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Journal
Aerosol Science and Technology, 56(6)

ISSN
0278-6826

Authors
Dal Porto, Rachael
Kunz, Monet N
Pistochini, Theresa
et al.

Publication Date
2022-06-03

DOI
10.1080/02786826.2022.2054674

Peer reviewed

Title: Characterizing the performance of a do-it-yourself (DIY) box fan air filter

Authors: Rachael Dal Porto[1], Monet N. Kunz[1], Theresa Pistochini[1,2], Richard L. Corsi[1,3], Christopher D. Cappa[1,*]

Affiliations:

[1] Dept. of Civil and Environmental Engineering, Univ. of California Davis; 1 Shields Ave., Davis, CA 95616 USA

[2] Western Cooling Efficiency Center, Univ. of California, Davis; 1 Shields Ave., Davis, CA 95616

[3] College of Engineering, Univ. of California Davis; 1 Shields Ave., Davis, CA 95616 USA

*Corresponding authors: cdcappa@ucdavis.edu

Abstract

Air filtration serves to reduce concentrations of particles in indoor environments. Most standalone, also referred to as portable or in-room, air filtration systems use HEPA filters, and cost generally scales with the clean air delivery rate. A "do-it-yourself" lower-cost alternative, known as the Corsi-Rosenthal Box, that uses MERV-13 filters coupled with a box fan has been recently proposed, but lacks systematic performance characterization. We have characterized the performance of a five-panel Corsi-Rosenthal air cleaner using both research-grade instrumentation (an aerodynamic particle sizer, APS) and a low-cost particle sensor. Measurements of size-resolved and overall decay rates of aerosol particles larger than 0.5 microns emitted into rooms of varying size with and without the air cleaner allowed for determination of the apparent clean air delivery rate—both as a function of size and integrated across particle sizes for a number-weighted median particle diameter of 1.2 ± 0.12 microns. The measurements made in the different rooms produced similar results, demonstrating the robustness of the method used. The size-integrated effective clean air delivery rate increases with fan speed, from about 600 to 850 ft^3 min^{-1} (1019 to 1444 m^3 h^{-1}) as determined with the APS. The low-cost sensor yields similar clean air delivery rates as the APS, demonstrating a method by which others who lack access to research-grade instruments can determine the effectiveness of Corsi-Rosenthal Boxes that use components that differ from those used here. Overall, our results demonstrate that our Corsi-Rosenthal air cleaner efficiently reduces suspended particle concentrations in indoor environments.

One Sentence Summary

A DIY air cleaner can effectively reduce aerosols in indoor spaces.

Short Title

Characterizing a DIY air filter

1 Introduction

Filtration is a robust and widely used method to reduce particle concentrations in indoor environments (Curtius, Granzin and Schrod 2021; Kelly and Fussell 2019; McNamara et al. 2017; MillerLeiden et al. 1996). Particle filters can be embedded in ventilation systems or added as stand-alone, portable units within rooms (Alavy and Siegel 2020; Shaughnessy and Sextro 2006). Filters vary widely in their efficiency and are characterized by the minimum efficiency reporting value (MERV), with the highest efficiency filters referred to as high efficiency particulate air (HEPA) filters (ASHRAE 2017). Filter efficiency varies with particle size, and HEPA filters remove at least 99.97% of particles having diameters of 0.3 microns, which is typically where the minimum filter efficiency occurs. While ventilation systems rarely use HEPA filters, owing to the accompanying large pressure drop and space requirements, most commercial in-room filtration systems rely on HEPA filters (Shaughnessy and Sextro 2006). Various studies support the benefits of portable HEPA-based air cleaners for reducing aerosol concentrations from many sources, including reducing risks of COVID-19 transmission. For example, Liu et al. (2021) reviewed portable HEPA-based air cleaners and concluded that such air cleaners have “potential to eliminate airborne SARS-CoV-2 and augment primary decontamination strategies such as ventilation.” Curtius, Granzin and Schrod (2021) reached similar conclusions based on measurements of aerosol concentration reductions in a classroom. Additionally, portable HEPA-based air cleaners have been shown to significantly reduce concentrations of traffic-related aerosol concentrations in homes close to highways (Cox et al. 2018), improve clinical manifestations for patients with allergic rhinitis by reducing particulate matter and dust mite allergen concentrations in bedroom air (Luo et al. 2021), and reduce woodsmoke particles in wood-burning communities with measurable health benefits in relatively young and healthy subjects (Allen et al. 2011).

The cost of HEPA-based air cleaners generally scales with their capacity, usually characterized by their clean air delivery rate (CADR) (Association of Home Appliance Manufacturers (AHAM)

2014). The CADR determines the number of equivalent air changes per hour (ACH) achievable in a room of a given size. For example, the typical floor size of a U.S. classroom is about 1,000 ft^2 (93 m^2) and with a volume of about 8,000 ft^3 (227 m^3). To achieve three ACH in a room this size, for example, requires a CADR of 400 ft^3 min^{-1} (680 m^3 h^{-1}). AHAM recommends that the CADR of an air filter is about two-thirds of the room floor area, corresponding to a CADR of 666 ft^3 min^{-1} for a 1,000 ft^2 classroom. In the context of airborne infectious disease transmission, the risk of long-range transmission continually decreases as the CADR increases (Shen et al. 2021). Limitations to in-room filtration include noise, energy consumption, and initial and maintenance costs for replacement filters. An initial cost-survey of commercially available Energy Star rated in-room filters (U.S.EPA 2021a) designed for the residential market found costs ranging from \$0.71 to \$2.66 per CADR in units of ft^3 min^{-1} (Pistochini 2021), making them inaccessible to many people and in many contexts.

A recently proposed, easy-to-construct, and low-cost alternative air filter constructed from MERV-13 filters and a box fan provides an opportunity for more people to access filter-based air cleaners in an affordable manner. This do-it-yourself (DIY) air filter, known as the "Corsi-Rosenthal Box" (hereafter, CR Box), is finding use in classrooms and other indoor environments across the U.S. through a grassroots movement driven by social media and the accessibility of the materials (Emanuel 2021). Although MERV-13 filters have a lower intrinsic filtration efficiency than HEPA filters, in-room air filtration using MERV-13 filters will still lead to a reduction in particle concentrations. While some work on airflow optimization in the CR Box has been done (Elfstrom 2021) and some initial characterization exists (Srikrishna 2021; Wieingartner, Rüggeberg and Wipf 2021), no systematic evaluation of the performance yet exists. Given the adoption of the CR Box in classrooms and other indoor environments, such evaluation is critical.

Here, we characterize the Corsi-Rosenthal Box performance via measurement of size-dependent particle decay for particles >0.5 microns in a classroom and a home office with and without the CR Box operating. Our method allows for determination of CADR values above the 450 ft^3 min^{-1} (765 m^3 h^{-1}) upper-limit of the standard method (Association of Home Appliance Manufacturers (AHAM) 2014). We make measurements using both research-grade instrumentation (i.e., an aerodynamic particle sizer) and using a low-cost sensor to illustrate how such measurements can be made by those who lack access to research-grade instrumentation. We compare the results for the CR Box to those measured for two commercial HEPA-based air cleaners in terms of overall efficacy and cost.

2 Materials and Methods

Here, we provide an overview of the methods used, with full details in the Supplementary Material. Decay rates of salt particles introduced to two rooms—a furnished but not occupied 5926 ft^3 (168 m^3) classroom and a 1277 ft^3 (36.2 m^3) furnished but not occupied home office—were measured with and without the filter-based air cleaners turned on (**Figure S1**). The salt particles were generated using a portable mesh nebulizer (Wellue) using an aqueous table salt solution (100 g/L). A box fan oriented at the wall operated at low speed throughout the measurements to maintain similar turbulence and mixing conditions between experiments. The measurements with this mixing fan on but the filter-based air cleaners turned off provides the baseline ventilation plus particle deposition rate, as these are the primary loss pathways for particles in a room. The measurements with the filter-based air cleaners turned on additionally include the influence of the filter. The equivalent air changes per hour (*ACH*) (actual air exchange + particle deposition to indoor surfaces + particle removal by an air cleaner) for each experiment were determined by fitting an exponential decay curve to the time-varying particle concentration ($C_{p,t}$) during the decay period with a y-offset that corresponds to the background particle concentration ($C_{p,bgd}$):

$$C_{p,t} = C_{p,bgd} + C_{p,t=0} \cdot \exp\left[-\frac{t}{\tau}\right] = C_{p,bgd} + C_{p,t=0} \cdot \exp[-ACH \cdot t] \quad (1)$$

where t is the time in hours, τ is the decay lifetime in hours, and $C_{p,t=0}$ is the concentration at the start of the decay period. Here, we consider both the particle number concentration (p cm^{-3}) and volume concentration (μm^{-3} cm^{-3}) for the C_p values, although focus on the number concentration measurements.

When the filter-based air cleaners are turned on there is additional turbulence induced by the air filter fan that could alter the baseline deposition rate above that with the mixing fan alone. To assess the influence of this added turbulence we conducted experiments using two fans, the mixing fan and an additional box fan set in the location of the air filter. These experiments indicated that the additional turbulence from the air filter fan increased the baseline natural ventilation rate by 17 ± 11% in the home office but only 3% ± 3% in the classroom (**Figure S2**). The difference results from the classroom having active ventilation and a substantially higher baseline *ACH* compared to the home office**Error! Reference source not found.**.

