difference in ventilation rate	Rosentrater (2003)
Induct ESP with voltage 6200 V	1908	Deposition rate by 2–3 h^{-1} in all size ranges	Townhouse	ESP lost its efficiency after few weeks	Wallace (2004)

NA not available

filters and production of by-products from ionizers and ESPs (Lee et al. 2020). Emerging technologies are concepts that are still on lab scale and, therefore, are not widely commercialized. Different emerging technologies like UV photolysis, botanical filtration and non-thermal plasma are discussed below.

3.2.1 UV Photolysis

Compared to other technologies mentioned in the study, UV photolysis does not capture indoor PM but deactivates bioaerosols, a category of indoor PM by utilizing high-energy ultraviolet (UV) radiation (Han et al. 2023). As this technology is operated at standard room temperature and pressure, there is no need for additional equipment. The deactivation rate of bio aerosols is found to depend on factors like absorptivity of target pollutant at the wavelength used, intensity of UV light source, concentration of pollutants in indoor environment, relative humidity and concentration of oxidant (UV) added. This technology is limited in use and usually used as pre-treatment technology due to possible emission of secondary pollutants like ozone as well as different toxic photoproducts, concerns of accidental exposure to UV rays and high energy consumption (Wang et al. 2009; Zhang et al. 2011).

3.2.2 Botanical Filtration

Botanical filtration is a novel idea for removal of indoor particles by using plants and microorganisms associated with them (Guieysse et al. 2008; Kim et al. 2018). Botanical filtration removes particles by two functional components, plant component and a growth substrate, which is packing media where plants are grown (Irga et al. 2017). Botanical filtration can be divided into potted plants and active walls based on equipment involved, direction of supply of contaminated air and means of water and nutrients supply (Ibrahim et al. 2018; Irga et al. 2017). Active wall is more efficient for indoor air treatment as it provides higher exchange of air thereby providing efficient pollutant removal (Soreanu et al. 2013).

In botanical filtration, particles are removed by physical mechanisms like diffusion, foliar interception, sedimentation, impaction across leaves by eddy currents (adsorption by anions around plant), precipitation or simply by substrate filtration (Irga et al. 2013; Lohr and Pearson-Mims 1996). Even though particles that remain on leaves for longer duration will be adsorbed and degraded by plants, process is dependent on different meteorological and environmental conditions (Gourdji 2018; Lohr and Pearson-Mims 1996). Micro morphological characteristics of leaves, flow rate of air and concentration and characteristics of particles affect the capture (Weerakkody et al. 2018). Leaf trait components like leaf size and shape, surface characteristics, hairs and stomata were found to affect rate of particle removal (Gourdji 2018; Leonard et al. 2016; Lohr and Pearson-Mims 1996; Weerakkody et al. 2018; Xu et al. 2019). Root structure of plant and properties of substrate are also found to affect the particle removal from botanical filters (Gawronska and Bakera 2014; Irga et al. 2017; Pettit et al. 2017).

Botanical filtration is a promising method as removal is achieved by plant material or microorganisms and not by chemicals or heat (Luengas et al. 2015; Parmar and Rao 2008). The method can remediate wide range of pollutants like particles and VOCs at higher concentrations for longer time (Nowak et al. 2014). This method was found to modulate temperature and humidity, thereby providing a better microclimate and refreshing environment (Kraakman et al. 2021; Liu et al. 2017a, b). This technology is best applicable to indoor environment as it can be easily integrated along with HVAC and ventilation systems (Ibrahim et al. 2019). It was also found to be a sustainable alternative to conventional methods of PM removal as it can reduce carbon footprint (Irga et al. 2017). Botanical bio-filter with species *Spathiphyllum wallisii* removed total cigarette-delivered suspended particles by 34.4% (Morgan et al. 2022). Permana et al. (2022) highlighted that distance of pollutants from bio-filter as well as air flow patterns are to be considered for the in situ application of bio-filtration (Permana et al. 2022). Some examples of practical biological systems are Junglefly breathing walls, Lend Lease Headquarters and another at a classroom in China and more details are provided in Table 3 (Liu et al. 2017a, b). This method has provided an efficiency of 53.53% for total suspended particles, 15.99% for PM_{10} and 48% for $PM_{2.5}$ operating at a flow rate of 11.25 L s^{-1} in Junglefly breathing walls (Irga et al. 2017). Indoor bio-filter provided removal efficiency of 54.5% and 65.32% for PM_{10} and $PM_{2.5,}$ respectively, for aromatic incense-derived particles (Irga et al. 2017).

Despite several advantages of botanical filtration, it is associated with certain issues such as inefficiency in material recovery, release of secondary wastes like dust and microorganisms, emission of biogenic VOCs which result in secondary organic aerosol (SOA) formation, high dependency on residence time, moisture and maintenance requirements (Ibrahim et al. 2018; Luengas et al. 2015; Parmar and Rao, 2009). Plant characteristics like removal and tolerance potential have to be considered while selecting suitable plant species for removal of specific pollutants (Guieysse et al. 2008). Another drawback is availability of lesser data on the effectiveness of this system under real-scale applications or full-scale ventilation methods. A study based on pull down results showed that 5 plants per square meter (680 plants per house) are required for efficient pollutant removal which does not seem a practical option. There is no quantitative evaluation available that supports that single potted plants

Table 3 Application of biofiltration in indoor environment

Bio filter	Flow rate (m^3 $\mathbf{hr}^{-1}$)	Efficiency	Application	Conclusion	Reference
Commercial active living wall filter	3.6	TSP—53.35 ± 9.73% PM_{10}—53.51 ± 15.99% $PM_{2.5}$—48.21 ± 14.71%	Commercial	Dependence of efficiency with air flow rate	Irga et al. (2017)
Active green wall	283.53	TSP—72.5%	Residential building	Higher particle removal efficiency of active wall compared to potted system due to combined removal by plants and substrate	Pettit et al. (2019)
Active green wall	320	TSP—42.6%	School classroom		

TSP total suspended particles

can reduce pollutant concentration (Soreanu et al. 2013). The method is still in chamber studies due to lack of knowledge of underlying mechanisms of removal. Therefore, botanical filtration does not seem to be a practical option for reducing pollutants from different indoor environments like residential and commercial buildings (Chen et al. 2005; Kraakman et al. 2021; Soreanu et al. 2013; Wolverton and Wolverton 1993). In future, it could be applicable in both traditional as well as sustainable buildings due to their characteristics like low energy consumption, usage of alternative energy sources and water recycling capabilities (Soreanu et al. 2013). Overall, better understanding of substrate type, operating conditions and mechanism of particle removal are necessary for revealing ultimate potential of method.

3.2.3 Non-thermal Plasma (NTP)

Non-thermal plasma (NTP) is the process of removal of particles by application of high voltage (Bahri et al. 2016; Chen et al. 2005; Luengas et al. 2015; Vandenbroucke et al. 2011). Once applied field exceeds threshold value, ionized gas, called non-thermal plasma, constituting different neutrals, ions, radicals, electrons and UV photons is produced (Brandenburg et al. 2014; Daniels 2002). Different energy transfer mechanism happening inside a plasma reactor are illustrated in Fig. 4.

Process happening inside a plasma reactor can be classified as primary and secondary based on time scale for which it is happening. The time scale of primary process is 10^{-8} s and that of secondary process is 10^{-3}s. Electrons, being lighter in mass, get accelerated easily and, therefore, gain temperature at faster rate. Energetic electrons ionise, excite and dissociate gas molecules producing chemically active species such as atomic oxygen, hydroxyl radical and ozone (Kim 2004). Produced primary and secondary active species oxidise pollutants and consequently converting into desirable products like CO_2 and H_2O (Fan et al. 2009; Hernandez-Diaz et al. 2021; Brandenburg et al. 2011).

Even though NTP can be produced by different methods, pulsed corona is the most suitable for indoor applications due to its high efficiency in removing $PM_{2.5}$, lower energy consumption and lower production of ozone as by-product (Bahri et al. 2016; Daniels 2002; Hernandez-Diaz et al. 2021).

Performance of NTP is dependent on humidity, initial concentration of pollutants, flow rate of air stream, reactants and involved pathways (Bahri et al. 2016; Bo et al. 2007; Hernández-Díaz et al. 2021; Kim 2004). This method can be applied to sustainable and energy efficient buildings as it is cost effective, works in room conditions and is efficient for low concentration levels as compared to thermal plasma (Kim 2004; Zhang et al. 2011). Additionally, there would not be any deposition of particles on surfaces compared to other particle removal methods (Daniels 2002). Even though this method provides high particle efficiency, its applicability in indoor environment is questionable due to poor energy

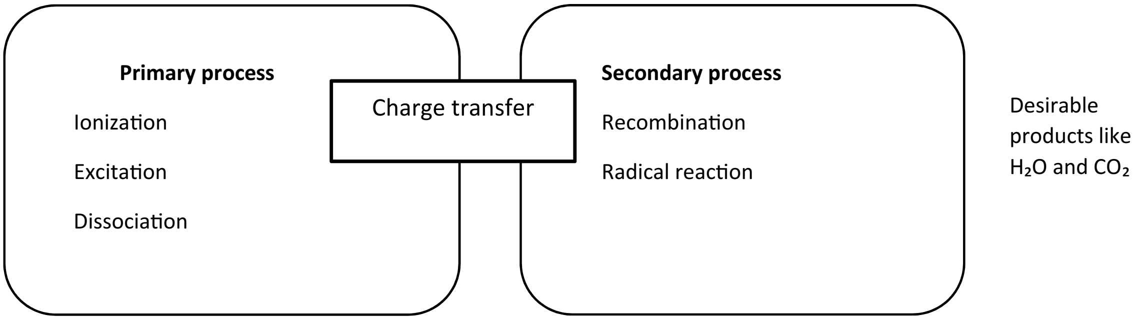


Fig. 4 Mechanism of PM removal by non-thermal plasma (Adapted from Kim 2004)

efficiency and generation of hazardous by-products like O_3, NO_x and CO (Bahri et al. 2016). All these aspects of NTP make the method impractical for indoor environment. This technology can be applied for special purposes where filtration is not applicable or particles are emitted intermittently, wherein NTP can dampen pollutant peaks and decrease the time that particles are suspended in the air before it gets decayed. Despite its drawbacks, there was substantial increase in use of NTP in last couple of years in generators in air processing in HVAC, air processing units like AHU (air handling units) and duct networks of purely commercial grounds. NTPs have been tested only on lab scale and lack scientific support for their performance (Hernández-Díaz et al. 2021).

