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Letter

Contextualizing Equivalent Clean Airflow Rates for Airborne Pathogens of Ionizers and Other Electronic Indoor Air Cleaners

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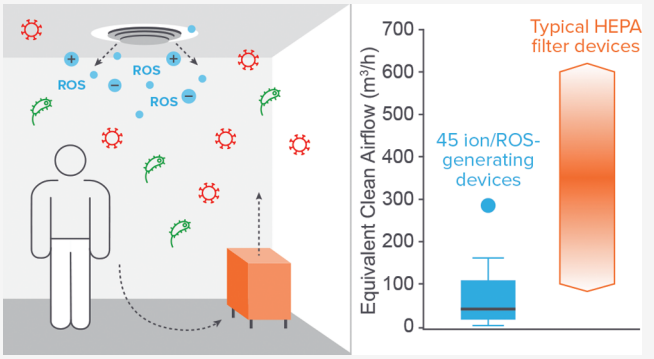
ABSTRACT: Additive electronic air cleaners like ionizers, photocatalytic oxidizers, and plasma devices intentionally release reactive species into indoor air so that they may inactivate infectious airborne pathogens. Third-party commercial testing and peer-reviewed studies alike typically report inactivation metrics in terms of percent- or log-reductions observed from chamber experiments that imply a nearly complete elimination of infection risks. However, these metrics are highly dependent upon the experimental volume and duration, so they do not directly translate to actual effectiveness indoors. We reviewed 45 experiments across 14 published studies and converted reported reduction metrics into equivalent clean airflow rates (ECA). Different studies yielded distinct ECA distributions, suggesting that differences in experimental procedures, device specifications, or environmental conditions may be more important ECA determinants than the target pathogen or the underlying device technology. Study-averaged ECAs spanned between 1.4 and 134 m^3/h, with the median study having an average ECA = 31 m^3/h. Even small off-the-shelf HEPA-filter air cleaners typically provide ECAs that exceed the best-performing additive devices analyzed herein. Their low efficacy relative to alternatives, environmental factors that can affect performance, and chemical byproduct concerns are discussed in the context of test standard development and system selection.



KEYWORDS: *Indoor air, Air cleaning, Bipolar ionization, Photocatalytic oxidation, Bioaerosol, Virus, Bacteria, Equivalent air flow rates, ECA*

1. INTRODUCTION

The need to rid indoor air of infectious pathogens has risen in saliency since the COVID-19 pandemic. Dedicated air cleaning that supplements outdoor air ventilation is often desired or required. Media filtration can be highly effective when sized correctly, but this approach is limited by practical constraints associated with fan power draw, noise, and air velocity. Electronic air cleaners are a possible alternative to media filtration. In this context, "electronic" refers to the use of electric energy to release reactive, oxidizing species into the air, so these devices are classified as operating in an *additive* manner.[1] Unipolar or bipolar ionizers (BPI), photocatalytic oxidizers (PCO), and nonthermal plasma devices are common variants of electronic air cleaners.[2] The added species may be either ions (e.g. H^+, OH^-, O_2^-) or reactive oxygen species (ROS), like the hydroxyl radical (OH) or hydrogen peroxide (H_2O_2).[2] The intended effect is for these species to react with the molecular structure of airborne pathogens, rendering them inviable. In contrast, subtractive technologies, like media filtration, work by removing pathogens from an airstream through physical contact with a filter media.[1]

Additive electronic air cleaners have recently grown in prominence for many reasons.[3−6] Their installation and operation is less intrusive than ventilation and filtration upgrades in terms of space taken, noise, pressure drop, energy consumption, and maintenance. They are often advertised to improve indoor air quality (IAQ) holistically by removing particles, gases, and pathogens.[7] Citing third-party tests, manufacturers often claim extremely high disinfection rates.