The *ACH* from filtration (*F*), ventilation (*V*), and deposition (*D*) add in series. Therefore, the equivalent *ACH* attributable to only the filter-based air cleaners (ACH_F) is simply the difference between the value measured with the air filter on (ACH_{F+V+D}) and the baseline *ACH* from room ventilation and particle deposition (ACH_{V+D}):

$$ACH_F = ACH_{F+V+D} - ACH_{V+D} \qquad (2)$$

The ACH_{V+D} values used in Eqn. 2 are taken as the values measured with the air filter off and the mixing fan operating, but adjusted upwards by 17% or 3% to account for additional turbulence from the air filter fan. Eqn. 2 can be used to determine the weighted-average equivalent ACH_F across all particle sizes (by fitting to the particle number or mass concentration) or for specific size ranges. The corresponding CADR is:

$$CADR = V_R \cdot ACH_F \qquad (3)$$

where V_R is the room volume. We use ACH_{X,N_p} and $CADR_{N_p}$ when referring to the value determined from the particle number concentration and ACH_{X,V_p} and $CADR_{V_p}$ when determined from the volume concentration, and where *X* corresponds to *F*, *V*, or *D* (or combinations thereof).

Particle concentrations and decay rates were measured at 5 s time resolution using an aerodynamic particle sizer (APS; TSI model 3321) and a low-cost sensor (LCS; Plantower PMS 5003). The APS characterizes particles into bins from 0.5-20 microns diameter according to their aerodynamic diameters (D_{pa}) and thus allows for determination of size-specific *ACH* values. Size-specific values are only considered up to D_{pa} = 5.425 μm as above this value the decays are too noisy to allow for robust fitting, owing to the very low concentrations of particles above this size. The APS yields both number and volume concentrations.. Note that, unless otherwise stated, results are reported based on the APS measurements. The LCS converts light scattering observations to report size-dependent particle mass and particle number concentrations using an unknown algorithm with a nominal lower diameter limit of 0.3 microns. The reported number concentrations observed here exhibit linear decays (after natural log transformation), as expected, whereas the mass concentrations from the LCS exhibit distinctly non-linear decays. We therefore consider only the number concentration data from the LCS and discourage the use of the reported mass concentrations in this context.

Three filter-based air cleaners were tested: the Corsi-Rosenthal Box and two commercial HEPA-based air cleaners. The Corsi-Rosenthal Box was originally proposed by Richard Corsi on Twitter and with Jim Rosenthal making the first prototype (Rosenthal 2020). The CR Box used here is constructed using three 20" x 20" x 2" and two 16" x 20" x 2" MERV-13 filters (Air Handler, LEED/Green Pleated Air Filter, total cost $34.75) and a 20" box fan (Air King Model 4CH71G, $23.68). (See **Figure S3** and the Supplemental Material for a full description and discussion of cost). The CR Box here sits on legs that hold it about 4" (10 cm) off the ground and with the fan pointed upwards or sideways. In one variation, we tested the CR Box inverted such that the fan pointed at the floor, sitting about 4" (10 cm) off the floor. An inverted CR Box would potentially be more robust against potential foreign objects being dropped into the fan. One of the HEPA-based air cleaners (HEPA #1) has a stated tobacco smoke CADR = 300 ft^3 min^{-1} (510 m^3 h^{-1}) when operated at maximum speed while the other (HEPA #2) has a stated tobacco smoke CADR = 141 ft^3 min^{-1} (240 m^3 h^{-1}) when operated at maximum speed.

The loudness of the filter-based air cleaners and of the box fan alone were measured using a decibel monitor (Extech Instruments HD600) that was situated 5 ft (1.52 m) from the center of the filter-based air cleaners and located perpendicular to the air exhaust. The power use by the filter-based air cleaners was measured using a power logger (Fluke 1735 Power Logger Analyst). The pressure drop for the CR Box was measured using a high-resolution pressure gauge (DG-700, TEC). Estimates of the fan airflow rate alone and as part of the CR box were estimated from air flow velocity measurements (see *Supplemental Material*).

3 Results and Discussion

Average particle size distributions are shown in **Figure 1a** for three periods: when particles were being actively produced, near the end of the natural decay, and near the end of the air filtration period. The number-weighted median particle aerodynamic diameter ($D_{pa,Np}$), as characterized by the aerodynamic particle sizer, averaged 1.2 ± 0.12 μm. The volume-weighted median particle aerodynamic diameter ($D_{pa,Vp}$) averaged 2.8 ± 0.5 μm. Both the $D_{pa,Np}$ and $D_{pa,Vp}$ generally decreased over the course of an experiment, with the $D_{pa,Np}$ starting at ~1.4 μm and decaying during both the natural decay period and, to a lesser extent, during the period when the filter-based air cleaners were turned on (**Figure 1b**). Technically, the *CADR* is defined relative to the size range for various particle types, specifically smoke (0.09-1 μm), dust (0.5-3 μm), and pollen (0.5-11 μm), and is measured in a sealed chamber of specific size (1008 ft^3). The size-dependent *CADR* values measured here overlap with all three particle types.

Example number-based particle decays from the APS measurements for the natural room ventilation and with the various air cleaners on are shown in **Figure 2**. The ACH_{V+D} was 3.5 ± 0.2 hr^{-1} (1σ, precision-based uncertainty) for the unoccupied classroom and the ACH_{V+D} was 1.3 ± 0.1 h^{-1} for the unoccupied home office. **Figure 3** shows the resulting clean air delivery rates for air cleaners that were tested in both the classroom and home office, along with values for noise level and power draw (discussed further below). (Individual graphs for each parameter are provided in **Figure S5**.) Replicate *CADR* values for each air filter exhibited only small variations within each room and across the two rooms, although were generally larger for the measurements made in the classroom. The difference between the *ACH* values with and without the filter on was greater for the smaller home office (**Table 1**). Further, individual ACH_{V+D} values were determined for every air filter measurement in the home office but not the classroom (see Methods). Therefore, we take the *CADR* values determined from the home office as generally more reliable and, unless otherwise stated, use them in the discussion that follows.

Generally, the $CADR_{Vp} > CADR_{Np}$ with the exception of HEPA #2 (**Table 1**). The larger value for the $CADR_{Vp}$ results from the volume distribution being characterized by a larger median diameter compared to the number distribution and the filtration efficiency for MERV-13 filters increasing with size for particles in the APS measurement range (>0.5 microns). For HEPA #1 the $CADR_{Np}$ = 322 ± 44 ft^3 min^{-1} (547 ± 75 m^3 h^{-1}) for the classroom and 285 ± 2 ft^3 min^{-1} (484 ± 3.4 m^3 h^{-1}) for the home office, both in very good agreement with the manufacturer's specification of 300 ft^3 min^{-1} (510 m^3 h^{-1}). For HEPA #2 the $CADR_{Np}$ = 113 ± 24 ft^3 min^{-1} (192 ± 41 m^3 h^{-1}) for the classroom and $CADR_{Np}$ = 129 ± 8 ft^3 min^{-1} (219 ± 14 m^3 h^{-1}) for the home office, also in very good agreement with the manufacturer's specification of 141 ft^3 min^{-1} (240 m^3 h^{-1}). The good agreement between the measured $CADR_{Np}$ and the manufacturer's specifications provides a validation of the method.

The $CADR_{Np}$ for the Corsi-Rosenthal Box increases reasonably linearly with fan speed (**Figure S4**), from 600 ± 27 ft^3 min^{-1} (1020 ± 46 m^3 h^{-1}) at low speed to 779 ± 32 ft^3 min^{-1} (1324 ±

54 m^3 h^{-1}) at medium speed to 852 ± 50 ft^3 min^{-1} (1450 ± 85 m^3 h^{-1}) at high speed, as measured for the home office, and from 615 ± 36 ft^3 min^{-1} (1045 ± 61 m^3 h^{-1}) to 823 ft^3 min^{-1} (1400 m^3 h^{-1}) for the classroom. A linear fit with zero intercept to the $CADR_{\mathrm{Np}}$ for the home office versus the fan total airflow rate estimates for the box fan at the three speeds indicates an effective filter efficiency of 41-58%, with the range indicating uncertainty in the CR Box airflow rates (see Supplementary Material; **Figure S4**). The air velocity measurements with the filters added indicated a 12% reduction in flow with a pressure drop (Δp) of 6.2 Pa at low speed. Accounting for this flow reduction increases the effective filter efficiency to 47-67%. The corresponding pressure drop at medium speed equaled 7.7 Pa and at high speed equaled 8.5 Pa. The $CADR_{\mathrm{Np}}$ also varies linearly with the Δp (**Figure S4**). The CADR increases by a greater amount going from low to medium speed than it does going from medium to high. Such behavior is consistent with the response of both the airflow rate and Δp to changing the fan speed.

