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# Primary and secondary consequences of indoor air cleaners

**Abstract** Air cleaning is broadly applied to reduce contaminant concentrations in many buildings. Although diverse in underlying technology, mode of application, target contaminants, and effectiveness, there are also commonalities in the framework for understanding their primary impact (i.e. concentration reductions) and secondary impacts (e.g. energy use and by-product production). Furthermore, both primary and secondary impacts are moderated by the specific indoor context in which an air cleaner is used. This investigation explores the dynamics of removal efficiency in a variety of air cleaners and combines efficiency and flow rate to put air cleaning in the context of real indoor environments. This allows for the direct comparison to other indoor pollutant loss mechanisms (ventilation and deposition) and further suggests that effective air cleaner use is context and contaminant specific. The concentration reduction impacts of air cleaning need to be contrasted with the secondary consequences that arise from the use of air cleaners. This study emphasizes two important secondary consequences: energy use of the air cleaning process and primary and secondary emissions from air cleaners. This study also identifies current research challenges and areas for large leaps in our understanding of the role of air cleaners in improving indoor environmental quality.

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**Practical Implications**

Effective use of air cleaners requires considerably more knowledge than simply a static contaminant removal efficiency. Removal efficiencies for many air cleaners are dynamic, and the removal efficiency needs to be put in the context of the system in which the air cleaner is used and the environment in which the air cleaner is deployed. The impacts of an air cleaner are not limited to contaminant removal: Important secondary impacts include energy use associated with an air cleaner and by-product emission.

## Introduction

Improving indoor air quality generally relies on three basic approaches: reducing sources of indoor air pollution, dilution ventilation, and air cleaning. It is a truism in indoor air quality practice that there is a hierarchy of these three techniques with source control being universally preferred, ventilation a distant second choice, and air cleaning a final approach, often to be used in combination with ventilation. The challenge that arises is that source control is often not possible or out of the control of building occupants. Ventilation also increasingly presents challenges both in terms of building energy use and because clean outdoor air is not a given in much of the world. Thus, air cleaning is receiving increasing attention as an indoor air strategy.

Although air cleaning has a long and rich history, the research on air cleaning technologies is much shorter. Air filtration has historically been used for a wide variety of specialized purposes, including controlling dust in industrial environments, infection in hospitals, and radioactive aerosols (e.g. First, 1998). Early building air filtration devices were often used to remove large debris from the air stream to avoid fouling fans, conditioning equipment, and indoor surfaces. The literature on air cleaning is also considerably shorter than that on ventilation and source control (e.g. the work of Pettenkofer in the 1800s). Recent decades have seen an increase in the scientific exploration of air cleaning, with approximately one hundred articles a year exploring some aspect of the connections between air cleaning and indoor air quality. The purpose of this study is not to provide a comprehensive review, as there are several reviews that exist on air cleaning overall (e.g. Zhang et al., 2011), specific air cleaning technologies (e.g. Mo et al., 2009), and associations between air cleaning and health (e.g. Fisk, 2013). Instead, the goal is to provide insight on the context for air cleaning and to explore the primary (concentration reduction) and secondary consequences (e.g. energy use and pollutant generation) that arise from the use of indoor air cleaning. The overall objective is to provide an integrated view of air cleaning and a framework for examining the overall impact an air cleaning strategy will have on an indoor environment.

To achieve this objective, this study is divided into four sections. The first section provides an overview of the literature on indoor air cleaning and a categorization scheme for understanding different air cleaners. The second section describes the primary impacts of air cleaning devices with a specific focus on some of the lesser-explored complexities and dynamic nature of the performance of air cleaners in indoor environments. The third section explores secondary consequences from the use of air cleaning devices. The final section identifies major needs for air cleaning research.

## Categorization of air cleaners

A general literature review in the Science Citation Index was performed on the terms that relate to air cleaners. The list was curated to remove articles that did not explicitly focus on air cleaning (e.g. investigations that explored contaminant removal with ventilation). Figure 1 shows the distribution of articles by year, indicating that the index contains a few articles each year in the 1980s and almost 100 articles per year in 2013. The citation indices tend to under-represent older articles and so an informal search of citations and consultations with members of the air cleaning community was conducted to find additional references. These articles are included in this study where appropriate, but not explicitly in this section because of issues with differences in terminology and other issues that make them difficult to integrate with more modern articles. A similar but more comprehensive literature review is detailed in Zhang et al. (2011).