4 Comparison of Different Technologies

Different performance metrics like single pass removal efficiency (SPRE) and clean air delivery rate (CADR) have been developed so that inter and intra performance comparison between different air cleaners are made possible (Afshari et al. 2020; Chen et al. 2005; Irga et al. 2017; Kim et al. 2018; Liu et al. 2017a, b; Offermann et al. 1985; US EPA 2018; Zhang et al. 2011). Even though the primary function of air cleaners is removal of pollutants, secondary functions like cost, energy consumption and by-product emission would impact long-term usage (Siegel 2015). Performance of particle removal, cost-commercialization, energy consumption and production of harmful by-products are the key factors that determine the selection of an air cleaner for a particular application. As only old papers have experimentally compared different control technologies, results from individual recent studies focussing on a particular technology have been also considered for the comparison purpose.

4.1 Performance in Removal of Particles

4.1.1 Reduction in Concentration of Targeted Pollutant

Although it is preferable to consider all performance metrics, CADR which is the product of SPRE and flow rate of air is found to be the best representative metric in a real conditions. This is because it considers the efficiency of filter, and mixing characteristics of space such as short-circuiting (re-entrainment of cleaned air from outlet back to inlet of air purifier without mixing in space) and also it is independent of the test environment unlike other metrics such as air cleaning factor (ACF) (Shaughnessy and Sextro 2006; Waring et al. 2008). Additionally, it considers flow rate which is an alternative parameter for efficiency for optimised performance but less bounded compared to efficiency (Siegel 2015).

Zhao et al. (2005) compared CADR for particle removal in size range 12.6–514 nm and found that it was highest for HEPA filter (324 $m^3\ h^{-1}$) followed by ESP (284 $m^3\ h^{-1}$). Ionizers were found to be least effective (35 $m^3\ h^{-1}$). Better performance of both HEPA and ESP as compared to ionizers of comparable cost may be due to employment of fans in their design (Zhao et al. 2005). Similar results were obtained by Shaughnessy et al. (1994) for particles from tobacco smoke and Molgaard et al. (2014) for particles in sizes from 0.029 to 2.8 µm in designed emission room (Molgaard et al. 2014; Shaughnessy et al. 1994). For capture of ultrafine particles HEPA, ESP as well as electret filters performed efficiently (60–498 m^3h^{-1}) and ionizers provided mediocre performance of removal (8–18 m^3h^{-1}). Emerging control technologies like photolysis provided nearly zero or no removal for ultrafine particles (Sultan et al. 2011). As most emerging technologies work by oxidation techniques for deactivation of bio-aerosols they must be integrated with some additional capture systems. Compared to pleated panel filter F5, the electrostatic precipitator filter (EPF) was 68% more effective for submicron particles (0.3–1 µm) removal in office building which could be due to increased face velocity attributed to lesser pressure drop in the latter (Zuraimi and Tham 2009). However, efficiency of electret filters is found to decrease with usage in comparison to mechanical filters as charges weaken due to charge decay (Chen et al. 2020). Fewer comparative studies were performed on electret filters and other standalone technologies as they are used mostly in duct devices. Particle deposition was found to be 2 h^{-1} for ESP and 2–3 h^{-1} for fibrous mechanical filter; however, performance of ESP reduced after a week which signifies need for regular maintenance (Wallace 2004). Waring et al. (2008) obtained an efficiency of 60% for HEPA in particle size range less than 200 nm which was unexpected for HEPA as they usually have removal efficiency of 99.97% for most size ranges. Reduced efficiency could be due to bypass of air that travels around filter or in device itself or due to short circuiting attributed to inadequate mixing (Waring et al. 2008). Electret filter has shown a reduced efficiency of removal because of low flow rate due to the gap which was a design feature rather than a manufacturing defect (Offermann et al. 1985). Efficiency of deactivation by photolysis process was reduced due to fouling and with reduced dose of radiation (First et al. 2007). Deposition of siloxane from consumer products was found to reduce efficiency in ESP by formation of amorphous silicon-oxide deposits which made the corona generation non uniform (Davidson and McKinney 1998). These indicate that design, maintenance and operating conditions play an important role in performance of PM removal by air cleaners. Although efficiency of particle removal is usually in range of 0–100%, it can be greater than 100% for electrostatic air cleaners as they even remove particles outside of the device by removal of charged particles to different surfaces (Waring et al. 2008). Likewise, removal efficiency can be negative if particle formation is more pronounced than particle removal either by secondary reaction or by shredding in an air cleaner (Siegel 2015).

4.1.2 Removal of Multiple Pollutants

Emerging standalone technologies like non-thermal plasma and botanical filtration are found to remove multiple indoor pollutants like particles, gas, and VOC simultaneously (Zhang et al. 2011).

4.2 Commercialization and Cost

4.2.1 Commercialization

The air purifier market in India has grown from barely anything to more than 150 crore rupees in the past couple of years due to the rise in market and sales attributed to increased awareness of indoor air quality (Hart et al. 2011). Limited information is available to consumers other than general claims by manufacturers and only fewer studies are accepting or rejecting the claims (Afshari et al. 2020; Grabarczyk 2001; Offermann et al. 1985). Ionization technologies and filtration consist of 67.5% of major shares in consumer markets in developed countries like France, Europe, Japan and USA (Luengas et al. 2015). ESPs are preferred over HEPA filters, due to lesser maintenance charges as only cleaning of collector plates is required rather than changing filters (Chen et al. 2020). A survey suggests that ionizers are used for 1% of homes in USA which can be due to reduced noise nuisance as fans are not operating (Zhao et al. 2005). Emerging technologies like photolysis are not widely commercialized, whereas NTP and botanical filtration are still on lab scale due to the lack of evidence on mechanism of particle removal. They are used only as pre- or post-treatment methods with conventional technologies.

4.2.2 Cost

Cost of an air cleaner includes initial cost, maintenance cost (filter replacement and associated labour charges) and energy cost. Costs incurred for different standalone models of air cleaners working under technologies like filtration, electrostatic precipitation and ionization designed for large room sizes in India were determined and compared based on cost performance index. Maintenance requirements of standalone models were calculated based on specifications by manufacturer even though they can vary widely based on pollution load, operational settings and environmental conditions. Initial cost, air flow rate, CADR and power consumption of air cleaners were reported by manufacturer as product details. Labour cost is taken nil for all tested models as manufactures have specified that replacement or cleaning can be done by customers themselves. Other costs included costs related to repairing works of different parts of air purifiers. Average cost of maintenance plans from reputed companies is assumed to be ₹1400 per month. As CADR labelled by manufacturer on air purifier is at max air flow, energy charges were calculated for 12 h continuous operation in a day throughout year operating at highest fan speed (US EPA 2018). Average energy charges in India (i.e. ₹ 5.36 per kWh) were used for calculation. Cost performance index was calculated for 5 years as done by Sultan et al. (2011) and was used to determine trade-offs between cost and performance (Sultan et al. 2011). Performance index was standardized based on standard room volume which is 62.3 m^3 (AHAM 2006).

As illustrated in Table 4, cost performance index was lowest for HEPA and ESP suggesting that they provide better value for money in terms of performance. Similar results were reported in a study performed by Sultan et al. (2011), wherein HEPA and ESP provided better performance in ultrafine particle removal as compared to ionizers (Sultan et al. 2011). However, the study lacked understanding of influence of each technology as different purifiers working on hybrid technology (integration of different technologies) available markets were only considered.