The size-dependent efficiency curves for the Air Handler MERV 13 filters indicates a minimum filtration efficiency (η_f) of ~55% for 0.35 micron diameter particles (D_p), which increases to ~85% for 0.75 micron diameter particles and to ~90% for 1 micron dimeter particles (Air Handler via Grainger: 2022). Multiplying the observed particle size distribution by 1 - $\eta_f(D_p)$ and comparing with the original particle size distribution indicates an expected size-averaged filtration efficiency of about 87% by number and 93% by mass, larger than observed. This difference may result from a much lower air velocity across the five parallel filters in this study (<148 ft min^{-1} = 1.07 m s^{-1}) relative to those typically used for HVAC filter testing to determine MERV ratings (492 ft min^{-1} = 2.5 m s^{-1}) (ASHRAE 2017). For MERV-13 filters, inertial impaction and interception are the dominant loss mechanisms for the size range of particles considered here (Flagan 1988). For these mechanisms, the single-fiber collection efficiency for fibers in a filter bed increases with the Stokes number, and therefore face velocity, and depends on the particle-to-fiber diameter ratio and fiber packing density. The Stokes number for a 1 micron diameter particle having a density of 1 g cm^{-1} encountering a 5 micron diameter fiber, fairly typical of modern filters (Kowalski and Bahnfelth 2002; Kowalski, Bahnfelth and Whittam 1999), at a face velocity of 492 ft min^{-1} (2.5 m s^{-1}) equals 3.58, which is in the range over which the single-fiber filtration efficiency is particularly sensitive to changes in velocity (Flagan 1988). As such, a lower face velocity should mean lower removal efficiency due to the lessened effect of inertial impaction and interception.

Alternatively, the reduced filtration efficiency measured in the experiment could also be attributed to leaks around the filter media, although the filter assembly was taped and visually inspected to seal any openings and thus we suspect that leaks play a minor role.

Size-dependent *ACH* and *CADR* values are determined by fitting decay curves to each particle size bin from the APS. The *ACH* for the natural room decay periods increase substantially with particle size (**Figure 4a**), likely due to higher particle deposition rates to indoor materials at larger aerodynamic diameters (Hussein and Kulmala 2008). The *ACH* for the filter-based air cleaners also increase with particle size, but to a lesser extent than the natural room decay (**Figure 4a**). Consequently, the *CADR* for the filter-based air cleaners, which derive from the difference between the filter on and natural room decay *ACH* values, exhibit a weaker dependence on particle size compared to the *ACH* (**Figure 4b**). The *CADR* for the CR Box vary only weakly with particle size for all speeds and are relatively constant from about 0.7 to 2.5 microns (**Figure 4b**). This weak size dependence helps explain why the $CADR_{\mathrm{Vp}}$ values are only slightly larger than the $CADR_{\mathrm{Np}}$ values. However, such a weak size dependence is somewhat unexpected given the MERV-13 filter efficiency should increase sharply above 700 nm to about 1 micron, above which it should be constant and near unity. It is possible that the low face velocities on the filters relative to standard test conditions (ASHRAE 2017) led to atypical size dependence. Alternatively, additional turbulence from the filter exhaust air could have altered the particle deposition rates in the room from the baseline measurements leading to a flatter than expected size dependence, although the measurements with the added fan in place of the CR box suggest this had negligible influence. Notably, comparison of the size-specific *CADR* for particles with $D_{\mathrm{p,a}} > 1$ μm to the specified fan speeds indicates an η_f much less than unity, even after accounting for the 12% reduction in flow owing to filter resistance. The reason for this apparent lower than expected η_f for the CR Box is unclear.

The CADR values for the Corsi-Rosenthal Box substantially exceed those of the particular commercial HEPA-based air cleaners used here (**Figure 3a**). For further comparison, no U.S. Energy Star certified air cleaners have CADR values (for either tobacco smoke, dust, or pollen) matching the CADR value for the CR Box even on low speed (**Figure S6**). Consideration of the cost-per-unit-air-cleaned for the low-speed CR Box (<\$0.072/(ft^3 min^{-1})) and for the two HEPA-based air cleaners (>\$0.7/(ft^3 min^{-1})) demonstrates that the DIY air filter is approximately onetenth the initial cost of a commercially available HEPA-based air cleaners per unit of air cleaned (**Figure 3**).

The CR Box loudness varied from 58 dB (low speed) to 67 dB (high speed) (**Figure 3**; **Table 1**). The low speed loudness is similar to that measured for HEPA #1 (59 dB) but higher than that for HEPA #2 (54 dB). For reference, a modern refrigerator has a noise rating of about 50 dB and a LEED certified vacuum must be <70 dB. To attain a CADR equivalent to the CR Box on low speed would require about two HEPA #1 units and 4 HEPA #2 units, which would yield 62 dB and 60 dB, respectively. The power draw for the CR Box varied from 67 W (low speed) to 98 W (high speed) and was 89 W for HEPA #1 and 43 W for HEPA #2, corresponding to 8.9 and 8.7 ft^3 $min^{-1}.W^{-1}$ (15.1 and 14.8 m^3 $h^{-1}.W^{-1}$) for the CR Box and 3.2 and 3.0 ft^3 $min^{-1}.W^{-1}$ (5.4 and 5.1 m^3 $h^{-1}.W^{-1}$) for the HEPA-based air cleaners. For comparison, the most efficient category of U.S. Energy Star certified portable air cleaners must have an efficiency equal or greater than 2.9 ft^3 $min^{-1}.W^{-1}$ (4.9 m^3 $h^{-1}.W^{-1}$, meaning the CR Box is three times more efficient than the Energy Star standard (U.S.EPA 2021b).

The *CADR* values for the inverted CR Box were all suppressed relative to the standard CR Box orientation (with the fan pointed upwards; **Table S1**). For example, in the inverted orientation the $CADR_{Np}$ = 481 ft^3 min^{-1} (817 m^3 h^{-1}) on the low setting, compared to ~600 ft^3 min^{-1} (1019 m^3 h^{-1}) in the standard orientation. This difference likely resulted from one or both of (i) short circuiting of the airflow wherein clean air exhausted by the fan is preferentially entrained into CR Box filters rather than being dispersed into the broader room, or (ii) increased shear forces that resuspended particles previously deposited on the floor and increase particle number concentrations in air. Therefore, we suggest that orienting a CR Box (or likely any air filter) such that the fan exhaust is towards the floor be avoided.

In addition to the measurements with the APS, we also characterized the CADR for the various air cleaners using a low-cost sensor. Such low-cost sensors are much more accessible to the public than research grade instrumentation, such as an APS. The CADR measurements made with the low-cost sensor yield generally similar results to those made with the APS (**Figure S7**), with the $CADR_{Np}$ increasing with fan speed for the CR Box and with values for the HEPA-based air cleaners similar to the manufacturer's specification. However, the specific $CADR_{Np}$ depended on which reported particle size regime was used for the fitting. Such a result is somewhat surprising given that the low-cost sensor is not fundamentally a particle counting measurement, but instead derives particle number from the measured light scattering. The root-mean square difference between the low-cost sensor and APS $CADR_{\mathrm{Np}}$ values was smallest for the $N_{\mathrm{p},>1.0}$ bin (72 ft^3 min^{-1}), marginally larger for the $N_{\mathrm{p},>0.5}$ (76 ft^3 min^{-1}) and $N_{\mathrm{p},>0.3}$ (78 ft^3 min^{-1}) bins, and substantially larger for the $N_{\mathrm{p},>2.5}$ (161 ft^3 min^{-1}) and $N_{\mathrm{p},>5.0}$ (220 ft^3 min^{-1}) bins. Without further knowledge of the algorithm behind the low-cost sensor data processing we cannot establish the origin of this apparent size dependence or why the $N_{\mathrm{p},>1.0}$ bin yields the most similar values. Nonetheless, our results suggest that the use of low-cost sensors can yield a reasonable measure of the relative *CADR* values between filter-based air cleaners and a reasonable estimate of the absolute *CADR* values, and thus a means by which those without access to expensive instrumentation can determine the efficacy of DIY filter-based air cleaners. This is particularly important as different combinations of fans and filters (e.g., filter size or MERV rating) may yield results that differ from those presented here. We note that preliminary results for a CR Box using the same filters but a different fan (Lasko, Model B20301) indicate a lower range of *CADR* values than reported here for the CR Box with the Air King fan.

4 Summary

We have measured the filtration efficiency for particles >0.5 microns of a DIY, open-source air filtration system, the Corsi-Rosenthal Box, comprised of a box fan and MERV-13 filters. At the lowest speed the clean air delivery rate for our Corsi-Rosenthal Box is >600 ft^3 min^{-1} (1019 m^3 h^{-1}) for a median particle diameter of 1.2 microns, demonstrating exceptional performance relative to most commercially available filter-based air cleaners. The CADR increases with fan speed, with the highest value about 850 ft^3 min^{-1} (1444 m^3 h^{-1}) for these particle sizes. However, the filter noise level also increases with fan speed, from 58 dB at low speed to 67 dB at high speed. The CR Box is cost efficient, with a cost-normalized CADR of <\$0.072/(ft^3 min^{-1}). We also demonstrate good agreement between results obtained using research-grade instrumentation and a low-cost sensor, which provides a methodology by which others can characterize the performance of other DIY air filtration systems. Future efforts to improve and characterize the CR Box might focus on decreasing the CR Box noise level without compromising filtration performance, characterizing the effectiveness for smaller particle sizes, or characterizing different CR Box designs that use different fans and filters or different numbers of filters, which may yield results that differ from those shown here.