Figure 2a–c classifies the investigations in Figure 1 in three different ways. Figure 2a categorizes investigations by the technology that is used for air

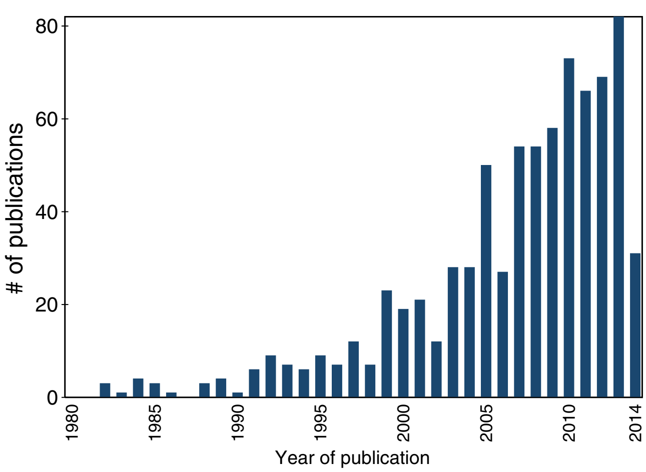


**Fig. 1** Air cleaner citations in the Science Citation Index as a function of year

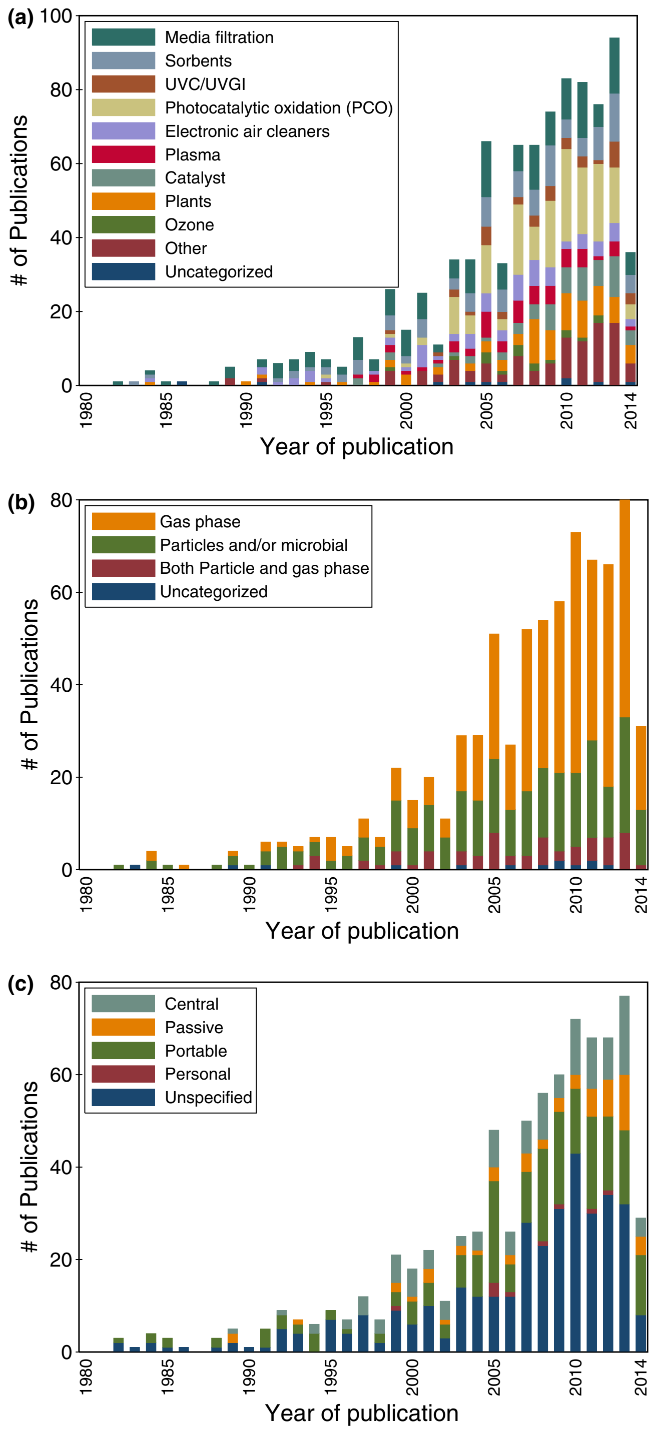


**Fig. 2** Air cleaner citations in the Science Citation Index as a function of year classified by technology (a), target contaminant (b), and scale of air cleaner (c)

**Table 1** Description of air cleaning technologies

| Technology | Description | Contaminant | Review article[a] |
|---|---|---|---|
| Media filtration | Porous media | Particles | Fisk (2013)[b] |
| Sorbents | Physio- or chemosorbents | Organic and inorganic gas-phase | Harper (2000) |
| UVC/UVGI | Ultraviolet (UV) lamp | Bioaerosols (airborne or on surfaces) | Miller et al. (2013) |
| Photocatalytic oxidation (PCO) | UV lamp and photocatalyst | Organic and inorganic gas-phase (occasionally bioaerosols) | Mo et al. (2009) |
| Electronic air cleaners (EACs) | Corona or pin ionizer, enhanced deposition in or out of device | Particles | Mizuno (2000)[c] |
| Plasma | Electrical discharge | Organic gas-phase | Chen et al. (2009) |
| Catalyst | Excludes PCO photocatalysts | Organic and inorganic gas-phase | |
| Plants | Various botanical systems | Particulate and gas-phase | Soreanu et al. (2013) |
| Ozone | UV or corona generation of ozone | Organic gas-phase (occasionally bioaerosols) | |

[a]If available.
[b]Review of health benefits of particle media filtration, not all aspects of media filters.
[c]Includes other applications besides just indoor air.

cleaning. The technology description is taken as that used by the study author and engineering judgement was used to resolve cases where nonstandard technology descriptions arose. Table 1 describes these technologies, identifies their target contaminants, and (where available) provides a recent review article on their application for air cleaning in indoor environments. Some articles were not able to be categorized easily because an article was unclear on the working principle of a device and thus were left in a generic uncategorized section.