4.3 Energy Consumption

Energy consumption is an important parameter when considering performance of air cleaners in the long run and is dependent on energy consumed for air cleaning and air movement devices like fans (Siegel 2015; Wen et al. 2015). In the case of portable air cleaners air movement as well as air cleaning happen simultaneously whereas for induct air cleaners, the calculation is complex and indirect due to varaiability in the design and operational characteristics of fan and motor. Moreover, sufficient data on their efficacies are not available (Siegel 2015). The energy consumptions by existing technologies like filtration and ESP are moderate as compared to emerging technologies but are higher than ionizers due to the usage of fans as airflow rate and electrical power drawn correlate with each other (Waring et al. 2008). Energy consumption was found to be medium to higher for emerging technologies like non-thermal plasma and photolysis. Botanical filtration, on the other hand, is found to have low power requirements (Luengas et al. 2015). Molgaard et al. (2014) obtained energy consumption of 0.1–1.5 kWh for HEPA filters, 0.6 kWh for ESP and 0 kWh for ionizer respectively in chosen test room setting (Molgaard et al. 2014). Pressure drop also influences energy consumption, which is higher for mechanical filters than ESP attributed to increased obstructions in airflow due to the mesh structure of mechanical filters as compared to parallel arrangement

Table 4 Costing of conventional indoor air pollution control technologies

Model number	HEPA		Electrostatic Air Purifier	Ioniser
	Honeywell 4-Speed True HEPA Black Air Purifier ENERGY STAR (Covers: 465 Sq.-ft)	Philips 1000 Series AC1215/20 Air Purifier (672 Sq.ft.)	Lasko Electrostatic Air Purifier (549 Sq.ft.)	Namma Shycocan SHCC 915 Portable Room Air Purifier (1000 Sq.ft)
Initial cost of the equipment (Rs.)	16,169.3	9974	14,999	23,490
Filter Replacement Cost (Rs.) for 5 years	10,986.48	18,055	0	0
Labour cost for 5 years (Rs.)	0	0	0	0
Maintenance cost (Rs.)	10,986.48	18,055	0	0
Other costs (Rs.)	84,000	84,000	84,000	84,000
Power (W h^{-1})	38	50	15	40
Power consumed (kWh day^{-1})	0.91	1.2	0.36	0.96
Electricity cost (Rs.$year^{-1}$)	1808.78	2379.97	713.99	1903.98
Cost of Electricity for lifetime of the equipment	9043.9	11,899.85	3569.95	9519.9
Total cost of the equipment (Rs.)	120,199.68	123,928.85	102,568.95	117,009.9
CADR (m^3 h^{-1})	300	270	230	64
Cleaning time (t, in h)	0.21	0.23	0.27	0.97
CADR (m^3 y^{-1})	2,629,743.83	2,366,769.45	2,016,136.94	561,012.02
Cost/CADR (INR. m^{-3})	0.05	0.05	0.05	0.21
Remarks	HEPA needs to be replaced once every year and prefilter four times an year	Air purifier has 3 stage filtration with pre-filter, HEPA and activated carbon filter. Pre-filter is washable and HEPA as well as AC need to be replaced once every year	Consist of series of stainless steel filter and an ozone emission removal filter both with 10 year life span	

of plate electrodes in direction of airflow in ESPs (Han and Ruan 2020; Wen et al. 2015). Moreover, particles start to accumulate over time, causing pressure drop and necessitating the fan to consume more power to maintain the same air flow rate (Wen et al. 2015). Electret filters have lesser pressure drop than fibrous filters due to their lighter packing attributed to differences in mechanism of removal. Unlike ESP, electret filters do not require electric power to continuously charge particles (Verto 1980). As efficiency and pressure drop is not always linear in a non-industrial environment to provide trade-offs between both energy efficiency can be calculated by either key energy performance (kep) or wattage method (Montgomery et al. 2012; Wen et al. 2015). Wen et al. (2015) obtained that tested ESPs were having kep value about 9 times that of fibrous electret filter with MERV-12 (minimum efficiency reporting value) due to reduced pressure drop and high removal efficiency for 0.3 µm in the former. This suggests that filters need to be replaced by ESP in HVAC systems for reduced energy consumption. In summary, energy consumed from an air purifier depends on system power consumption, characteristics of fan and pressure drop in the system.

4.4 Production of by-Products from Particle Indoor Control Technologies

Even though the primary function of an air cleaner is to remove contaminants, different control technologies can act as pollutant sources by producing by-products (Siegel 2015).

4.4.1 Formation of Ozone

Different indoor control technologies were found to produce hazardous ozone either intentionally or as by-product during their operation (Britigan et al. 2006). Ozonizers produce ozone intentionally to decontaminate or deodorise indoor air. ESPs, ionizers, NTP and photolysis produce ozone as by-products (Siegel 2015). Ozone is produced either by photochemical mechanism (as in UV-photolysis) or from corona discharge mechanism (as in ESPs) (Afshari et al. 2020; Guo et al. 2019). Being highly toxic gas and due to its oxidizing power ozone is hazardous to human health and initiates formation of hazardous pollutants like secondary aerosols, oxygenated gases, carbonyls and free radicals (Britigan et al. 2006; Zhao et al. 2005; Guo et al. 2019). Recent innovative designs like triboelectric nanogenerator, and ozone removal unit equipped with Mn-Fe catalyst were found to capture ozone from automobile exhausts as well as from many indoor environments (He and Wang 2018; Xu et al. 2018). Barkjohn et al. (2020) could not find any influence of operation of air cleaner on ozone concentration that could be due to lesser concentration of pollutant in tested space or lower detection limit of O_3 of instrument used (Barkjohn et al. 2020). Different air cleaners are found to emit ozone at a particular rate (termed ozone emission rate (OER). Emitted ozone can undergo loss either due to chemical decomposition to different surfaces or physical removal by ventilation. Thus, it is required to calculate steady state concentration of ozone (Siegel 2015; Guo et al. 2019). Calculated value of steady concentration as per Eq. (1) is compared with 8 h average ozone concentration of 0.1 mg m^{-1} (Guo et al. 2019) as follows:

$$\text{Steady ozone concentration Ozone}_{\text{SS}}\ (\text{ppm}) = \frac{E_{\text{ozone}}\left(\text{mgh}^{-1}\right)T(\text{min})}{118V\left(\text{m}^3\right)}, \tag{1}$$

where E_{ozone} is ozone emission rate; T is the lifetime of ozone taken as 20 min in calculation; V is volume of room and the conversion factor for 25 °C temperature and 1 atm pressure is taken as 118 (Schwarzenegger 2008; Mang et al. 2009). Table 5 illustrates steady-state concentration of ozone from different indoor air cleaners in different volumes of rooms. Even though considered particle removal technologies produced less ozone than ozoniser, they are still a concern for health as some of the tested air cleaners are found to emit 1.7 times more ozone than claimed by manufacturers (Britigan et al. 2006). Even though the ozone concentration was under limit for most of the air cleaners, they still produce a health concern as many studies are done in test environments that don't cover all conditions of the real environment. Induct air cleaners showed higher steady ozone concentration as they work mostly on ionization technologies (Guo et al. 2019). Photolysis showed higher ozone concentration in both the studies signifying the need to restrict it in indoor environments (Britigan et al. 2006; Phllips and Jakobe 2006). When other values remained the same, period of operation, setting and floor area are found to influence steady ozone concentration (Britigan et al. 2006). Even though Niu et al. (2001) tested both ionizers in same volume, operational time and other settings, there was a significant difference in ozone emission rates. This could be due to air flow or difference in designs of wire/pin or plate arrangements (Niu et al. 2001). HEPA filters are found to have zero ozone emission (Waring et al. 2008). Ozone emission rate of ESPs depends on current, polarity, humidity, temperature and characteristics of wire (Boelter and Davidson 1997). Even though multiple studies have listed ozone as a by-product of NTP, many stand-alone experimental results are not available in indoor environments (Diaz et al. 2021). Study done on NTP application in diesel exhaust signifies that negative correlation exists between particle removal and produced ozone (Babaie et al. 2015). However, no correlation was found between rate of particle removal and ozone emission for ESPs and ionizers. ESPs produced ozone at 3.8 mg h^{-1} and ionizers produced at 3.3–4.3 mg h^{-1} respectively thus indicating that the processes of ionisation and ozone formation are independent

Table 5 Emission of ozone from different air cleaners

S. no	Technology	Design characteristics	Ozone emission rate (mg h^{-1})	Volume of room (m^3)	Steady ozone concentration (mg/m^3)	Remarks	References
1	ESP 1	Low setting; measured velocity-0.7 m s^{-1}; flow rate-0.0096 m^3 s^{-1}	0.5	20	0.025	Under limit	Jakober and Phillips (2008)
2	ESP 2	Power consumption—102.2 W and air flow rate— 850 m^3 h^{-1}	3.8	50	0.025	Under limit	Waring et al. (2008)
3	ESP 3	Small spaced rooms; Power less than 1 kW	0.17	5.9	0.010	Under limit	Britigan et al. (2006)
4	Photolysis 1	Designed for specific spaces like car	0.74	1.4	0.176	Not in limit	Britigan et al. (2006)
5	Photolysis 2	Continuous mode; velocity—1.13 m s^{-1}; Flow rate— 0.0092 m^3 s^{-1}	88	20	1.464	Not in limit	Phllips and Jakobe (2006)
6	Ioniser 1	Wire/pin or plate model; Test chamber	2.757	6.4	0.143	Not in limit	Niu et al. (2001)
7	Ioniser 2	Wire/pin or plate model test chamber	0.056	6.4	0.003	Under limit	Niu et al. (2001)
8	Ioniser 3	Pressure difference greater than 1 Pa at 30 m^3 hr^{-1}	4	11	0.121	Not in limit	Zhao et al. (2005)
9	Ioniser 4	Power consumption-8.4 W; Air flow rate-51 m^3 h^{-1}	3.3	50	0.022	Under limit	Waring et al. (2008)
10	Ioniser 5	Power consumption-4.9 W; Air flow rate $<$ 30 m^3 h^{-1}	4.3	50	0.029	Under limit	Waring et al. (2008)
11	Induct ESP cleaner 1	Closed loop chamber	20	6.62	1.005	Not in limit	Guo et al. (2019)
12	Induct ESP 2	Dimension of collection plate-62 cm × 41 cm × 13 cm and an ionizing voltage of 6.2 kV	51.3	340	0.050	Under limit	Poppendieck et al. (2014)
13	HEPA	Air flow rate—640 m^3 h^{-1}	0	11	0	Limit	Zhao et al. (2005)
14	Ozoniser	Used as a reference	132	27.1	1.621	Reference	

of each other (Chen et al. 2005; Zhao et al. 2005). Properly designed models of photolysis, ionizer and ESP based air purifiers with a reduced period of operation and adequate cleaning, as well as periodic maintenance, are found to decrease ozone emission rates (Guo et al. 2008; Niu et al. 2001). Concentration of steady state ozone in a room where such ionization based air cleaners are in operation can also be reduced either by providing ventilation or by reducing usage of ozone reactive compounds (Britigan et al. 2006).