Historically, there have not been standardized testing methods or evaluation metrics for the removal of biological contaminants by electronic air cleaners. In this absence, many experimental studies have reported impressive-sounding inactivation levels, like "multiple log reductions" or "more than 99% removed," that suggest a greater impact in indoor settings than these cleaners can realistically achieve.[8−21] These tests typically occur in controlled laboratory environments, like sealed chambers, where the decay rate of an airborne pathogen is measured with and without the device in operation. A

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Table 1. General Experimental Parameters of the 14 Analyzed Studies

Key	Authors	No. of experiments	Device type	Pathogen(s)	Timeseries provided?
A[a]	Li et al.[8]	2	Plasma	Bacteria	√
B[b]	Scarlett and Duffy[9]	6	PCO	MRSA MS2	x
C[a]	Baselga et al.[10]	1	BPI	Bacteria	√
D[a]	Ratliff et al.[11]	3	BPI PCO	MS2	√
E[a]	Sobek and Elias[12]	6	BPI	Influenza RSV SARS-CoV-2	√
F[f]	Gomez et al.[13]	1	–	MHV	x
G[d,g]	Innovative Bioanalysis, Inc.[14]	3	BPI	SARS-CoV-2	√
H[a]	Aytekin et al.[15]	5	BPI	HCoV-229E Bacteria	√
I[c]	Peel et al.[16]	5	PCO	MPXV RSV SARS-CoV-2	x
J[e,g]	Balarashti and Trolinger[17]	3	BPI	MS2	x
K[f]	Mohamadi et al.[18]	4	–	Bacteriophage T4	x
L[a]	Jangra et al.[19]	2	Plasma	*E. coli* MS2	√
M[a]	Matsuura et al.[20]	1	PCO	SARS-CoV-2	√
N[a]	Angel et al.[21]	3	BPI	Bacteriophage Φ6	x

[a]Did not disclose a specific product or manufacturer. [b]Device manufacturer: CASPR Technologies. [c]Device manufacturer: ActivePure. [d]Model: Plasma Air 662. [e]Model: Plasma Air 603. [f]Injected H_2O_2 directly. [g]Data not peer-reviewed; from laboratory report.

percent- or log-reduction compared to the control test is calculated after a certain amount of time elapses. This reduction metric is highly dependent upon experimental conditions, like its duration and spatial volume. As such, the expected impact in a building cannot be extrapolated from the reduction metric alone without additional context. A device that negligibly impacts real-room pathogens can produce an arbitrarily large percent reduction given a sufficiently long experiment time and/or a sufficiently small experimental volume. In fact, a recent study showed that ionizers did not measurably inactivate airborne pathogens in a building.[22]

Stephens et al.[1] first brought attention to the issues described above. Using hypothetical examples, they demonstrated how to convert experimentally derived reductions into either a clean air delivery rate (CADR) or an equivalent clean airflow (ECA) rate. Both metrics are identical concepts that can specify the volumetric flow rate of pathogen-free air provided by either a system or a standalone device. Thus, they describe a device's performance independently of room or test conditions. In 2023, ASHRAE Standard 241 introduced the first testing standard for determining ECAs.[23] By applying similar analytical procedures to the available literature and product test reports, we aim to clarify the in situ effectiveness of electronic air cleaners for removing airborne pathogens and establish a first database of their ECAs.

2. MATERIALS AND METHODS

2.1. Standardizing Experimental Results. The methods we applied to derive an air cleaner's ECA (m^3/h) from experimental decay test results depended on the character of the provided data. Some studies reported a single reduction in concentration after an elapsed amount of time, for which eqs 1 and 2 were used:[1,23]

$$\mathrm{ECA} = V(k_{\mathrm{test}} - k_{\mathrm{control}}) \tag{1}$$

$$k = -\ln\left(\frac{C(t)}{C(0)}\right)\frac{1}{t} \tag{2}$$

where V (m^3) is the chamber volume, k (h^{-1}) is a first-order pathogen decay rate constant, and $C(0)$ and $C(t)$ represent initial airborne concentrations of viable pathogens at the start of an experiment and after an elapsed time, t (h), respectively; subscripts indicate whether the cleaner was in use or not during an experiment. This approach assumes strictly first-order decay and that the lone data point at time t is representative. Other studies reported k directly. Only eq 1 was used in those cases. However, biological inactivation by photochemical means often deviates from first-order kinetics,[24] so conventional first-order approaches for calculating ECA (e.g., fitting a log-linear curve to decay data[1]) may yield erroneous or biased results. Haratian et al.[25] developed an integral approach for obtaining a more accurate and generalizable steady state ECA metric:

$$\mathrm{ECA} = \frac{V(C_{\mathrm{test}}(0) - C_{\mathrm{test}}(t))}{\int_0^t C_{\mathrm{test}}\mathrm{d}t} - \frac{V(C_{\mathrm{control}}(0) - C_{\mathrm{control}}(t))}{\int_0^t C_{\mathrm{control}}\mathrm{d}t} \tag{3}$$

where integrals can be approximated numerically. When timeseries data was made available, we calculated ECA with eq 3. The raw data and ECA computation details for all experiments analyzed herein are provided in the Supporting Information.