Figure 2b divides the articles by contaminant categories (particle- or gas-phase) addressed by the air cleaner. Although the articles, especially in recent years, appear to focus predominantly on gas-phase contaminants, many of these investigations include prototype technologies that are not commercialized. The application of air cleaning technologies in actual buildings is much more likely to be focussed on particle removal. Figure 2c organizes by scale, where central air cleaners are used in a system that addresses multiple spaces in the building, portable air cleaners are air cleaners used for a room or a portion of a room, passive air cleaners do not induce air movement but instead rely on existing room airflows to bring contaminants into contact, and personal air cleaners are typically worn and remove contaminants from the immediate vicinity of the wearer. The unspecified category includes investigations of technologies that are used at multiple scales or components (e.g. filter media) that could be used at multiple scales.

### Primary impacts of air cleaners

The primary performance metric often used to describe an air cleaner is its single-pass removal efficiency, $\eta$, defined in Equation 1.

$$\eta = 1 - \frac{C_{\text{downstream}}}{C_{\text{upstream}}} \quad (1)$$

where $C_{\text{downstream}}$ and $C_{\text{upstream}}$ are the downstream and upstream concentrations of a pollutant, respectively. Removal efficiency is generally bounded to the range of 0–100% but an air cleaner can effectively have a negative efficiency, for example, by generating more of a contaminant than is removed through secondary reactions or shedding (both discussed below). Similarly, some electrostatic air cleaners can remove particles outside of the air cleaner by enhanced removal of charged particles to room surfaces and thus effectively have an efficiency greater than 100% (Waring et al., 2008). Particle removal by many air cleaners is a strong function of particle size (e.g. Hanley et al., 1994) and particle composition, and most air cleaners exhibit different efficiencies for different gas-phase pollutants (e.g. Destaillats et al., 2012; Mo et al., 2009). Additionally increased air velocity in an air cleaner can affect removal efficiency either by increasing loss by inertial mechanisms for larger particles (e.g. Hanley et al., 1994) or by reducing loss because of reduced residence time for small particles and gas-phase contaminants (e.g. Destaillats et al., 2012). There are several standard test methods for laboratory measurement of efficiency for filter media, filters, and other air cleaning devices including ASHRAE Standard 52.2, EN 779, ISO 10121-2, and ASHRAE Standard 145.2.