4.4.2 Emission of Other by-Products

Along with ozone, several other by-products are produced from different particle control technologies. Table 6 illustrates some of the by-products produced by each indoor air cleaning technology. Emerging control technologies like photolysis, NTP and botanical filtration produce multiple by-products simultaneously which questions their applicability in a real indoor environment (Zhang et al. 2011). Clogging of filters can cause formation of bio-aerosols and emission of biogenic volatile organic compounds from botanical filtration can aid generation of PM in ultrafine and finer size ranges (from 4.61 to 157 nm) in presence of ozone (Sidheswaran et al. 2013; Waring et al. 2008). Similarly, ESP was found to act as an additional particle source when produced ozone reacts with unsaturated VOCs such as limonene (Alshawa et al. 2007). Offermann et al. (1985) observed an increase in particle concentration in size range of 0.01–0.05 µm from ESP which is attributed to electric arcing or sparking between corona wire and plate (Offermann et al. 1985; Shaughnessy et al. 1994). In the literature, few studies have studied the generation of VOCs and NOx from

Table 6 By-products produced from different technologies of indoor air cleaning

Technology	Byproduct	References
Fiberglass media filters	Bioaerosols, VOCs like formaldehyde, sensory and odorous pollutants	Sidheswaran et al. (2013)
ESP	Ozone, ultrafine particles	Zhao et al. (2005)
Ionizer	O_3, ultrafine particles	Waring et al. (2008)
Photolysis	O_3, VOCs like formaldehyde	Zhao et al. (2013)
Nonthermal plasma	O_3, NO_x, CO, different VOCs like acetaldehyde and formaldehyde	Chen et al. (2005)
Biofiltration	Dust, microorganisms, humidity, VOCs	Wang et al. (2004)

different indoor PM capture technologies. Zeng et al. (2022) have studied by-product emission from a commercial in duct bipolar ionisation devices. Oxygenated VOCs like acetone, toluene and ethanol were emitted from these technologies due to different chemical reactions happening between ionisation and PM removal resulting in production of uncharged neutral molecules which are difficult to be removed (Zeng et al. 2022). Additionally, different studies have proved the fact that increased emission of NOx as by-product could hinder the emission of O_3 in ionisation-based technologies as pathways involved and factors affecting formation such as residence time, applied voltage and polarity for the formation of both gases are different (Yagi and Tanaka 1979). Proper design and maintenance of air cleaners determine whether they act as source of pollutants or sink of particles (Siegel 2015).

5 Summary and Recommendations for Future Research

Indoor air quality is one of the major concerns in the modern environment as people spend 80–90% time inside. Due to highly sealed modern buildings (that are intended to provide efficient thermal comforts), multiple pollutants like particulate matter (PM), gases and VOC that are produced indoors tend to coexist in indoor environment. Among all the indoor air pollutants, PM is seen to have major health impacts. Even though different existing indoor particle control technologies are available in the market and emerging control technologies are available on lab scale, selection of technology for a particular application was rarely documented. With the help of further calculations, the study critically analysed different technologies and compared them based on particle removal, cost-commercialization, energy consumption and by-product formation. Study also provided an overview of previous studies in respect of mechanism, influencing factors, recent advancements, and different applications in a real indoor environment. This techno-commercial comparison will benefit customers in the selection of cleaning technology suited for a particular requirement. For example, if the requirement of consumer is to reduce a targeted pollutant, highly efficient particle removal technologies such as HEPA filters and ESP can be safely adapted. Emerging technologies like botanical filtration and NTP are found to remove multiple pollutants like particles, gases and VOCs simultaneously. However, they should be used in pre- and post-phases as no sufficient data is available for their practical application. By comparing cost performance index, ESP and HEPA provided best value for money in terms of performance compared to other conventional technologies. This study signifies the need for proper design, maintenance and operational conditions so that air cleaner should not act as a source than sink of the pollutants. Additionally, none of the technologies can remove all pollutants and some even emit by-products; therefore, air purifiers cannot replace source control or ventilation but can supplement them. Considering the applications, high efficiency particulate air (HEPA) filters and electrostatic precipitators (ESPs) can be preferred for highly efficient particle removal from indoor environments of the places like hospitals and dental clinics. Likewise, when multiple pollutants are present like smoking rooms, space heaters or kitchens one can go for emerging technologies. ESP is an economical and low-maintenance option in sustainable and energy efficient applications like public buildings and can be incorporated with heating ventilation and air conditioning (HVAC) for domestic applications such as homes and offices as well as commercial applications due to their high volumetric airflow rate. ESPs are also suitable for high-temperature environments and in air conditioning devices where a high airflow rate per volume is required. However, they are not efficient in removing particles of all sizes, therefore they are required to be integrated with pre or post filters. Similarly, as most emerging PM control technologies work on oxidation technique, they need to be integrated with separate PM capture systems. As ionizers remove particles by emitting different ions, they work better in confined places with a high surface to volume ratios such as automobile cabins, flights, bathrooms, cellular offices, animal sheds, and small residential areas. As ionizers, ESPs and UV photolysis cleaners are found to produce toxic by-products, they should be avoided in case of applications related to sensitive populations like asthmatics, elderly, and children.

In the future, researchers can look into development of an index that signifies overall performance of air cleaners in terms of particle removal, cost-commercialization, energy consumption and by-product emission. This is a novel idea as trade-off has been previously done only between efficiency and cost as well as between efficiency and pressure drop. There is paucity of experimental studies on indoor control technologies. Further research in this direction may provide a qualitative clarification for negative reviews received by different available models of indoor air purifiers on their less efficient performances as compared to the promised claims by manufactures. By-product formation from air cleaners is poorly studied and is very essential as they can be even more toxic than targeted pollutants. Therefore, it is required to have a standard rating system that makes consumers aware of the extent of emission of harmful by-products from air cleaners. The mechanism of ultrafine particle formation from ESPs is still not completely clear and consideration of that may explain operating conditions to be maintained for the reduction of ultrafine particle emission. Additionally, studies can be done on integration of different technologies that could remove or remediate ozone with ozone producing air purifiers for reduced exposure. Further research on mechanism of removal, conditions causing the formation of by-products and innovative methods to reduce energy consumption could help in scaling up emerging technologies to a commercial scal.

Acknowledgements This work has been supported by the Central Pollution Control Board has supported this work as a part of the study "Pilot Study for Assessment of Reducing Particulate Air Pollution in Urban Areas by Using Air Cleaning System (sometimes called Smog Tower)" (Grant no: RD/0120-CPCB000-001). Partial support from the study "Application of Nanoparticles in ESP for Inactivation of Microorganisms and Degradation of VOCs for Air Purification" (Grant no: RD/0119-DST0000-048) is acknowledged.

Data availability All data used in the study has been taken from various published literature.

Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Afshari A, Ekberg L, Forejt L, Mo J, Rahimi S, Siegel J, Chen W, Wargocki P, Zurami S, Zhang J (2020) Electrostatic precipitators as an indoor air cleaner—a literature review. Sustainability 12(21):8774. https://doi.org/10.3390/su12218774

Agarwal N, Meena CS, Raj BP, Saini L, Kumar A, Gopalakrishnan N, Kumar A, Balam NB, Alam T, Kapoor NR, Aggarwal V (2021) Indoor air quality improvement in COVID-19 pandemic: review. Sustain Cities Soc 70:102942. https://doi.org/10.1016/j.scs.2021.102942

AHAM (2006) Method for measuring the performance of portable household electric room air cleaners (pp 1–4).