5 Acknowledgements

The authors greatly appreciate the contributions from students in ECI/ATM 149 at UC Davis, who performed some preliminary experiments as part of a lab activity. Jim Rosenthal is thanked for constructing and promoting the first Corsi-Rosenthal box. **Author contributions:**.RDP, MNK, TP, and CDC made measurements; RDP and CDC analyzed data; all authors interpreted results; RC designed the DIY air filter; CDC and RDP led the writing with contributions from all authors. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the supplementary materials.

6 Funding

N/A

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8 Tables

Table 1: Measured equivalent air changes per hour and clean air delivery rates.

Air Filter	ACH_{F+V+D} # (h^{-1})	$CADR_{Np}$ * ($ft^3\ min^{-1}$)	ACH_{F+V+D} # (h^{-1})	$CADR_{Np}$ * ($ft^3\ min^{-1}$)	$CADR_{Vp}$ * ($ft^3\ min^{-1}$)	Noise level (dB)	Power Draw (W)	$ per CADR
	Classroom			***Home office***				
None	3.5	--	1.3 ± 0.14	--		40		
CR Box (low)	9.8±0.4	614±36	29.6 ± 1.5	599 ± 27	614 ± 26	58 ± 2	67	0.11
CR Box (med)	11.4	780^	38.0 ± 0.1	780 ± 32	824 ± 32	63 ± 2	84	0.08
CR Box (high)	11.9	823^	41.5 ± 1.7	852 ± 50	903 ± 49	67 ± 1	98	0.08
HEPA #1	6.8±0.4	323±44	15.4 ± 0.5	285 ± 2	300 ± 2	59 ± 1	89	0.86
HEPA #2	4.7±0.3	114±24	7.9 ± 0.2	129 ± 8	118 ± 3	54 ± 1	43	0.74

#Based on number concentration measurement; not adjusted for additional turbulence

*Calculated from individual pairs of ACH_{V+D} and adjusted ACH_{F+V+D} and so may not match with the CADR determined from the average ACH_{F+V+D}

^Only one measurement was made

9 Figures & Captions

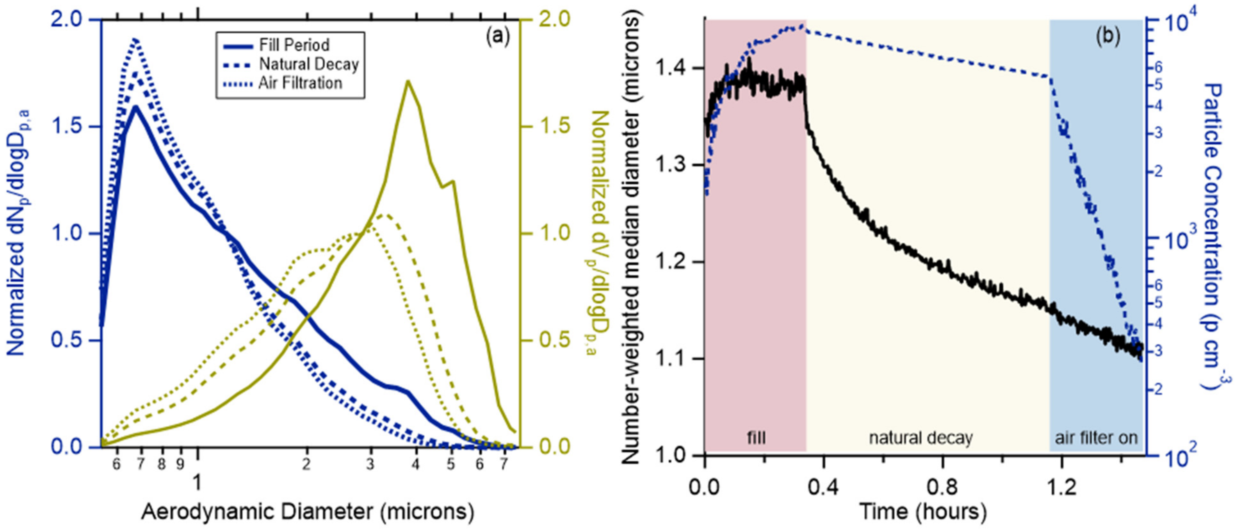

Figure 1. (a) Example number-weighted (left axis, blue) and volume weighted (right axis, gold) particle size distributions measured with the APS and shown for averages during the fill period with active particle production (solid line) period, near the end of the natural decay period (dashed line), and near the end of the active air filtration period (dotted line) for the home office. Number-weighted distributions are normalized to a diameter of 1.2 microns and volume weighted to 2.8 microns, corresponding to the number-weighted and volume-weighted median diameters, respectively. (b) Example results for one experiment in the home office showing the number-weighted median diameter (black solid line) and the particle number concentration (blue dashed line) across the fill period, natural decay period, and active air filtration period.

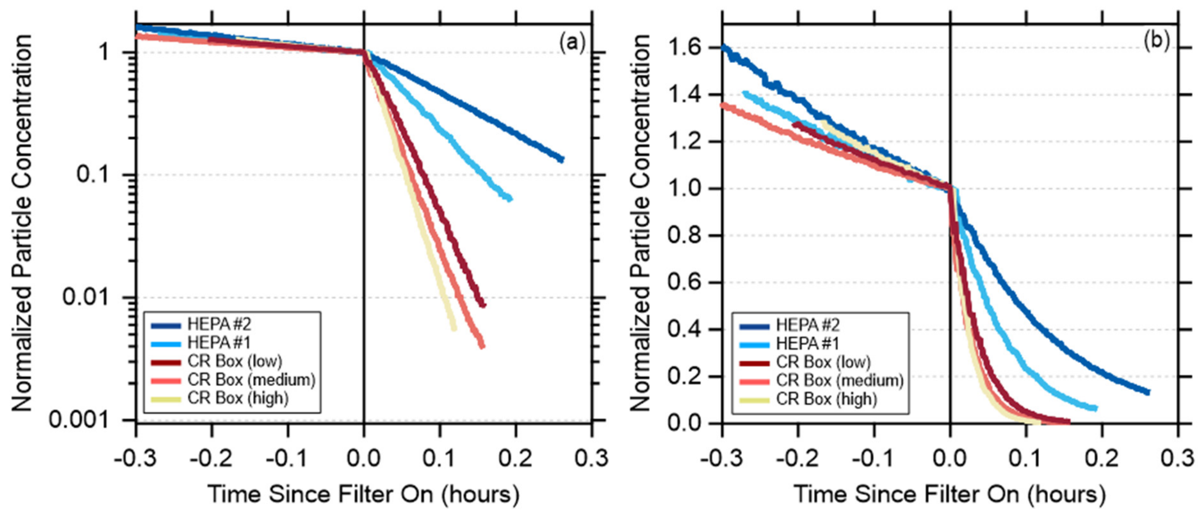

Figure 2. Example particle number decays measured in the home office for the natural ventilation + particle deposition (at $t < 0$) and with the filter-based air cleaners on ($t > 0$) shown on a (a) log scale and (b) linear scale. Particle concentrations have been normalized to unity at $t = 0$.