2.2. Selection of Experimental Studies to Be Analyzed. For a study to be included for analysis, the

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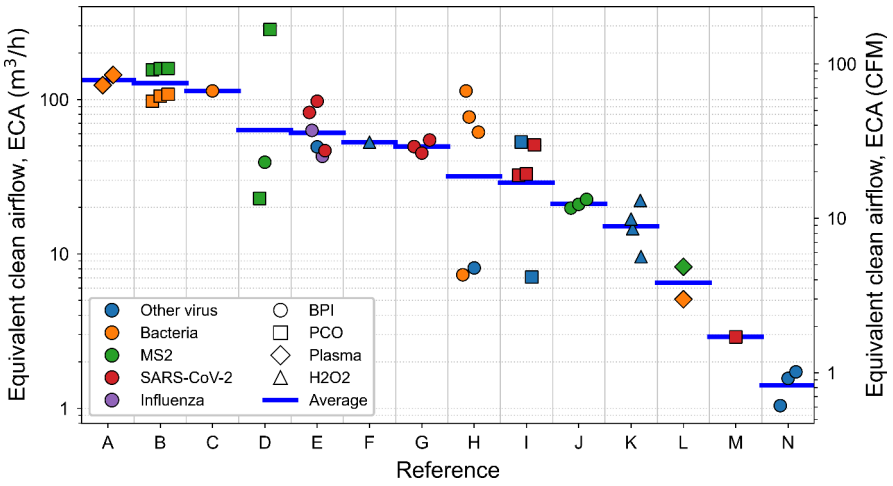

Figure 1. Electronic air cleaner ECA rates calculated for the 45 analyzed experiments. Results are grouped by study, sorted in descending order of its average ECA (marked by the blue horizontal lines). The tested airborne pathogen and device technology associated with each individual experiment is noted with the marker color and shape, respectively. Refer to Table 1 for study details and the Supporting Information for ECA calculation details.

following four criteria must have been met: (1) To isolate its effect, the device must rely *solely* on electronic air cleaning rather than as a supplement to filtration media; (2) Decay must be measured in a controlled environment (e.g., a laboratory chamber); (3) Airborne pathogens must be the target contaminant—not particulate matter (PM), volatile organic compounds (VOC), or surface pathogens; (4) The time elapsed and the experimental volume must be reported. Browsing manufacturer websites, pragmatic searches on Google and Google Scholar (with search terms including combinations of various air cleaner types, keywords for "pathogens", "viruses", and "bacteria", etc., and keywords like "air" or "airborne"), and tracing references in recent peer-reviewed articles were done to find usable studies.

Much of the peer-reviewed literature returned from online searches investigated underlying technology, such as photocatalytic substrates, rather than disinfection efficacy. Of the studies that did quantify disinfection, many measured surface disinfection rather than the inactivation of airborne pathogens. Some third-party laboratory reports are available from manufacturer websites directly, others are discoverable from online searches, but many remain difficult to access. Thus, only 14 studies,[8−21] summarized in Table 1, were found to be suitable for inclusion herein, providing 45 unique decay experiments for which ECAs were able to be computed. Most studies investigated BPI or PCO, two studied nonthermal plasma devices, and two injected H_2O_2 directly in lieu of analyzing a packaged air cleaner. Four studies used commercially available products and disclosed their manufacturers. The challenge pathogens encompassed various viruses and bacteria, with bacteriophage MS2 being the most common one in this data set, followed by SARS-CoV-2.

3. RESULTS AND DISCUSSION

3.1. Air Cleaning Efficacy. The calculated electronic air cleaner ECAs were highly variable, spanning about two orders of magnitude (Figure 1). Twenty-two percent of the calculated ECAs exceeded 100 m^3/h. One device's ECA was 283 m^3/h, but all others were <160 m^3/h. Another 22% of the calculated ECAs were below 10 m^3/h, but none were <1 m^3/h. Three studies produced average ECAs >100 m^3/h, with 134 m^3/h being the largest study-averaged ECA. Eight study-averaged ECAs were between 10 and 100 m^3/h, and three were between 1 and 10 m^3/h. (Because of the large variance, geometric means were used to compute subgroup averages.)