Removal efficiency is generally considered to be static for purposes of evaluating air cleaner performance; however, this can be a poor assumption. In many systems, air velocity varies either intentionally as a means of controlling conditioning and ventilation or unintentionally because of changing component pressure drop (i.e. media filter loading). Furthermore, it is well known that media filters intended to remove particles can either improve in performance as they load because the deposited particles serve to add filtration media (e.g. Hanley et al., 1994) or decline in performance because deposited particles mask or discharge statically charged media (Lehtimaki et al., 2005; Raynor and Chae, 2004). These reductions can reduce filtration efficiency by a factor of two or more and are complicated to assess because they depend in unknown ways on the amount and composition of dust loading, both of which are also rarely known. Corona-based air cleaning technologies also have removal efficiencies that can vary with time. For example, electrostatic precipitators can decline in efficiency when siloxanes from consumer products deposit on the corona wire (Davidson and Mckinney, 1998). Ultraviolet lights, such as other fluorescent lamps, can decline in output as they age or become fouled and face a decline in the dose of radiation delivered to microorganisms (First et al., 2006). Activated carbon can decline in efficiency because of particulate fouling, poisoning, and saturation, among other factors (e.g. Metts and Batterman, 2006). Photocatalytic oxidation devices are subject to the declines associated with the degradation of their UV light sources, as well as potential fouling of the catalyst. In many cases, we have some insight into device lifetimes and/or cleaning procedures, but efficiency for an in-service air cleaner is generally unknown without an in-situ measurement (Stephens and Siegel, 2012). Some air cleaning test standards (such as ASHRAE Standard 52.2-2012 for particle filtration) involve testing air cleaners at clean- and dust-loaded conditions, but there are open questions of the similarity of loading dust used in standards to challenges faced in real environments.

Efficiency can be further degraded by how that air cleaner is installed and maintained. One common reason for degradation is bypass, where air travels around, rather than through, an air cleaner (Ward and Siegel, 2005). Bypass is rarely quantified in air cleaning system audits, but is an important component of efficiency. Bypass has been shown in central systems (e.g. Vershaw et al., 2009) and causes degradation in effective efficiency that ranges from negligible for small gaps around low-efficiency and low-pressure drop air cleaners to very large penalties for high-efficiency and high-pressure drop air cleaners (Chojnowski et al., 2009). Another source of bypass occurs with portable air cleaners that unintentionally recirculate some clean air back into the device inlet (e.g. Offermann et al., 1985).

Even a known air cleaner efficiency does not tell a complete picture of air cleaner performance. To compare the removal rate of an air cleaner with other loss mechanisms (such as ventilation and deposition), the product of the airflow rate through the air cleaner and its efficiency is a more relevant parameter. Often called clean air delivery rate (CADR), among other terms, this term allows for air cleaner performance to be put in context for a real indoor environment. Thus, flow provides an alternative parameter to efficiency for optimizing air cleaning performance and has the advantage of not being bounded (other than by practical issues such as noise and fan energy use) as is efficiency. CADR is typically measured directly with a contaminant decay test for portable air cleaners (e.g. AHAM AC-1) and can differ from the product of flow rate and efficiency because of several issues, including bypass. The definition of CADR for central air cleaners is complicated by the fact that the fan and the air cleaner are distinct pieces of equipment and the air cleaner is one component of a larger distribution system. Thus, CADR is generally system specific for central systems.