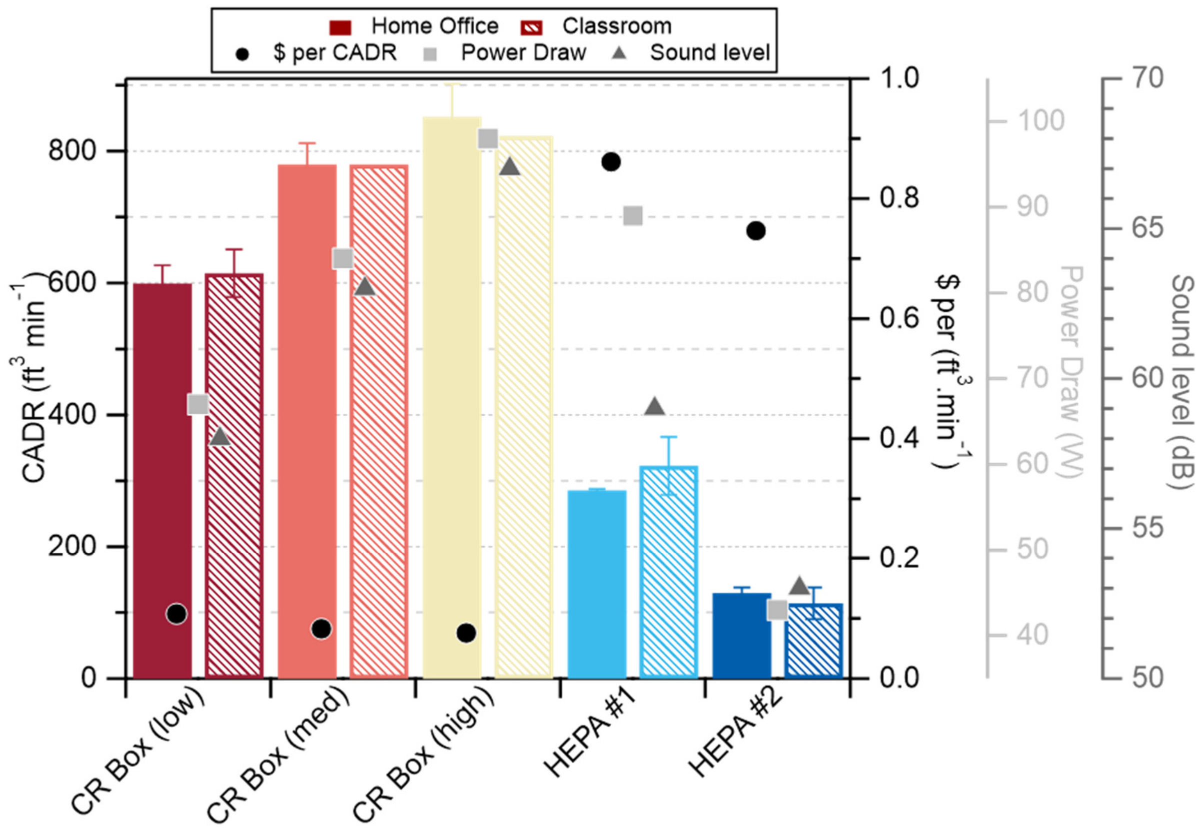

Figure 3. (left axis) The number-weighted clean air delivery rate for the various filter-based air cleaners (left axis, bars) as measured in the home office (left hash marks) and classroom (right hash marks) . (right axis) The price normalized CADR (black circles), sound level (dark gray triangles), and power (light gray squares).

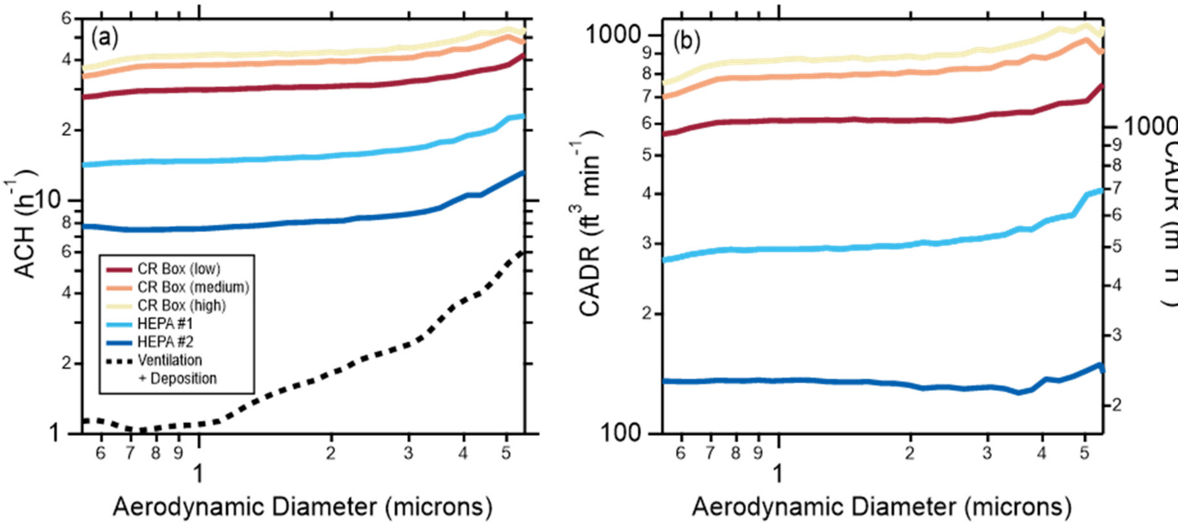

Figure 4. (a) Size-dependent equivalent air changes per hour with the various filter-based air cleaners operating (solid lines) and for the natural room ventilation + particle deposition alone (dashed line), as measured in the home office. (b) The corresponding clean air delivery rates for the various filter-based air cleaners. Results for the classroom are similar (not shown).

Supplemental Materials for: Characterizing the performance of a DIY air filter

Authors: Rachael Dal Porto[1], Monet N. Kunz[1], Theresa Pistochini[1,2], Richard L. Corsi[1,3], Christopher D. Cappa[1,*]

Affiliations:

[1] Dept. of Civil and Environmental Engineering, Univ. of California Davis; 1 Shields Ave., Davis, CA 95616 USA

[2] Western Cooling Efficiency Center, Univ. of California, Davis; 1 Shields Ave., Davis, CA 95616

[3] College of Engineering, Univ. of California Davis; 1 Shields Ave., Davis, CA 95616 USA

*Corresponding authors: cdcappa@ucdavis.edu

The supplemental materials contains:

- A fuller description of the materials and methods
- Tables S1-S2
- Figures S1-S6

Materials and Methods

Particle Generation and Measurement

Our overall approach to determining equivalent air changes per hour, either with or without added air filtration, generally follows from the measurement of decay rates of particles introduced into rooms at concentrations well above background. Particles were generated using portable mesh nebulizers (Wellue®) filled with an aqueous solution of table salt (100 g L^{-1}). The nebulizers were operated on their maximum setting (0.9 ml min^{-1}) and up to two were used per room. A representative particle size distribution is shown in Figure 1**Error! Reference source not found.**. A box fan was turned on its low setting and positioned about 0.5 m from one wall of the room, pointing at the wall, to induce mixing in the room, ideally leading to a reasonably well-mixed condition throughout the room.

Although a similar approach was taken for measurements made in the classroom and the home office, the experimental details differed slightly. For the classroom, experiments began with measurement of the background particle concentration with all doors to the room closed. Following the background measurement the nebulizer was turned on with the filter-based air cleaners turned off. The nebulizer automatically shut off after ~10 minutes at which point the filter-based air cleaners were turned on. Particle measurements continued for an additional ~30 minutes during which the particle decay was measured. The first experiment was conducted with the CR Box turned off to determine the baseline effective room air exchange rate owing to the ventilation or natural infiltration or particle deposition to surfaces. Subsequent experiments had the CR Box turned on to either the low, medium, or high setting or the HEPA filters turned on to their highest setting. For the classroom, two replicate measurements were made for each of the HEPA filters and for the CR Box on low speed, but only one measurement each was made for the CR box at medium and high speed. For the home office the protocol differed slightly. Specifically, following the background particle measurement and subsequent particle generation the decay from natural ventilation/infiltration plus deposition was measured for ~20 minutes. At this point the air filter of interest was turned on and the decay with the air filter on was measured for ~15 minutes. This allowed for determination of a unique baseline air changes per hour for every filter measurement resulting from passive or active ventilation and particle deposition to surfaces. For the CR Box three replicate measurements at each speed were made, while only two replicates were made for the commercial HEPA filters in the home office.

The air exchange rate was determined by fitting an exponential decay curve to the particle concentration (C_{p}) with a y-offset corresponding to the background concentration ($C_{\mathrm{p,bgd}}$) period starting approximately one minute after the nebulizer stopped, where:

$$C_{p,t} = C_{p,bgd} + C_{p,t=0} \cdot \exp\left[-\frac{t}{\tau}\right] = C_{p,bgd} + C_{p,t=0} \cdot \exp[-ACH \cdot t] \qquad \text{(S1)}$$

where t is the time in hours, τ is the decay lifetime, and $C_{\mathrm{p,t=0}}$ is the particle concentration at the start of the decay period. The value for $C_{\mathrm{p,t=0}}$ depends on the particle source rate relative to the overall air exchange rate. The particle background concentration depends on the particle concentration in the exchanged air from outside the room and in-room sources besides the nebulizer. In our experiments, the background particle concentrations were sufficiently small that we could assume $C_{\mathrm{p,bgd}} = 0$ as opposed to a free-fit with the derived *ACH* values differing by less than 1%. The *ACH* attributable to only the CR Box (ACH_{F}) is simply the difference between the value measured with the CR Box on and the baseline *ACH* from room ventilation and particle deposition (that is, with the filter off, $ACH_{\mathrm{V+D}}$), as these add in series.

$$ACH_F = ACH_{F+V+D} - ACH_{V+D} \qquad \text{(S2)}$$

The robustness of the fits from Eqn. 1 were verified via linear fitting to the natural log transformed and background-subtracted particle concentration data. Eqn. 1 can be used to determine the weighted-average ACH_F across all particle sizes (by fitting to the particle number or mass concentration) or for specific size ranges. The corresponding CADR is:

$$CADR = V_R \cdot ACH_F \tag{3}$$

where V_R is the room volume, and with appropriate unit conversion. We use $ACH_{X,Np}$ and $CADR_{Np}$ when referring to the value determined from the particle number concentration and $ACH_{X,Mp}$ and $CADR_{Mp}$ when determined from the mass concentration, and where X corresponds to V+D (natural room ventilation and deposition only), F (filter only), or F+V+D (filter + natural room ventilation + deposition).