To contextualize these ECAs, even small, low-cost, off-the-shelf HEPA filter devices intended for personal use usually have CADRs >100 m^3/h.[26] Readily available HEPA filter devices sized for larger residential rooms have CADRs between 500 and 800 m^3/h.[26] (Note that manufacturer-rated CADRs have been shown to be in agreement with bioaerosol CADRs for HEPA filters.[27]) Meanwhile, custom-built box fan filters (i.e., "Corsi-Rosenthal" boxes) are capable of CADRs >1300 m^3/h.[28] The electronic air cleaners with the highest calculated ECAs herein are only as effective as small HEPA filter devices. Those on the bottom of our calculated distribution are about 1000 times less effective than good HEPA filter devices or Corsi-Rosenthal boxes.

Germicidal ultraviolet (GUV) irradiation, another possible supplement to ventilation and filtration, has been shown to be a highly effective indoor air disinfectant if appropriately specified, designed, and implemented.[29−35] One representative study measured ∼50 equivalent air changes per hour of disinfection from a single 222 nm GUV lamp in a 32 m^3 room.[33] If a high-performing additive device that provides 100 m^3/h of clean air were used in this room, 16 of them would be required to match GUV's performance.

3.2. ECA Variance. This data set was examined to explore whether device types or specific pathogens influence ECA. While the statistical significance of device- or pathogen-based patterns cannot be ascertained from visual inspection of the data alone, it appears that different studies often produce distinct ECA distributions. For example, Li et al.[8] (Study A) and Jangra et al.[19] (Study L) both tested a plasma device on *E. coli*, but their ECAs differed by a factor of 28. Similarly, Peel et al.[16] (Study I) and Matsuura et al.[20] (Study M) tested SARS-CoV-2 inactivation with a PCO device and yielded average ECAs that differ by a factor of 13.

To quantify how the reference study, underlying device technology, and pathogen each impacted ECA in this data, we fitted an ordinary least-squares model and conducted an ANOVA to compute each category's effect size, measured by

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Environ. Sci. Technol. Lett. XXXX, XXX, XXX−XXX

the partial ω^2 statistic.[36,37] The reference study had a large and highly significant effect ($\omega^2 = 0.72$, $p = 1.5 \times 10^{-8}$). Although the effect of the device technology is moderately significant, its magnitude is small ($\omega^2 = 0.059$, $p = 4.4 \times 10^{-3}$). Because this data is confounded, part of this effect may actually reflect study differences. The challenge pathogen did not have a statistically significant effect on ECA ($\omega^2 = 0.018$, $p = 0.12$). Interactions between devices and pathogens may exist but could not be well-assessed given the confounded nature of the data. Additional statistics and a discussion of the robustness of this analysis are provided in the Supporting Information.

Various factors may be behind the outsize effect of the reference study. Differences in equipment and experimental protocols or deviations from well-mixed conditions can affect decay tests in general. In the case of electronic air cleaners specifically, differences in the reactive species produced and their production rates may drive this effect. For example, the ECAs derived from Mohamadi et al.[18] more than doubled (from 9.6 to 22.2 m^3/h) when H_2O_2 concentrations increased from 1.6 to 16 ppm. Unfortunately, studies and product specifications rarely report the generation rates of the oxidants produced. It is possible that two studies that investigated the inactivation of the same pathogen by devices of the same type use particular devices with contrasting ion/ROS generation rates.

Ambient air conditions can also affect inactivation. It is thought that bipolar ionizers dissociate water vapor into H^+ and OH^-,[21,22] which may explain why Angel et al.[21] found ECA to rise by 70% (from 1.0 to 1.7 m^3/h, with a p-value of 0.018) when the relative humidity increased from ∼25% to ∼75%. Moreover, the presence of other gases may inhibit effectiveness. Many VOCs that are routinely emitted from cooking and cleaning,[38−40] furnishings and building materials,[41,42] personal care products,[43,44] and occupants[45−47] are known oxidant scavengers. It therefore follows that reported inactivation results would likely be higher for an experiment done in a pure nitrogen−oxygen mixture than in more typically polluted room air. In a real indoor setting, electronic air cleaner ECAs may degrade as a room fills with occupants who introduce oxidant scavengers into their air via their worn clothes, fragrances, and activities. Ironically, it is precisely in these crowded indoor conditions when pathogen inactivation is most desired. Using filtration media to remove airborne pathogens, on the other hand, provides more consistent performance across a diverse range of environmental conditions.