Like efficiency, flow can vary greatly in a given system. In many portable air cleaners, the user can adjust the amount of flow. In some commercial systems, a variable air volume approach is used to maintain thermal and ventilation conditions with less fan energy. In most residential and some commercial systems, the conditioning system cycles on and off to meet the needs of the thermostat. Particle media filters increase in pressure drop as they load and this often leads to a reduction in flow (discussed in more detail below). Thus, an accurate assessment of CADR requires either a direct measurement or knowledge of both the flow and efficiency of an air cleaner.

Once CADR is known, the performance of an air cleaner can be used to assess concentrations in a given environment using a mass balance or alternative modeling approach. One way of characterizing air cleaner performance is by defining the effectiveness, $H$, (Miller-Leiden et al., 1996) as shown in Equation 2.

$$H = 1 - \frac{C_{\mathrm{ac}}}{C_{\mathrm{no\ ac}}} = 1 - \frac{L_{\mathrm{no\ ac}}}{L_{\mathrm{ac}}} \quad (2)$$

where $C$ is the concentration, $L$ is the loss rate, and the subscripts ac and no ac refer to the presence or absence of an air cleaner, respectively. Equations 3 and 4 are the examples of Equation 2 considering ventilation and deposition loss as well as loss by air cleaners for portable and central air cleaners, respectively.

$$H = 1 - \frac{\lambda + \beta}{\lambda + \beta + \frac{\mathrm{CADR}}{V}} \quad (3)$$

$$H = 1 - \frac{\lambda + \beta}{\lambda + f\frac{Q_{\mathrm{r}}}{V}\eta_{\mathrm{c}} + \beta} \quad (4)$$

where $\lambda$ is the ventilation loss rate, $\beta$ is the deposition loss rate, $V$ is the volume of the environment, $f$ is the central system on-time fraction, $Q_{\mathrm{r}}$ is the airflow rate through the central system, and $\eta$ is the central air cleaner removal efficiency. Equations 3 and 4 are based on a time-averaged mass balance and are subject to the associated assumptions (well-mixed environment, constant air density, and parameters that are constant and uncorrelated with each other). Equations 3 and 4 also only account for loss by ventilation and deposition to surfaces (in addition to the air cleaner) and are expressed here for a simple HVAC system with no mechanical ventilation.

Equation 3 demonstrates that to be effective a portable air cleaner has to compete with other loss mechanisms and many air cleaners with low CADRs are unlikely to cause a large reduction in the indoor contaminant that they target. Classic examples of air cleaners that have been shown to be ineffective include many plant-based systems for volatile organic compounds (VOCs) and particles (Chen et al., 2005; Hanoune et al., 2013), ion-generating air cleaners for particles (e.g. Shaughnessy and Sextro, 2006), and many types of portable air cleaners for larger particles (e.g. Offermann et al., 1985). Any portable air cleaner, regardless of underlying technology and target contaminant, is going to be less effective in an environment with a larger ventilation rate or other increased losses. Central air cleaners (Equation 4) typically have the benefit of large flow rates (Stephens et al., 2011), however, as mentioned above, systems cycle on and off and the on-time fractions can range from zero in mild seasons to 20–40% in more extreme seasons (Stephens et al., 2011; Thornburg et al., 2004), potentially limiting the effectiveness of central air cleaner approaches.

### Secondary impacts of air cleaners

Although much of the academic and practical focus is on the primary impacts of air cleaners, there are many secondary impacts that are essential for a holistic understanding of air cleaning. For the purposes of comparing air cleaning with ventilation as a contaminant reduction approach, one of the key parameters is the amount of energy that an air cleaner uses. From the perspective of improving indoor air quality, air cleaners and air cleaning processes can also emit by-products of their operation. Fundamentally, air cleaners serve to remove contaminants from an airstream and thus can reemit those contaminants or serve as a site for chemical reactions or microbiological growth. The purpose of this section is to explore these secondary impacts in more depth.

There are two main ways that an air cleaner can use energy: through the operation of a fan or other air movement device and by the direct use of energy for the air cleaning process. In the case of a portable air cleaner, these processes operate together and assessing energy use is relatively straightforward. Energy effectiveness, defined as CADR divided by electrical power draw, has been shown to range from near zero for a portable panel filter with low flow (Offermann et al., 1985) to 4.6 $m^3/h/W$ for portable high-efficiency particulate air (HEPA, also high-efficiency particle arresting) filters (Offermann et al., 1985; Waring et al., 2008) to 6.3 $m^3/h/W$ for an ion generator (Waring et al., 2008). Thus, for portable air cleaners, the energy cost can be directly assessed in the context of pollutant removal.