The influence of additional turbulence induced by the fan in the CR Box on particle deposition to surfaces was also assessed for the classroom and the home office. In both, a single fan, oriented towards a wall, was first turned on similar to the filtration experiments above. The nebulizer was then started and particles were produced for about 10 minutes and the concentration of particles in the room increased. Once the nebulizer stopped the particle concentration in the room was allowed to decay for 10-20 minutes with just the single fan operating. Then, a second fan with no filters attached was started and the particle decay was measured for an additional 20-30 minutes. This second fan was placed in the same position and with the same orientation as the fan in the CR Box. Example decays are shown in Figure S2.

Particle concentrations and decay rates were measured using two independent methods. An aerodynamic particle sizer (APS; TSI model 3321) characterized particles having aerodynamic diameters from 0.5-20 microns with 5-second time resolution. The APS characterizes particles into bins according to their aerodynamic diameters (D_{pa}) and thus allows for determination of size-specific ACH values. Size-specific values are only considered up to D_{pa} = 5.425 μm as above this value the decays are too noisy to allow for robust fitting. The APS is a well-established research-grade instrument for the characterization of particle concentrations and size distributions. As such, we use the measurements made with the APS for the main analysis in the main text.

A low-cost Plantower sensor (PMS 5003) characterized particles having optical diameters above about 0.3 microns with 5-second time resolution. Particle concentrations from the Plantower sensor were logged to an SD card using an Arduino METRO microcontroller with a Hi-LetGo data logging shield.[1] Temperature and relative humidity measurements measured using an Si7021 sensor (Adafruit) were also logged. The Plantower sensor converts and reports observations of scattering to size-dependent particle mass and particle number using an algorithm that is unknown. Also unknown is the relationship between particle number and mass concentration. The reported number concentrations observed here exhibit linear decays (after natural log transformation) whereas the mass concentrations exhibit distinctly non-linear decays. The reason for this is unclear, as one would expect that the number concentration and mass concentrations are related through a simple linear transformation for this type of instrument. Regardless of reason, since the number concentration measurements exhibit a linear decay, similar to the APS, we consider only the number concentration data from the Plantower sensor.

Filter-based Air Cleaners

Three filter-based air cleaners were tested: the Corsi-Rosenthal Box and two commercial HEPA filters.

The Corsi-Rosenthal Box

The Corsi-Rosenthal Box was originally proposed by Rich Corsi on Twitter and with Jim Rosenthal making the first prototype (Rosenthal 2020). The CR Box used here is constructed using three 20" x 20" x 2" and two 16" x 20" x 2" MERV-13 filters (Air Handler, LEED/Green Pleated Air Filter, total cost $34.75) and a 20" box fan (Air King Model 4CH71G (9723), $23.68). The assembled Corsi-Rosenthal Box is shown in Figure S3. We note that the cost of the filters here was about half that from many vendors, possible owing to purchasing agreements between UC Davis and specific vendors. In a non-comprehensive internet search conducted on 21 November 2021 we found that the average price for a MERV-13 20" x 20" x 2" filter averaged $13.19 ± $2.22 and for a 16" x 20" x 2" filter averaged $15.39 ± $3.96, corresponding to a total cost of $70.36.

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[1] For those who have interest in constructing their own low-cost sensor using a plantower sensor, there are a variety of resources available on the internet to get started. We also provide some basic documentation and code, as used in the ECI 149 class at UC Davis, that can be downloaded from https://ucdavis.box.com/s/pswqa1hr62ed4vvbzxmxw0ua39u3rr3f. Per the terms of the code from which we have borrowed, "the software is provided "as is", without warranty of any kind, express or implied, including but not limited to the warranties of merchantability, fitness for a particular purpose and noninfringement. In no event shall the authors or copyright holders be liable for any claim, damages or other liability, whether in an action of contract, tort or otherwise, arising from, out of or in connection with the software or the use or other dealings in the software."

Similarly, the particular Air King fan used here retails for about twice our purchase price when not on sale. Two of the 16" x 20" and two of the 20" x 20" filters are used to construct the side walls that sit on the 20" x 20" filter. The box fan is attached to the top and the seams are sealed with duct tape ($6). The box fan is oriented such that the fan blows out of the constructed filter box. This creates a slight negative pressure that may help to seal the box and limit leaks, although any persistent leaks from e.g., holes in the filters or the tape would be independent of the flow direction. The box fan includes a ~circular "shroud" that covers the box fan corners and prevents backflow of unfiltered air into the fan. (The use of a shroud was proposed for square box fans by David Elfstrom on Twitter (Elfstrom 2021).) Here the diameter of the open shroud is 17". The CR Box sits on legs that hold it about 4" (10 cm) off the ground and with the fan pointed upwards or sideways. In one variation, we tested the CR Box inverted such that the fan pointed at the floor, sitting about 4" (10 cm) off the floor. An inverted CR Box would potentially be more robust against potential foreign objects being dropped into the fan.

Commercial HEPA filters

Two commercial HEPA filters were tested. One (HEPA #1) has a stated tobacco smoke CADR = 300 ft^3 min^{-1} (508 m^3 h^{-1}) when operated at maximum speed and includes two prefilters to capture larger particles and reduce volatile organic compounds, and a HEPA filter. It retails for about $250. The other (HEPA #2) has a stated tobacco smoke CADR = 141 ft^3 min^{-1} (240 m^3 h^{-1}) when operated at maximum speed, includes an activated carbon prefilter, and a noise level of 50 dB as specified by the manufacturer. It retails for about $100.

Measurement Environment

Measurements were made initially in three environments: (i) a 5926 ft^3 (167.8 m^3) classroom in Ghausi Hall at UC Davis; (ii) a 2890 ft^3 (81.8 m^3) office/meeting space in Ghausi Hall; and (iii) a 1277 ft^3 (36.2 m^3) home office in a residential building dating to 1923. For the home office the HVAC system was kept off throughout the measurements and thus the natural decay depended only on infiltration/exfiltration rates and particle deposition. Ultimately, only two of these environments were considered (the classroom and the home office) because the ventilation rates were sufficiently constant. In the office/meeting space the ventilation rate reduced when the occupancy sensors detected no movement for 15 minutes and shut off airflow after an additional 15 minutes of no movement. The ventilation rate in this room was too variable to allow for robust determination of the filter-specific *ACH* values. The smaller size of the home office compared to the classroom led to a greater difference in the *ACH* values measured with an air filter on versus with it off.

Fan Speed & Measurement

The fan has a manufacturer specified air flowrate of 1463, 1900, and 2163 ft^3 min^{-1} (2486, 3228, 3675 m^3 h^{-1}) for low, medium, and high settings, respectively, tested under AMCA 230-99, which tends to overestimate fan speeds by 30% (Taber and Ivanovich 2018), although it is questionable how well this applies to box fans as the AMCA 230-99 method was developed for ceiling fans. Regardless, a 30% reduction corresponds to reduced air flowrates of 1024, 1330, and 1514 ft^3 min^{-1} (1740, 2260, 2572 m^3 h^{-1}). The face velocities on the five filters (area ~ 10.25 ft^2 or 0.95 m^2) are 143, 185, and 211 ft min^{-1} (0.75, 0.94, 1.07 m s^{-1}) using the manufacturer's values and 100, 130, and 148 ft min^{-1} (0.51, 0.66, 0.75 m s^{-1}) using the reduced values. However, taping the corners of the box fans can also lead to an increase in the air flow rate through the filters as it reduces the potential for back flow.

To assess these estimates, we measured the air velocity in feet per minute using a Veloci Calc Model 9555-P. Measurements were made at six radial positions approximately equidistant from each other, starting at the center of the fan, moving to the outer edge. These six positions were measured at the mid-point of each edge of the fan. Measurements were first taken with the fan as purchased, with no modifications, at both high and low speeds. Then, the corners of the fan were taped, and a measurement at low speed was taken with no filters and with 5 filters in the Corsi-Rosenthal Box configuration. The face velocity was integrated over the 24 measurements and their distance from the center. Average face velocities for the unaltered fan at high speed were 880 ft min^{-1} (268 m min^{-1}), 650 ft min^{-1} (198 m min^{-1}) for the unaltered fan on low speed, 668 ft min^{-1} (204 m min^{-1}) for the fan on low speed with taped edges, and 578 ft min^{-1} (176 m min^{-1}) for the Corsi-Rosenthal on low speed. Multiplying by the fan area but without accounting for the area taken up by the fan protective grate, these equate to air flowrates of 1800 ft^3 min^{-1} (3058 m^3 h^{-1}) for the high velocity fan with no modifications, 1331 ft^3 min^{-1} (2261 m^3 h^{-1}) for the low setting with no modifications, 1361 ft^3 min^{-1} (2312 m^3 h^{-1}) for the low setting with the fan edges taped, and 1171 ft^3 min^{-1} (1990 m^3 h^{-1}) for the low speed in CR configuration. Accounting for the protective grate area would increase these slightly. These values for the unadulterated fan are in between the reported and reduced manufacturers' specified values, but within the likely uncertainties. The fan flow rate in the CR Box configuration with the fan edges taped is reduced by only 12% from the unaltered fan.