3.3. Byproducts and IAQ Impacts. Operating electronic air cleaners may degrade certain aspects of IAQ. The health effects of exposure to air ions remains unclear.[48] Unipolar ionization may cause an accumulation of electrical charges on indoor surfaces, leading to electrostatic discharge.[49] Certain exogenous ROS exposures have been identified as causing adverse health outcomes.[50,51] However, the chemical reactions between the generated oxidants and indoor VOCs that also diminish the device's disinfection potential are thought to be the primary mechanism by which electronic air cleaners likely worsen IAQ.[52] Manufacturers often claim that these reactions will fully mineralize VOCs, converting them into CO_2 and water vapor as a cobenefit to providing disinfection.[7,53−55] But the science of indoor VOC oxidation is well established.[40,56−58] While some degree of mineralization may occur, the production of more-oxidized VOCs and ultrafine PM has been documented as the functional outcome of using additive devices indoors.[59−63]

Additive cleaners are not the only interventions that chemically alter indoor air; 222 nm GUV is another such technology. Its use may produce ozone and other oxidants that affect indoor chemistry.[64−67] However, 222 nm GUV can provide very high rates of disinfection,[33−35] so more situations may exist where its benefits outweigh its risks than for additive electronic air cleaners.

3.4. Research and Industry Implications. These results build upon existing evidence that additive electronic air cleaners are not strongly efficacious indoor air disinfectants and their net public health effects remain unclear.[22,52,60,68,69] Additional study is nevertheless warranted to fill key knowledge gaps as the proliferation of these products continues. In-situ performance can be confirmed with additional field studies. Studying the generation rates of ions and ROS and the susceptibility of various pathogens to them can lead to standardized inactivation metrics that are less variable than ECA by normalizing for ion/ROS concentrations. Angel et al.[69] recently took a step in this direction by measuring the susceptibility of SARS-CoV-2 to bipolar ions to be 2.5×10^{-5} cm^3 $ions^{-1}$ h^{-1}, which corresponds to negligible air cleaning in a room with realistic dimensions and BPI-supplied ion concentrations. Better specifications can also facilitate the use of explicit chemical models, like INCHEM-Py and others,[70,71] to establish quantitative dynamic trade-offs between disinfection and byproduct generation in various environments.

Equivalent clean airflows computed from decay tests appeared to depend strongly on inherent yet unaccounted for study conditions. This phenomenon is not unique to electronic air cleaner experiments,[72] motivating a broad need for future decay tests to adhere to more unified methodological and reporting standards. Normative Appendix A in ASHRAE Standard 241 represents the first standardized testing procedure for obtaining an ECA for biological contaminants.[23] Although it only stipulates first-order kinetics, it represents a marked improvement compared to unstandardized experimental reduction metrics. It also requires testing for ozone, formaldehyde, and PM production and establishes required thresholds for compliance. Issued in 2025, ASTM D8625 is a standalone and rigorous test for chemical byproducts from air cleaners.[73] It requires that the chemical composition of the ambient air while testing occurs reflects typical indoor conditions. Future ECA test standards should have a similar provision when studying additive devices to ensure that laboratory-measured ECAs may be reasonably extrapolated to indoor environments. Also requiring the disclosure of the ROS and ions generated by additive cleaners and their production rates would be useful for indicating oxidative potential in addition to disinfection ability.

Certain electronic air cleaners may be well-suited for particular applications where mild disinfection or oxidation catalyzation is desired. However, for occupied spaces, other technologies are likely to be more effective and cost-effective and less likely to pose health risks derived from chemical byproducts. Media and sorbent filters effectively remove particulates (including bioaerosols) and VOCs, respectively.[26,74] Upper-room 254 nm GUV can provide high rates of disinfection[29−31] without appreciable byproduct risks.[64] While GUV technologies are longstanding,[29] continuous innovations are ongoing, like the development of whole-

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Environ. Sci. Technol. Lett. XXXX, XXX, XXX−XXX

room 222 nm GUV[32−35] and the study of its chemical byproducts.[64−67] Research and development resources may be better spent pursuing innovations in the aforementioned technologies. Owners, designers, and operators of occupied spaces should holistically consider ECA magnitudes, ECA consistency, and byproduct concerns when selecting and specifying supplemental air cleaning.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.5c01201.

Decay test raw data and ECA calculation details; Additional ANOVA details (PDF)

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Notes

The authors declare no competing financial interest.

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