The energy impacts of central air cleaners are considerably more complex. The first issue that arises is the diversity of fans used in central systems. A variety of fan designs and motors are used in HVAC systems and each fan has a different performance curve. A change in the pressure distribution of a system can have a large or a small impact on the energy used by the fan depending on a number of factors (e.g. Stephens et al., 2010a). Additionally, measured fan efficacies, defined as the airflow produced by the electrical power input, range from approximately 2–4.5 $m^3/h/W$ for typical permanent split capacitor (PSC) motor fans used in most residential systems (Stephens et al., 2011) to over 6 $m^3/h/W$ for electrically commutated motor (ECM) fans (Ionel, 2010; Stephens et al., 2011). There are less data on fan efficacy for commercial systems, but measured and assumed values range from similar values to residential PSC motor fans in commercial rooftop systems (Zaatari et al., 2014) to much higher values in commercial central systems (Fisk et al., 2002; Bekö et al., 2008a). A second issue is the control strategy for fan speed. Some systems (most residential and some commercial systems) do not actively adjust fan speed. Therefore, the installation of an air cleaner with a greater pressure drop will lead to diminished airflow and decreased fan power draw. Other systems have a fan-speed control that will increase fan speed and power draw to maintain flow when confronted with an air cleaner with a greater pressure drop. Thus, both the sign and the magnitude of any energy impacts associated with air cleaner pressure drop are both fan specific and air cleaner specific.

Additionally, it is traditionally assumed that the air cleaner is the dominant pressure drop in an HVAC system. For residential and light-commercial systems, filters have been measured to account for 21–100% of the total pressure loss in an HVAC system (Stephens et al., 2010b) and thus in some cases a change in filter pressure drop may be either very important or largely inconsequential to the pressure drop in a system. There are less data on commercial systems, but the diversity of system designs and components utilized suggest the potential for a similar result. The pressure drop of seemingly similar air cleaners also can vary greatly. Figure 3 shows the pressure drop of 91 media filters sorted into efficiency categories (data are from various sources that were summarized in Zaatari et al., 2014). Although there is a clear increasing trend in median filter pressure drop with increasing filter efficiency, particularly for the higher efficiency categories, there is clear overlap between categories and no statistically significant differences in pressure drop. These trends are furthered by more recent filter designs, which utilize very thin media, but have deep pleats to maximize

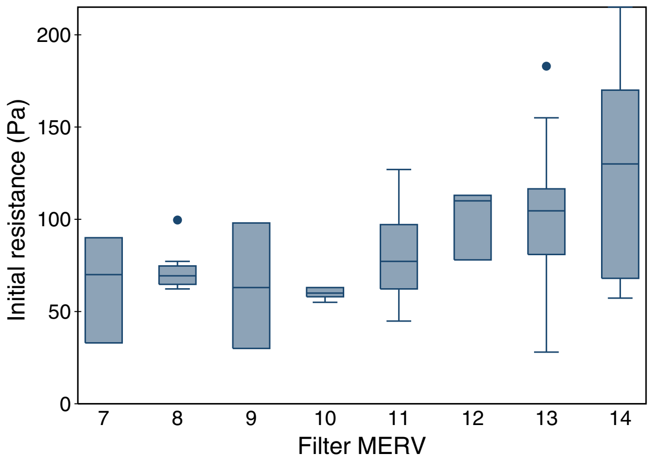


**Fig. 3** Clean filter pressure drop as a function of efficiency category (MERV = Minimum Efficiency Reporting Value from ASHRAE Standard 52.2-1999). Data sources were summarized in Zaatari et al. (2014) and Rivers and Murphy (1999). In this plot, the bottom of the boxes indicates the 25th percentile, the horizontal line indicates the median, and the top of the box indicates the 75th percentile. The whiskers indicate the data range within 1.5 times the interquartile range of the 25th and 75th percentile

media area and efficiency, particularly for small particles (e.g. Stephens et al., 2013).