Loudness & Current Measurement

The loudness of the filter-based air cleaners was measured using a decibel monitor that was situated 5 ft (= 1.52 m) from the center of the filter-based air cleaners and located perpendicular to the air exhaust. The background room noise level was 40 dB. Measurements were also made for the box fan separate from the filters. The power draw by the filter-based air cleaners were measured using a Fluke power meter. Because dB is a logarithmic scale, noise levels (L) must be added after log transformation as:

$$L = 10 \cdot \log\left(\sum_{i=1}^{n} 10^{\frac{L_i}{10}}\right)$$

Supplementary Tables

Table S1: Measured clean air delivery rates (ft^3 min^{-1}) for the Corsi-Rosenthal Box in the inverted orientation

Air Filter	$\boldsymbol{CADR_{Np}}$ (ft^3 min^{-1})	$\boldsymbol{CADR_{Mp}}$ (ft^3 min^{-1})
CR Box (low)	481	489
CR Box (med)	728	763
CR Box (high)	809	854

Supplementary Figures

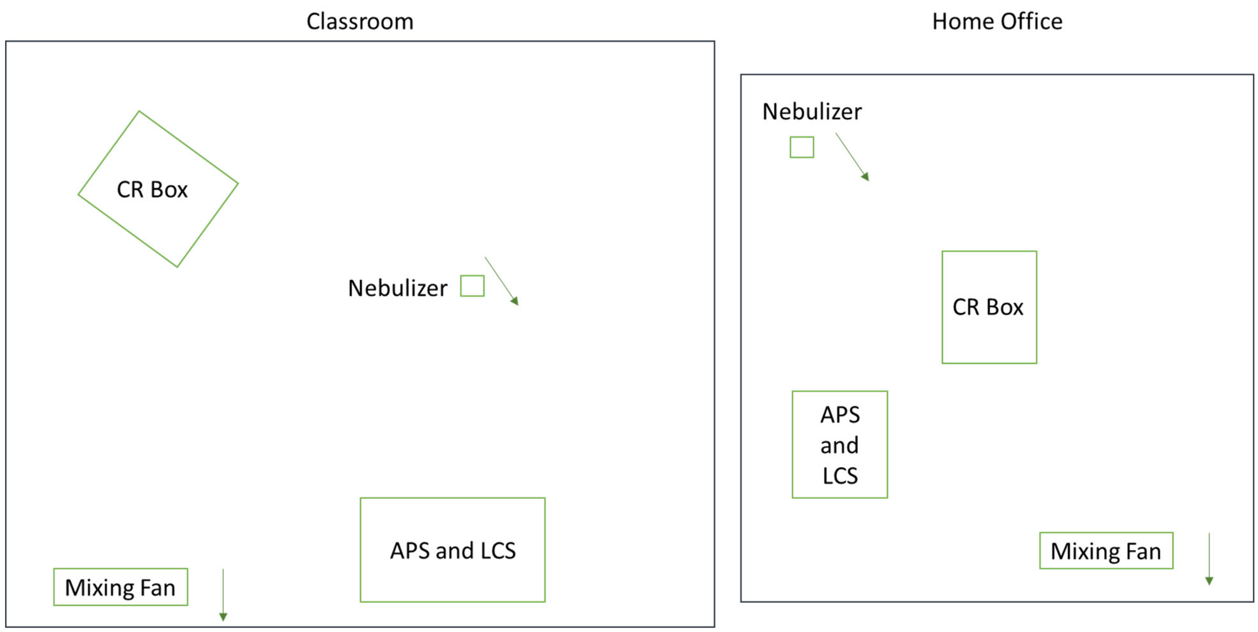

Figure S1. Overview experimental schematic for the setups in the (left) classroom and (right) home office showing the positions of the instrumentation, mixing fan, nebulizer, and filter-based air cleaners.

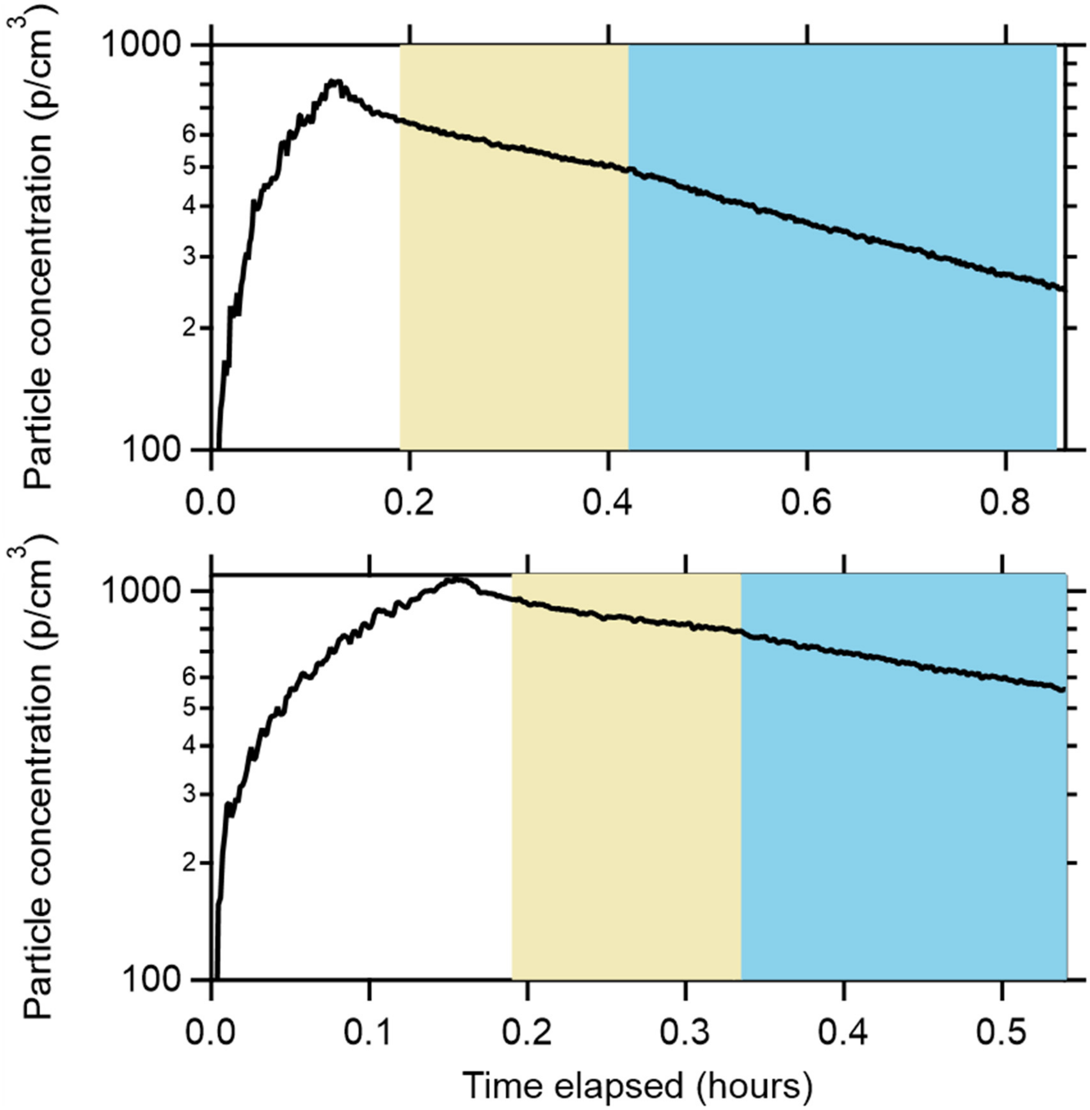

Figure S2. Particle decay with one fan (yellow) and with two fans (blue) for the home office (top) and classroom (bottom).

Figure S3. A photo of the assembled Corsi-Rosenthal Box.

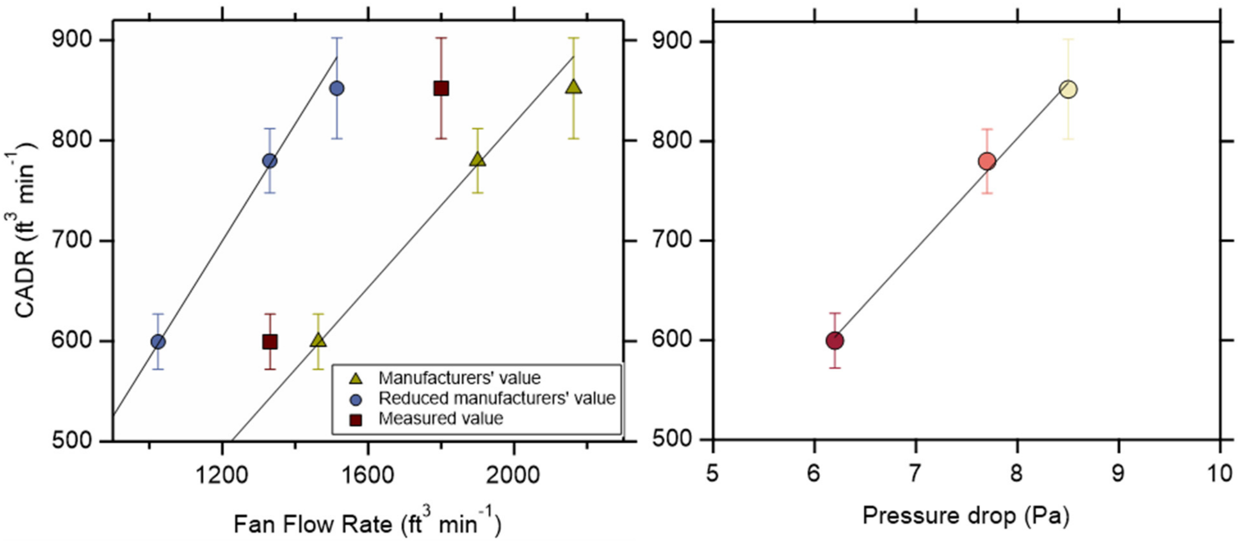

Figure S4. (left) Relationship between CADR for the Corsi-Rosenthal Box and the manufacturer reported (yellow triangles), the reduced manufacturer reported (blue circles), and air-velocity-estimated (red squares) air flow rates for the original box fan. The lines are linear fits forced through zero (slopes = 0.41, 0.58, and 0.47, respectively). (right) Relationship between CADR for the Corsi-Rosenthal Box and the measured pressure drop at low, medium, and high fan speeds.