Alshawa A, Russell AR, Nizkorodov SA (2007) Kinetic analysis of competition between aerosol particle removal and generation by ionization air purifiers. Environ Sci Technol 41(7):2498–2504. https://doi.org/10.1021/es061760y

Altun AF, Kilic M (2019) Utilization of electrostatic precipitators for healthy indoor environments. E3S Web Conf 111:02020. https://doi.org/10.1051/e3sconf/201911102020

ANSI/ASHRAE Standard 62.1-2019 (2019) Ventilation for acceptable indoor air quality

Aydogan A, Montoya LD (2011) Formaldehyde removal by common indoor plant species and various growing media. Atmos Environ 45(16):2675–2682. https://doi.org/10.1016/j.atmosenv.2011.02.062

Babaie M, Davari P, Talebizadeh P, Zare F, Rahimzadeh H, Ristovski Z, Brown R (2015) Performance evaluation of non-thermal plasma on particulate matter, ozone and CO2 correlation for diesel exhaust emission reduction. Chem Eng J 276:240–248. https://doi.org/10.1016/j.cej.2015.04.086

Bahri M, Haghighat F, Rohani S, Kazemian H (2016) Impact of design parameters on the performance of non-thermal plasma air purification system. Chem Eng J 302:204–212. https://doi.org/10.1016/j.cej.2016.05.035

Bandehali S, Miri T, Onyeaka H, Kumar P (2021) Current state of indoor air phytoremediation using potted plants and green walls. Atmosphere 12(4):473. https://doi.org/10.3390/atmos12040473

Barkjohn KK, Norris C, Cui X, Fang L, He L, Schauer JJ, Zhang Y, Black M, Zhang J, Bergin MH (2020) Children's microenvironmental exposure to PM2.5 and ozone and the impact of indoor air filtration. J Expos Sci Environ Epidemiol 30(6):971–980. https://doi.org/10.1038/s41370-020-00266-5

Beckman IP, Berry G, Cho H, Riveros G (2022) Alternative high-performance fibers for nonwoven HEPA filter media. Aerosol Sci Eng. https://doi.org/10.1007/s41810-022-00161-6

Bennett A (2009) Strategies and technologies: controlling indoor air quality. Filtr Sep 46(4):14–17. https://doi.org/10.1016/s0015-1882(09)70155-7

Bian Y, Wang S, Zhang L, Chen C (2019) Influence of fiber diameter, filter thickness, and packing density on PM2.5 removal efficiency of electrospun nanofiber air filters for indoor applications. Build Environ 1:106628. https://doi.org/10.1016/j.buildenv.2019.106628

Bo Zh, Yan JH, Li XD, Chi Y, Cen KF, Cheron BG (2007) Effects of oxygen and water vapor on volatile organic compounds decomposition using gliding arc gas discharge. Plasma Chem Plasma Process 27(5):546–558. https://doi.org/10.1007/s11090-007-9081-3

Boedicker EK, Emerson EW, McMeeking GR, Patel S, Vance ME, Farmer DK (2021) Fates and spatial variations of accumulation mode particles in a multi-zone indoor environment during the HOMEChem campaign. Environ Sci. https://doi.org/10.1039/d1em00087j

Boelter KJ, Davidson JH (1997) Ozone generation by indoor, electrostatic air cleaners. Aerosol Sci Technol 27(6):689–708. https://doi.org/10.1080/02786829708965505

Bohanon H, Zaatari M (2020) Effect of ventilation and filtration on viral infection in residences. ASHRAE J 62(12):38–45

Brager G, Alspach P, Nall D (2011) Natural vs. mechanical ventilation and cooling. UC Berkeley HVAC Systems

Brandenburg R, Barankova H, Bardos L, Chmielewski A, Dors M, Grosch H, Stamate A (2011) Plasma-based depollution of exhausts: principles, state of the art and future prospects. InTech

Brandenburg R, Kovačević VV, Schmidt M, Basner R, Kettlitz M, Sretenović GB, Obradović BM, Kuraica MM, Weltmann K-D (2014) Plasma-based pollutant degradation in gas streams: status, examples and outlook. Contrib Plasma Phys 54(2):202–214. https://doi.org/10.1002/ctpp.201310059

Britigan N, Alshawa A, Nizkorodov SA (2006) Quantification of ozone levels in indoor environments generated by ionization and ozonolysis air purifiers. J Air Waste Manag Assoc 56(5):601–610. https://doi.org/10.1080/10473289.2006.10464467

Carminati M, Sinha GR, Mohdiwale S, Ullo SL (2021) Miniaturized pervasive sensors for indoor health monitoring in smart cities. Smart Cities 4(1):146–155. https://doi.org/10.3390/smartcities4010008

Cheek E, Guercio V, Shrubsole C, Dimitroulopoulou S (2020) Portable air purification: review of impacts on indoor air quality and health. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2020.142585

Chen C, Ji W, Zhao B (2019) Size-dependent efficiencies of ultrafine particle removal of various filter media. Build Environ 160:106171. https://doi.org/10.1016/j.buildenv.2019.106171

Chen L, Evelyne G, Michel O, Yves G (2020) Electrostatic precipitator for fine and ultrafine particle removal from indoor air environments. Sep Purif Technol 247:116964. https://doi.org/10.1016/j.seppur.2020.116964

Chen W, Jensen Z & Z B Z (2005) Performance of air cleaners for removing multiple volatile organic compounds in indoor air (pp 1101–1114). ASHRAE Transactions

Colbeck I, Lazaridis M (2009) Aerosols and environmental pollution. Naturwissenschaften 97(2):117–131. https://doi.org/10.1007/s00114-009-0594-x

Daniels SL (2002) Air ionization of indoor environments for control of volatile and particulate contaminants with nonthermal plasmas generated by dielectric-barrier discharge. IEEE Trans Plasma Sci 30(4):1471–1481. https://doi.org/10.1109/tps.2002.804211

Davidson JH, McKinney PJ (1998) Chemical vapor deposition in the corona discharge of electrostatic air cleaners. Aerosol Sci Technol 29(2):102–110. https://doi.org/10.1080/02786829808965555

Demanega I, Mujan I, Singer BC, Anđelković AS, Babich F, Licina D (2021) Performance assessment of low-cost environmental monitors and single sensors under variable indoor air quality and thermal conditions. Build Environ 187:107415. https://doi.org/10.1016/j.buildenv.2020.107415

Fan X, Zhu TL, Wang MY, Li XM (2009) Removal of low-concentration BTX in air using a combined plasma catalysis system. Chemosphere 75(10):1301–1306. https://doi.org/10.1016/j.chemosphere.2009.03.029

First MW, Banahan KF, Dumyahn TS (2007) Performance of ultraviolet germicidal irradiation lamps and luminaires in long-term service. Leukos 3(3):181–188. https://doi.org/10.1582/leukos.2007.03.03.005

Gawrońska H, Bakera B (2014) Phytoremediation of particulate matter from indoor air by *Chlorophytum comosum* L. plants. Air Qual Atmos Health 8(3):265–272. https://doi.org/10.1007/s11869-014-0285-4

Godish T, Spengler JD (1996) Relationships between ventilation and indoor air quality: a review. Indoor Air 6(2):135–145. https://doi.org/10.1111/j.1600-0668.1996.00010.x

Gonzalez-Martin J, Kraakman NJR, Perez C, Lebrero R, Munoz R (2021) A state–of–the-art review on indoor air pollution and strategies for indoor air pollution control. Chemosphere 262:128376. https://doi.org/10.1016/j.chemosphere.2020.128376

Gourdji S (2018) Review of plants to mitigate particulate matter, ozone as well as nitrogen dioxide air pollutants and applicable recommendations for green roofs in Montreal, Quebec. Environ Pollut 241:378–387. https://doi.org/10.1016/j.envpol.2018.05.053

Grabarczyk Z (2001) Effectiveness of indoor air cleaning with corona ionizers. J Electrostat 51–52:278–283. https://doi.org/10.1016/S0304-3886(01)00058-4

Grinshpun SA, Mainelis G, Trunov M, Adhikari A, Reponen T, Willeke K (2005) Evaluation of ionic air purifiers for reducing aerosol exposure in confined indoor spaces. Indoor Air 15(4):235–245. https://doi.org/10.1111/j.1600-0668.2005.00364.x

Guieysse B, Hort C, Platel V, Munoz R, Ondarts M, Revah S (2008) Biological treatment of indoor air for voc removal: potential and challenges. Biotechnol Adv 26(5):398–410. https://doi.org/10.1016/j.biotechadv.2008.03.005

Guo H, Morawska L, He C, Gilbert D (2008) Impact of ventilation scenario on air exchange rates and on indoor particle number concentrations in an air-conditioned classroom. Atmos Environ 42(4):757–768. https://doi.org/10.1016/j.atmosenv.2007.09.070

Guo C, Gao Z, Shen J (2019) Emission rates of indoor ozone emission devices: a literature review. Build Environ 158:302–318. https://doi.org/10.1016/j.buildenv.2019.05.024

Han K-T, Ruan L-W (2020) Effects of indoor plants on air quality: a systematic review. Environ Sci Pollut Res 27(14):16019–16051. https://doi.org/10.1007/s11356-020-08174-9

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

Han S, Li X, Tan Y, Huang Y, Wu Z, Wang M, Ho W, Lee S (2023) In-situ self-sacrificed fabrication of insulator-based $SrTiO_3/SrCO_3$ heterojunction interface for gaseous HCHO and NO photocatalytic degradation. Appl Surf Sci 612:155806. https://doi.org/10.1016/j.apsusc.2022.155806

Hart JF, Ward TJ, Spear TM, Rossi RJ, Holland NN, Loushin BG (2011) Evaluating the effectiveness of a commercial portable air purifier in homes with wood burning stoves: a preliminary study. J Environ Public Health 2011:1–7. https://doi.org/10.1155/2011/324809

Hao G, Zhengwei L, Zhuangbo F, Bencheng L, Tao Y (2022) Numerical simulation of the characteristics of oil mist particles deposition in electrostatic precipitator. Process Safety Environ Prot 164:335–344. https://www.sciencedirect.com/science/article/pii/S0957582022005444. https://doi.org/10.1016/j.psep.2022.06.022