The above discussion focuses largely on the energy consumption of the fan. For systems with no fan-speed control, a change in flow may have an impact on conditioning capacity and efficiency, especially for cooling systems. These impacts are extremely complex and are dependent on many details of system operation as well as indoor and outdoor environmental conditions. However, field measurements have shown, on average, negligible energy impacts from the use of higher efficiency filters in residential, light-commercial, and commercial rooftop systems (Stephens et al., 2010a,b; Walker et al., 2013; Zaatari et al., 2014).

Some forms of air cleaning require little or no energy input. Passive air cleaners are materials that are introduced in indoor spaces with the goal of reducing contaminant concentrations. Examples in the literature include manganese oxide (e.g. Sekine and Nishimura, 2001), $TiO_2$-containing paints (Salthammer and Fuhrmann, 2007), activated carbon mats (e.g. Kunkel et al., 2010), clay plaster (Darling et al., 2012), and cement renders (Taylor-Lange et al., 2013). Most of the passive air cleaner approaches target ozone and, less commonly, formaldehyde, although the potential exists to passively remove a wide range of contaminants. Gall et al. (2011) explores some of the challenges and opportunities of passive air cleaning devices.

In addition to energy consequences of air cleaners, we are also concerned with emissions from air cleaner operations. Air cleaner emissions primarily come in three forms:

- Direct emission of a by-product of the operation of the cleaner.
- Secondary emissions that can be attributed to the reaction between the by-product of the air cleaner operation and the environment.
- Secondary emissions that arise from physical, chemical, or biological interactions with contaminants that are removed to the air cleaner.

Each of these forms and relevant examples are discussed below.

Given that an air cleaner's primary function is to reduce contaminant concentrations, it would seem unusual that they may also generate contaminants. This is performed intentionally by some air cleaners, such as ozone generators, which nominally produce ozone for deodorization or microbiological sterilization purposes. There are other air cleaners that emit scented compounds into the air for odor masking purposes. For the purposes of this study, a device that intentionally emits any compound into indoor air is not considered to truly be an air cleaner as the contamination can outweigh any air cleaning benefit (e.g. Hubbard et al., 2005). However, several air cleaning technologies can also emit contaminants as unintentional by-products of their operation. This include ozone production by ionizers (e.g. Britigan et al., 2006), some UV lamps including those contained in some PCO systems (e.g. Mo et al., 2009), electrostatic precipitators (e.g. Viner et al., 1992), and plasma systems (e.g. Chen et al., 2009). The indoor concentration of ozone that results from the use of an ozone-generating air cleaner will depend on its emission rate and the characteristics (e.g. ventilation rate, deposition loss to surfaces, and volume) of the environment in which the air cleaner operates. Although ozone has received the most attention, there is documentation of other emissions from new air cleaners including formaldehyde from fiberglass media filters (Sidheswaran et al., 2013) and botanical air cleaners may be associated with either increased humidity and or the release of microorganisms (e.g. Darlington et al., 2000; Wang and Zhang, 2011).

Another form of direct emission of by-products arises from the generation of intermediate compounds in the air cleaning process. Measured by-products for PCO air cleaners include formaldehyde, acetaldehyde, propionaldehdye, and crotonaldehyde (Farhanian and Haghighat, 2014), among many others (Mo et al., 2009). A similar wide range of by-products have been reported for plasma air cleaners (Chen et al., 2009).

Once emitted, by-products can lead to secondary pollution. As with many of the other research in the section, most of the focus in the literature has been on ozone emission. Hubbard et al. (2005) reported increases in indoor particulate matter concentrations when an ozone-generating air cleaner was used in the presence of a terpene source in a residential indoor environment. Alshawa et al. (2007), Waring et al. (2008), and Waring and Siegel (2011) all report ultrafine particle formation when an ion-generating air cleaner is used in the presence of a terpene source in laboratory and residential environments, despite the fact that these air cleaners are intended to remove particles. Several articles report the formation of gas-phase by-products from the ozone-emitted from air cleaners (e.g. Waring and Siegel, 2011). The characteristics of the environment (e.g. contents and surface coverings, and air exchange rate), the strength of the emission source, and the presence, amount, and type of ozone-reactive compounds will all influence the type and amount of by-products formed.