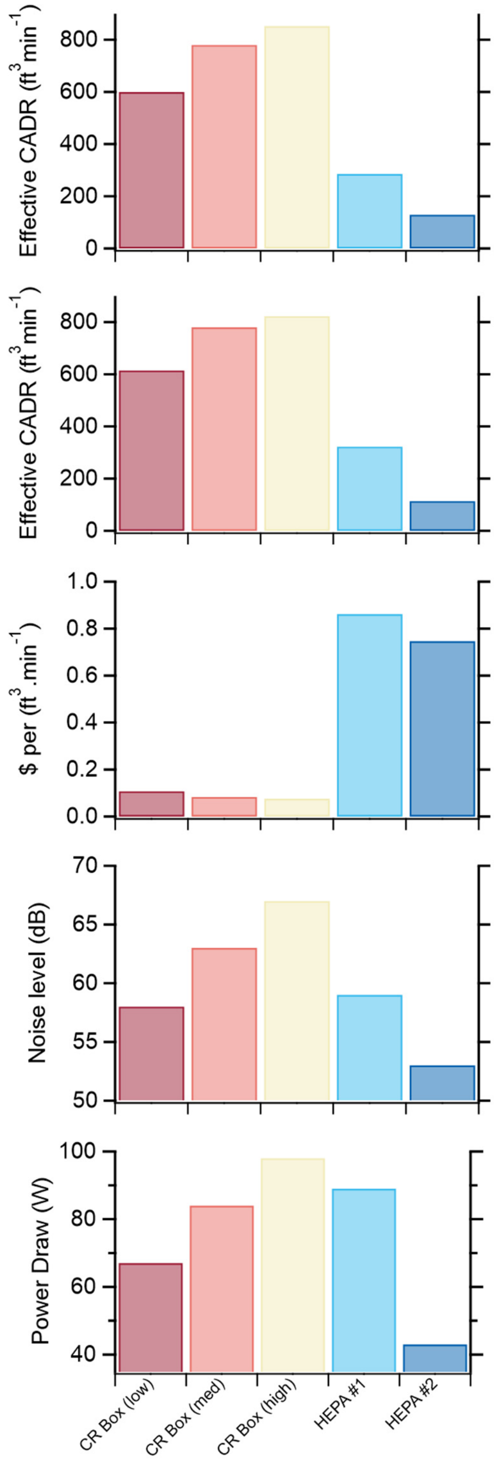

Figure S5. Results from **Figure 3**, shown as individual graphs rather than all together. Shown are (top to bottom) the effective CADR values determined in the home office and the classroom, the cost per effective CADR, the noise level, and the power draw.

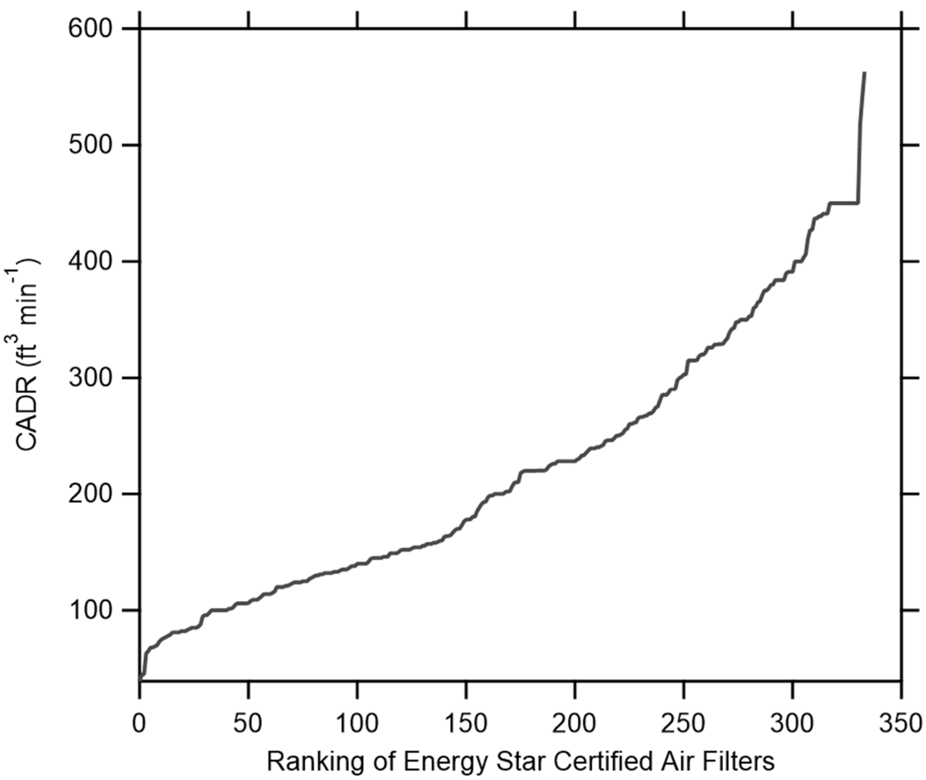

Figure S6. The distribution of maximum CADR values for commercially available filter-based air cleaners in the Energy Star database. These can be compared with the Corsi-Rosenthal Box.

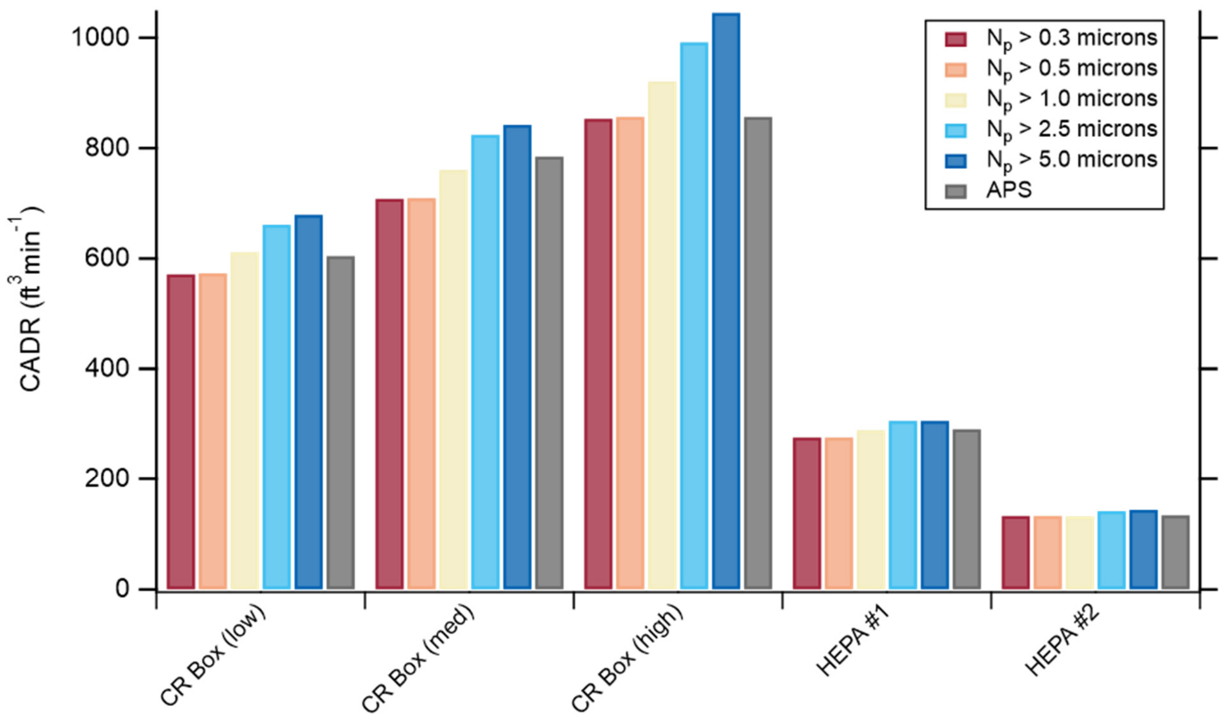

Figure S7. Comparison of the CADR values determined using the different apparent size bin number concentrations from the low-cost sensor (colors) compared to the $CADR_{\mathrm{Np}}$ determined from the APS. Measurements are from the home office.