He C, Wang ZL (2018) Triboelectric nanogenerator as a new technology for effective PM2.5 removing with zero ozone emission. Progress Nat Sci 28(2):99–112. https://doi.org/10.1016/j.pnsc.2018.01.017

Hernandez-Diaz D, Martos-Ferreira D, Hernandez-Abad V, Villar-Ribera R, Tarres Q, Rojas-Sola JI (2021) Indoor PM2.5 removal efficiency of two different non-thermal plasma systems. J Environ Manage 278:111515. https://doi.org/10.1016/j.jenvman.2020.111515

Hinds WC (1998) Properties, behavior measurement of air borne particles

Huang Y, Ho S, Lu Y, Niu R, Xu L, Cao J, Lee S (2016) Removal of indoor volatile organic compounds via photocatalytic oxidation: a short review and prospect. Molecules 21(1):56. https://doi.org/10.3390/molecules21010056

Hung Y-T, Eldridge J, Taricska JR, Li KH (2007) Cooling of thermal discharges. Handbook Environ Eng. https://doi.org/10.1007/978-1-59259-779-6_10

Ibrahim IZ, Chong WT, Yusoff S, Wang C-T, Xiang X, Muzammil WK (2019) Evaluation of common indoor air pollutant reduction by a botanical indoor air biofilter system. Indoor Built Environ 30(1):7–21. https://doi.org/10.1177/1420326x19882080

Ibrahim Z, Chong W-T & Yusoff S (2018) The design of the botanical indoor air biofilter system for the atmospheric particle removal.

The 4th International Conference on Engineering, Applied Sciences and Technology, 192. https://doi.org/10.1051/matecconf/201819202035

Irga PJ, Torpy FR, Burchett MD (2013) Can hydroculture be used to enhance the performance of indoor plants for the removal of air pollutants? Atmos Environ 77:267–271. https://doi.org/10.1016/j.atmosenv.2013.04.078

Irga PJ, Paull NJ, Abdo P, Torpy FR (2017) An assessment of the atmospheric particle removal efficiency of an in-room botanical biofilter system. Build Environ 115:281–290. https://doi.org/10.1016/j.buildenv.2017.01.035

Irga PJ, Pettit TJ, Torpy FR (2018) The phytoremediation of indoor air pollution: a review on the technology development from the potted plant through to functional green wall biofilters. Rev Environ Sci Bio/Technol 17(2):395–415. https://doi.org/10.1007/s11157-018-9465-2

Jeong S-G, Wallace L, Rim D (2021) Contributions of coagulation, deposition, and ventilation to the removal of airborne nanoparticles in indoor environments. Environ Sci Technol 55(14):9730–9739. https://doi.org/10.1021/acs.est.0c08739

Ji W, Chen C, Zhao B (2020) A comparative study of the effects of ventilation-purification strategies on air quality and energy consumption in Beijing, China. Build Simul 14(3):813–825. https://doi.org/10.1007/s12273-020-0694-2

Kang K, Kim H, Kim DD, Lee YG, Kim T (2019) Characteristics of cooking-generated PM10 and PM2.5 in residential buildings with different cooking and ventilation types. Sci Total Environ 668:56–66. https://doi.org/10.1016/j.scitotenv.2019.02.316

Khandare P, Joshi M, Nakhwa A, Khan A, Mariam M, Sapra BK (2019) Unexplored aspects of unipolar ionizer characteristics in context of indoor air cleaning. Environ Sci Pollut Res 26(18):18191–18199. https://doi.org/10.1007/s11356-019-05118-w

Kim H-H (2004) Nonthermal plasma processing for air-pollution control: a historical review, current issues, and future prospects. Plasma Processes Polym 1(2):91–110. https://doi.org/10.1002/ppap.200400028

Kim H-J, Han B, Kim Y-J, Oda T, Won H (2013) Submicrometer particle removal indoors by a novel electrostatic precipitator with high clean air delivery rate, low ozone emissions, and carbon fiber ionizer. Indoor Air 23(5):369–378. https://doi.org/10.1111/ina.12037

Kim KJ, Khalekuzzaman M, Jung Nam S, Hyeon Ju K, Shagol C, Kim H, Joo Kim H (2018) Phytoremediation of volatile organic compounds by indoor plants: a review. Hortic Environ Biotechnol 59:143–157

Komaladewi AAIAS, Khoiruddin K, Surata IW, Subagia IDGA, Wenten IG (2018) Recent advances in antimicrobial air filter. E3S Web Conf 67:03016. https://doi.org/10.1051/e3sconf/20186703016

Kraakman NJR, González-Martín J, Pérez C, Lebrero R, Muñoz R (2021) Recent advances in biological systems for improving indoor air quality. Rev Environ Sci Bio/Technol 20(2):363–387. https://doi.org/10.1007/s11157-021-09569-x

Lai D, Qi Y, Liu J, Dai X, Zhao L, Wei S (2018) Ventilation behavior in residential buildings with mechanical ventilation systems across different climate zones in China. Build Environ 143:679–690. https://doi.org/10.1016/j.buildenv.2018.08.006

Lee ES, Fung C-CD, Zhu Y (2015) Evaluation of a high efficiency cabin air (heca) filtration system for reducing particulate pollutants inside school buses. Environ Sci Technol 49(6):3358–3365. https://doi.org/10.1021/es505419m

Lee BXY, Hadibarata T, Yuniarto A (2020) Phytoremediation mechanisms in air pollution control: a review. Water Air Soil Pollut 231(8):1. https://doi.org/10.1007/s11270-020-04813-6

Leonard RJ, McArthur C, Hochuli DF (2016) Particulate matter deposition on roadside plants and the importance of leaf trait combinations. Urban Forest Urban Green 20:249–253. https://doi.org/10.1016/j.ufug.2016.09.008

Levin H (1992) Controlling sources of indoor air pollution. Eurocourses. https://doi.org/10.1007/978-94-015-8088-5_22

Li Y-W, Ma W-L (2021) Photocatalytic oxidation technology for indoor air pollutants elimination: a review. Chemosphere 280:130667. https://doi.org/10.1016/j.chemosphere.2021.130667

Lin C-W, Huang S-H, Kuo Y-M, Chang K-N, Wu C-S, Chen C-C (2012) From electrostatic precipitation to nanoparticle generation. J Aerosol Sci 51:57–65. https://doi.org/10.1016/j.jaerosci.2012.03.005

Liu G, Xiao M, Zhang X, Gal C, Chen X, Liu L, Pan S, Wu J, Tang L, Clements-Croome D (2017a) A review of air filtration technologies for sustainable and healthy building ventilation. Sustain Cities Soc 32:375–396. https://doi.org/10.1016/j.scs.2017.04.011

Liu Y, Wang Y, Liu Z, Wang Q (2017b) Oxidation removal of nitric oxide from flue gas using UV photolysis of aqueous hypochlorite. Environ Sci Technol 51(20):11950–11959. https://doi.org/10.1021/acs.est.7b03628

Liu S, Wu R, Zhu Y, Wang T, Fang J, Xie Y, Yuan N, Xu H, Song X, Huang W (2022) The effect of using personal-level indoor air cleaners and respirators on biomarkers of cardiorespiratory health: a systematic review. Environ Int 158:106981. https://doi.org/10.1016/j.envint.2021.106981

Lohr VI, Pearson-mims CH (1996) Particulate matter accumulation on horizontal surfaces in interiors: influence of foliage plants. Atmos Environ 30(14):2565–2568. https://doi.org/10.1016/1352-2310(95)00465-3

Lu Y, Hiroshi Y, Rie T, Genta K (2011) Effect of ventilation strategies for removing indoor house dust: An experimental and simulation study. HVAC&R Res 17(4):410–418. https://doi.org/10.1080/10789669.2011.585420

Luengas A, Barona A, Hort C, Gallastegui G, Platel V, Elias A (2015) A review of indoor air treatment technologies. Rev Environ Sci Bio/Technol 14(3):499–522. https://doi.org/10.1007/s11157-015-9363-9

Macintosh DL, Myatt TA, Ludwig JF, Baker BJ, Suh HH, Spengler JD (2008) Whole house particle removal and clean air delivery rates for in-duct and portable ventilation systems. J Air Waste Manag Assoc (1995) 58(11):1474–1482. https://doi.org/10.3155/1047-3289.58.11.1474

MacIntosh DL, Minegishi T, Kaufman M, Baker BJ, Allen JG, Levy JI, Myatt TA (2009) The benefits of whole-house in-duct air cleaning in reducing exposures to fine particulate matter of outdoor origin: a modeling analysis. J Eposure Sci Environ Epidemiol 20(2):213–224. https://doi.org/10.1038/jes.2009.16

Mang SA, Walser ML, Nizkorodov SA, Laux JM (2009) Measurement of ozone emission and particle removal rates from portable air purifiers. J Chem Educ 86(2):219. https://doi.org/10.1021/ed086p219

Manisalidis I, Stavropoulou E, Stavropoulos A, Bezirtzoglou E (2020) Environmental and health impacts of air pollution: a review. Front Public Health. https://doi.org/10.3389/fpubh.2020.00014

Mannan M, Al-Ghamdi SG (2021) Indoor air quality in buildings: a comprehensive review on the factors influencing air pollution in residential and commercial structure. Int J Environ Res Public Health 18(6):3276. https://doi.org/10.3390/ijerph18063276

Manuzon RB (2012) Electrostatic precipitation technologies for the mitigation of particulate matter emissions from poultry facilities. The Ohio State University, Doctoral dissertion

McNamara ML, Thornburg J, Semmens EO, Ward TJ, Noonan CW (2017) Reducing indoor air pollutants with air filtration units in wood stove homes. Sci Total Environ 592:488–494. https://doi.org/10.1016/j.scitotenv.2017.03.111

Molgaard B, Koivisto AJ, Hussein T, Hämeri K (2014) A new clean air delivery rate test applied to five portable indoor air cleaners.