The third form of secondary emissions arises generally from the function of the air cleaner. There is a paradox in air cleaning: An effective air cleaner removes contaminants from the air stream and then continually passes air over those contaminants. Used air cleaning devices, particularly media filters, have been associated with a variety of sensory and odor implications (Bekö et al., 2006, 2007, 2008b; Hyttinen et al., 2007). Direct emissions of VOCs from media filters have been reported by many (Destaillats et al., 2011; Hyttinen et al., 2001, 2007; Lin and Chen, 2014; Sidheswaran et al., 2013) with ozone reactions often being the source of VOCs (Hyttinen et al., 2003; Zhao et al., 2007). Media filters can also create particles either from ozone reactions (Bekö et al., 2005) or directly from shedding of particles for low-efficiency filters. The latter is often assumed to be responsible for the dip in efficiency that occurs for larger particles for low-efficiency filters (e.g. the furnace filter in Hanley et al., 1994). Bekö et al. (2009) demonstrate that some of the sensory impacts of ozone reactions can be ameliorated by the inclusion of relatively small amounts of activated carbon in some media filters. Biological growth and associated odors have also been associated with used media filters (e.g. Simmons and Crow, 1995). Although much of the summarized research has occurred on media filters intended to remove particles, heterogeneous reactions between ozone and sorbed VOCs on activated carbon sorbent filters can also lead to the production of by-products (Metts and Batterman, 2006).

It is clear that air cleaners can act as sources as well as sinks of pollution. We rarely have sufficiently small uncertainties in health impacts data to evaluate the comprehensive impacts of air cleaner operation, but it is clear that primary and secondary emissions are important criteria to consider when conducting research on air cleaners as well as the practical application of selecting an air cleaner.

#### Future directions and conclusions

Although there is a robust literature on indoor air cleaning, there are still areas where there are substantial gaps in the literature. The purpose of this section is to outline some of the major gaps where future research could add greatly to our understanding of indoor air cleaning.

Much of air cleaner performance data is based on relatively short-term tests and much of it has occurred in laboratory test chambers. To better characterize the dynamic and long-term performance of air cleaners, we need testing that is (i) conducted in well-characterized indoor environments, (ii) occurs for a long duration to capture any changes in performance, (iii) examines both the primary and secondary impacts of air cleaners, and (iv) considers air cleaning impacts on multiple contaminants. Well-designed studies that meet these criteria will have the dual benefit of providing both a more realistic picture of air cleaner performance as well as an opportunity to explore the fundamental factors that lead to changes in performance. An understanding of these factors opens the opportunity for design of air cleaner technologies with improved secondary performance.

One of the main reasons to use air cleaners is to improve human health. Despite this, there are very few examples of carefully performed experiments on the associations between air cleaner use and human health (e.g. Mendell et al., 2002; Menzies et al., 2003) and those that do exist generally focus on the impact of air cleaners on short-term symptoms. Review of the literature on the associations between air cleaning and health on either general (e.g. Fisk, 2013) or specific health outcomes (e.g. Sublett, 2011) is limited to media filtration, largely because of the lack of investigations on other types of air cleaning technologies. Well-designed and controlled intervention studies that allow for the assessment of either long-term or short-term heath benefits that arise from the use of air cleaning technologies would allow for a much clearer assessment of the costs and benefits that arise from the use of air cleaner use, as well as aid in the selection of particular air cleaners for specific applications.

Although the energy consequences of air cleaners are well explored in residential and smaller commercial systems, we have almost no measured data on the impact of air cleaning on larger commercial systems. Such an exploration would both add nuance to our understanding of air cleaners, as well as allow a rational basis to explore tradeoffs between ventilation and air cleaning for pollutant removal. In general, research into passive and low-energy air cleaning, as well as approaches such as pollutant-controlled air cleaning, removing pollutants only when needed, would allow for practical energy and maintenance saving approaches.

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