Aerosol Sci Technol 48(4):409–417. https://doi.org/10.1080/02786826.2014.883063

Montgomery JF, Green SI, Rogak SN, Bartlett K (2012) Predicting the energy use and operation cost of HVAC air filters. Energy and Buildings 47:643–650. https://doi.org/10.1016/j.enbuild.2012.01.001

Morgan AL, Torpy FR, Irga PJ, Fleck R, Gill RL, Pettit T (2022) The botanical biofiltration of volatile organic compounds and particulate matter derived from cigarette smoke. Chemosphere 295:133942. https://doi.org/10.1016/j.chemosphere.2022.133942

Morishita M, Adar SD, D'Souza J, Ziemba RA, Bard RL, Spino C, Brook RD (2018) Effect of portable air filtration systems on personal exposure to fine particulate matter and blood pressure among residents in a low-income senior facility. JAMA Intern Med 178(10):1350. https://doi.org/10.1001/jamainternmed.2018.3308

Mukhopadhyay K, Ramasamy R, Mukhopadhyay B, Ghosh S, Sambandam S, Balakrishnan K (2014) Use of ventilation-index in the development of exposure model for indoor air pollution—a review. Open J Air Pollut 03(02):33–41. https://doi.org/10.4236/ojap.2014.32004

Nagy R, Meciarova L, VilCekova S, Kridlova Burdova E, Kosicanova D (2019) Investigation of a ventilation system for energy efficiency and indoor environmental quality in a renovated historical building: a case study. Int J Environ Res Public Health. https://doi.org/10.3390/ijerph16214133

Niu JL, Tung TCW, Burnett J (2001) Quantification of dust removal and ozone emission of ionizer air-cleaners by chamber testing. J Electrostat 51–52:20–24. https://doi.org/10.1016/s0304-3886(01)00118-8

Nowak DJ, Hirabayashi S, Bodine A, Greenfield E (2014) Tree and forest effects on air quality and human health in the United States. Environ Pollut 193:119–129. https://doi.org/10.1016/j.envpol.2014.05.028

Offermann FJ, Sextro RG, Fisk WJ, Grimsrud DT, Nazaroff WW, Nero AV, Revzan KL, Yater J (1985) Control of respirable particles in indoor air with portable air cleaners. Atmos Environ (1967) 19(11):1761–1771. https://doi.org/10.1016/0004-6981(85)90003-4

Oliveira D, Guerra VG (2021) Process Safety and Environmental Protection. Process Saf Environ Prot 153:422–438

Park JS, Jee N-Y, Jeong J-W (2014) Effects of types of ventilation system on indoor particle concentrations in residential buildings. Indoor Air 24(6):629–638. https://doi.org/10.1111/ina.12117

Parker K (2016) Electrostatic precipitation. Part Technol Appl 7(5):281–300. https://doi.org/10.1201/noe0849398438.ch20

Parmar GR, Rao NN (2008) Emerging control technologies for volatile organic compounds. Crit Rev Environ Sci Technol 39(1):41–78. https://doi.org/10.1080/10643380701413658

Pei J, Dong C, Liu J (2019) Operating behavior and corresponding performance of portable air cleaners in residential buildings, China. Build Environ 147:473–481. https://doi.org/10.1016/j.buildenv.2018.08.009

Permana BH, Thiravetyan P, Treesubsuntorn C (2022) Effect of airflow pattern and distance on removal of particulate matters and volatile organic compounds from cigarette smoke using Sansevieria trifasciata botanical biofilter. Chemosphere 295:133919. https://doi.org/10.1016/j.chemosphere.2022.133919

Pettit T, Irga PJ, Abdo P, Torpy FR (2017) Do the plants in functional green walls contribute to their ability to filter particulate matter? Build Environ 125:299–307. https://doi.org/10.1016/j.buildenv.2017.09.004

Phllips T and Jakobe C (2006) Evaluation of ozone emissions that intentionally generate ozone

Poppendieck DG, Rim D, Persily AK (2014) Ultrafine particle removal and ozone generation by in-duct electrostatic precipitators. Environ Sci Technol 48(3):2067–2074. https://doi.org/10.1021/es404884p

Pushpawela B, Jayaratne R, Nguy A, Morawska L (2017) Efficiency of ionizers in removing airborne particles in indoor environments. J Electrostat 90:79–84. https://doi.org/10.1016/j.elstat.2017.10.002

Ren Y-F, Huang Q, Marzouk T, Richard R, Pembroke K, Martone P, Venner T, Malmstrom H, Eliav E (2021) Effects of mechanical ventilation and portable air cleaner on aerosol removal from dental treatment rooms. J Dentistry 105:103576. https://doi.org/10.1016/j.jdent.2020.103576

Rosentrater KA (2003) Performance of an electrostatic dust collection system in swine facilities. Agric Eng Int CGIR J 3(3):1–10

Ruan T, Rim D (2019) Indoor air pollution in office buildings in megacities: effects of filtration efficiency and outdoor air ventilation rates. Sustain Cities Soc 49:101609. https://doi.org/10.1016/j.scs.2019.101609

Russell M, Sherman M, Rudd A (2007) Review of residential ventilation technologies. HVAC&R Res 13(2):325–348. https://doi.org/10.1080/10789669.2007.10390957

Saini J, Dutta M, Marques G (2020a) A comprehensive review on indoor air quality monitoring systems for enhanced public health. Sustain Environ Res. https://doi.org/10.1186/s42834-020-0047-y

Saini J, Dutta M, Marques G (2020b) Indoor air quality monitoring systems based on internet of things: a systematic review. Int J Environ Res Public Health 17(14):4942. https://doi.org/10.3390/ijerph17144942

Saini J, Dutta M, Marques G (2021) Sensors for indoor air quality monitoring and assessment through Internet of Things: a systematic review. Environ Monitor Assess. https://doi.org/10.1007/s10661-020-08781-6

Schwarzenegger A (2008) Evaluation of ozone emissions from portable indoor air cleaners: electrostatic precipitators and ionizers Staff Technical Report Air Resources Board. Retrieved from https://www.arb.ca.gov/research/indoor/esp_report.pdf

Shaughnessy RJ, Sextro RG (2006) What is an effective portable air cleaning device? A review. J Occup Environ Hyg 3(4):169–181. https://doi.org/10.1080/15459620600580129

Shaughnessy RJ, Levetin E, Blocker J, Sublette KL (1994) Effectiveness of portable indoor air cleaners: sensory testing results. Indoor Air 4(3):179–188. https://doi.org/10.1111/j.1600-0668.1994.t01-1-00006.x

Shiue A, Hu S-C, Tu M-L (2011) Particles removal by negative ionic air purifier in cleanroom. Aerosol Air Qual Res 11(2):179–186. https://doi.org/10.4209/aaqr.2010.06.0048

Sidheswaran M, Chen W, Chang A, Miller R, Cohn S, Sullivan D et al (2013) Formaldehyde emissions from ventilation filters under different relative humidity conditions. Environ Sci Technol 47(10):5336–5343. https://doi.org/10.1021/es400290p

Siegel JA (2015) Primary and secondary consequences of indoor air cleaners. Indoor Air 26(1):88–96. https://doi.org/10.1111/ina.12194

Singer BC, Pass RZ, Delp WW, Lorenzetti DM, Maddalena RL (2017) Pollutant concentrations and emission rates from natural gas cooking burners without and with range hood exhaust in nine California homes. Build Environ 122:215–229. https://doi.org/10.1016/j.buildenv.2017.06.021

Smith KR (2008) WHO air quality guidelines: moving indoors. Air Qual Atmos Health 1(1):17–18. https://doi.org/10.1007/s11869-008-0010-2

Soreanu G, Dixon M, Darlington A (2013) Botanical biofiltration of indoor gaseous pollutants—a mini-review. Chem Eng J 229:585–594. https://doi.org/10.1016/j.cej.2013.06.074

Still DK, Bentson S, Murray N, Andres J, Yue Z, MacCarty NA (2018) Laboratory experiments regarding the use of filtration and retained heat to reduce particulate matter emissions from biomass cooking. Energy Sustain Dev 42:129–135. https://doi.org/10.1016/j.esd.2017.09.011

Sultan Z, Nilsson G, Magee R (2011) Removal of ultrafine particles in indoor air: performance of various portable air cleaner technologies. HVAC&R Res 17(4):513–525. https://doi.org/10.1080/10789669.2011.579219

Sung J-H, Lee Y, Han B, Kim Y-J, Kim H-J (2020) Improvement of particle clean air delivery rate of an ion spray electrostatic air cleaner with zero-ozone based on diffusion charging. Build Environ 186:107335. https://doi.org/10.1016/j.buildenv.2020.107335

Tan Z, Zhang Y (2004) A review of effects and control methods of particulate matter in animal indoor environments. J Air Waste Manag Assoc 54(7):845–854. https://doi.org/10.1080/10473289.2004.10470950

Totful L, Canepari S, Sargolini T, Perrino C (2021) Indoor air quality in a domestic environment: combined contribution of indoor and outdoor PM sources. Build Environ 202:108050. https://doi.org/10.1016/j.buildenv.2021.108050

Tong Z, Li Y, Westerdahl D, Freeman RB (2020) The impact of air filtration units on primary school students indoor exposure to particulate matter in China. Environ Pollut 266:115107. https://doi.org/10.1016/j.envpol.2020.115107

Tran VV, Park D, Lee Y-C (2020) Indoor air pollution, related human diseases, and recent trends in the control and improvement of indoor air quality. Int J Environ Res Public Health 17(8):2927. https://doi.org/10.3390/ijerph17082927

US EPA (2018) Guide to air cleaners in the home portable air cleaners and furnace or hvac filters in the home, 2nd Edition. pp 1–7

Uk Lee B, Yermakov M, Grinshpun SA (2004) Removal of fine and ultrafine particles from indoor air environments by the unipolar ion emission. Atmos Environ 38(29):4815–4823. https://doi.org/10.1016/j.atmosenv.2004.06.010

Vandenbroucke AM, Morent R, De Geyter N, Leys C (2011) Non-thermal plasmas for non-catalytic and catalytic VOC abatement. J Hazard Mater 195:30–54. https://doi.org/10.1016/j.jhazmat.2011.08.060

Venkataraman C, Brauer M, Tibrewal K, Sadavarte P, Ma Q, Cohen A, Chaliyakunnel S, Frostad J, Klimont Z, Martin RV, Millet DB, Philip S, Walker K, Wang S (2018) Source influence on emission pathways and ambient PM2.5 pollution over India (2015–2050). Atmos Chem Phys 18(11):8017–8039. https://doi.org/10.5194/acp-18-8017-2018

Verto NV (1980) Electrets are a relatively new development in the field of electrostatics. pp 369–379

Vijayan V, Paramesh H, Salvi S, Dalal AK (2015) Enhancing indoor air quality—the air filter advantage. Lung India 32(5):473. https://doi.org/10.4103/0970-2113.164174

Wallace L (2004) Effect of central fans and in-duct filters on deposition rates of ultrafine and fine particles in an occupied townhouse. Atmos Environ 38(3):405–413. https://doi.org/10.1016/j.atmosenv.2003.10.003

Wang Z, Bai Z, Yu H, Zhang J, Zhu T (2004) Regulatory standards related to building energy conservation and indoor-air-quality during rapid urbanization in China. Energy Build 36(12):1299–1308. https://doi.org/10.1016/j.enbuild.2003.09.013

Wang C, Jin-Ying X, Hong-Ying H, Yuan Y (2019) Advantages of combined UV photodegradation and biofiltration processes to treat gaseous chlorobenzene. J Hazardous Mater 171(1–3):1120–1125. https://doi.org/10.1016/j.jhazmat.2009.06.129

Ward TJ, Semmens EO, Weiler E, Harrar S, Noonan CW (2017) Efficacy of interventions targeting household air pollution from residential wood stoves. J Eposure Sci Environ Epidemiol 27(1):64–71. https://doi.org/10.1038/jes.2015.73

Waring MS, Siegel JA, Corsi RL (2008) Ultrafine particle removal and generation by portable air cleaners. Atmos Environ 42(20):5003–5014. https://doi.org/10.1016/j.atmosenv.2008.02.011

Weerakkody U, Dover JW, Mitchell P, Reiling K (2018) Quantification of the traffic-generated particulate matter capture by plant species in a living wall and evaluation of the important leaf characteristics. Sci Total Environ 635:1012–1024. https://doi.org/10.1016/j.scitotenv.2018.04.106

Wen T-Y, Krichtafovitch I, Mamishev AV (2015) The key energy performance of novel electrostatic precipitators. J Build Eng 2:77–84. https://doi.org/10.1016/j.jobe.2015.04.006

Wheeler AJ, Gibson MD, MacNeill M, Ward TJ, Wallace LA, Kuchta J, Seaboyer M, Dabek-Zlotorzynska E, Guernsey JR, Stieb DM (2014) Impacts of air cleaners on indoor air quality in residences impacted by wood smoke. Environ Sci Technol 48(20):12157–12163. https://doi.org/10.1021/es503144h

WHO guidelines for air quality (1998) Guidance for setting air quality standards: report on a WHO working group. Indian Pediatr 35(18):812–815

Wolverton B, Wolverton J (1993) Plants and soil microorganisms: removal of formaldehyde, xylene, and ammonia from the indoor environment. J Mississippi Acad Sci 38(2):11–15

Xu T, Zheng H, Zhang P (2018) Performance of an innovative VUV-PCO purifier with nanoporous TiO_2 film for simultaneous elimination of VOCs and by-product ozone in indoor air. Build Environ 142:379–387. https://doi.org/10.1016/j.buildenv.2018.06.047

Xu X, Xia J, Gao Y, Zheng W (2019) Additional focus on particulate matter wash-off events from leaves is required: A review of studies of urban plants used to reduce airborne particulate matter pollution. Urban Forest Urban Green. https://doi.org/10.1016/j.ufug.2019.126559

Yagi S, Tanaka M (1979) Mechanism of ozone generation in air-fed ozonisers. J Phys D Appl Phys 12(9):1509–1520. https://doi.org/10.1088/0022-3727/12/9/013

Ye W, Zhang X, Gao J, Cao G, Zhou X, Su X (2017) Indoor air pollutants, ventilation rate determinants and potential control strategies in Chinese dwellings: a literature review. Sci Total Environ 586:696–729. https://doi.org/10.1016/j.scitotenv.2017.02.047

Yu BF, Hu ZB, Liu M, Yang HL, Kong QX, Liu YH (2009) Review of research on air-conditioning systems and indoor air quality control for human health. Int J Refrig 32(1):3–20. https://doi.org/10.1016/j.ijrefrig.2008.05.004

Zeng Y, Manwatkar P, Laguerre A, Beke M, Kang I, Ali A, Farmer D, Gall E, Heidarinejad M, Stephens B (2022) Corrigendum to "Evaluating a commercially available in-duct bipolar ionization device for pollutant removal and potential byproduct formation"[Build. Environ, Volume 195, May 2021, 107750]. Build Environ 214:108910. https://doi.org/10.1016/j.buildenv.2022.108910

Zhang Y, Mo J, Li Y, Sundell J, Wargocki P, Zhang J, Little JC, Corsi R, Deng Q, Leung MHK, Fang L, Chen W, Li J, Sun Y (2011) Can commonly-used fan-driven air cleaning technologies improve indoor air quality? A literature review. Atmos Environ 45(26):4329–4343. https://doi.org/10.1016/j.atmosenv.2011.05.041

Zhang C, Pomianowski M, Heiselberg PK, Yu T (2020) A review of integrated radiant heating/cooling with ventilation systems—thermal comfort and indoor air quality. Energy Build 223:110094. https://doi.org/10.1016/j.enbuild.2020.110094

Zhang S, Mumovic D, Stamp S, Curran K, Cooper E (2021) What do we know about indoor air quality of nurseries? A review of the literature. Build Serv Eng Res Technol. https://doi.org/10.1177/01436244211009829

Zhao W, Yang Y, Dai J, Liu F, Wang Y (2013) VUV photolysis of naphthalene in indoor air: Intermediates, pathways, and health risk. Chemosphere 91(7):1002–1008. https://doi.org/10.1016/j.chemosphere.2013.01.086

Zhao P, Siegel J and Corsi R (2005) Experimental characterization of portable ion generators. Indoor Air, 2957–2961

Zhong K, Yang X, Kang Y (2010) Effects of ventilation strategies and source locations on indoor particle deposition. Build Environ 45(3):655–662. https://doi.org/10.1016/j.buildenv.2009.08.003

Zhou P, Yang Y, Huang G, Lai ACK (2018) Numerical and experimental study on airborne disinfection by negative ions in air duct flow. Build Environ 127:204–210. https://doi.org/10.1016/j.buildenv.2017.11.006

Zhu Y, Tao S, Chen C, Liu J, Chen M, Shangguan W (2021) Highly effective removal of PM2.5 from combustion products: an application of integrated two-stage electrostatic precipitator. Chem Eng J 424:130569. https://doi.org/10.1016/j.cej.2021.130569

Zhuang Y, Jin Kim Y, Gyu Lee T, Biswas P (2000) Experimental and theoretical studies of ultra-fine particle behavior in electrostatic precipitators. J Electrostat 48(3–4):245–260. https://doi.org/10.1016/s0304-3886(99)00072-8

Zuraimi MS, Tham KW (2009) Reducing particle exposures in a tropical office building using electrostatic precipitators. Build Environ 44(12):2475–2485. https://doi.org/10.1016/j.buildenv.2009.04.011

Authors and Affiliations

Aiswarya Kumar[1] · Vasudev Malyan[1] · Manoranjan Sahu[1,2,3]

✉ Manoranjan Sahu
mrsahu@iitb.ac.in

[1] Environmental Science and Engineering Department, 507, Aerosol and Nanoparticle Technology Laboratory, Indian Institute of Technology Bombay, Mumbai 400076, India

[2] Interdisciplinary Program in Climate Studies, Indian Institute of Technology Bombay, Mumbai 400076, India

[3] Centre for Machine Intelligence and Data Science, Indian Institute of Technology Bombay, Mumbai 400076, India