



Evaluating DIY air cleaner variability and potential for post-construction emission of aromatic VOCs during wildfire events



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ABSTRACT

While do-it-yourself (DIY) air cleaners such as the Corsi-Rosenthal Box (CR Box) are an increasingly popular choice for low-cost, accessible air cleaning during a wildfire event, construction and performance variability remains a concern. Using the same set of instructions, materials, and location of assembly, seven CR Boxes are constructed by individuals with no prior DIY air cleaner experience and clean air delivery rates (CADRs) are experimentally determined for each of the devices. Against a challenge aerosol consisting of fresh smoke generated via pine needle combustion, average number-based, $PM_{2.5}$ CR Box CADRs range from 313–396 m^3/h (relative standard deviation = 7.6%). Over this modest range of observed variability, constructed units outperform many higher-cost commercial air cleaners. A review of the literature demonstrates that across studies, substantial CADR variability is observed (285–1448 m^3/h); differences in materials (including filter type) used during air cleaner construction, challenge aerosols tested, and evaluation protocol are major contributors to variability. To evaluate the potential for exposure to aromatic volatile organic compounds (VOCs) from CR Box materials, we place three devices in a large chamber for 24–72 hours immediately following construction. Toluene and C8 aromatics (ethylbenzene and xylenes) are emitted at 2289 and 89 $\mu g/h$, respectively, with emission rates decreasing by 94% and 82% after 12 hours. Using experimentally determined $PM_{2.5}$ CADRs and VOC emission rates, a hypothetical wildfire event impacting the bedroom of a home is modeled at four outdoor air exchange rates (AERs) to assess tradeoffs between building airtightness, particle removal effectiveness, and VOC off-gassing from a newly built CR Box. $PM_{2.5}$ effectiveness ranges from 0.88 to 0.95, depending on AER (0.1–1 h^{-1}). While modeled maximum VOC concentrations remain orders of magnitude below short-term permissible exposure limits at all AERs considered, modeled and observed VOC dynamics imply that an off-gassing period of ~6–12 hours would avoid episodic emission of VOCs at rates that may cause accumulation in excess of the lower-limit of toluene odor threshold estimates.

1. Introduction

In recent years, the western United States has experienced increasingly frequent and severe wildfires due to warm and dry weather conditions [1–4]. Wildfires elevate outdoor air pollutants such as fine particulate matter ($PM_{2.5}$) to concentrations that can adversely impact human health, exacerbating the risk of respiratory disease [5–8], cardiovascular complications [9,10], and all-cause mortality [11–14]. Though public health officials typically recommend sheltering inside with doors and windows sealed during a wildfire event [15], outdoor air infiltrates into all buildings [16,17]. While staying indoors may offer some protection from wildfire smoke exposure (due to removal mechanisms such as penetrative [18] and deposition losses [19]), portable

air cleaners (PACs)—which have been proven to meaningfully reduce wildfire-related $PM_{2.5}$ concentrations indoors [20–22]—are generally necessary to achieve substantial reductions of indoor $PM_{2.5}$ compared to outdoor levels. However, implementation of wildfire mitigation measures is associated with income level [23], and cleaning systems may be in short supply during wildfire emergencies [24]. Such accessibility issues have contributed to the increased popularity of do-it-yourself (DIY) air cleaning solutions.

The Corsi-Rosenthal Box (CR Box) [25]—which is comprised of four (or in some configurations, five) MERV 13 furnace filters, a cardboard base, and a cardboard shroud, all affixed to a box fan with duct tape—is one such DIY configuration that has gained popularity in recent years. Like many common commercial PACs, the CR Box relies upon a fan to

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move air through a fibrous or mechanical filter [26]. The MERV 13 filters and base are arranged to form a cube around the inlet side of the box fan; along with the cardboard shroud affixed to its outlet side, this large surface area of particle filter facilitates high air flowrates and low pressure drops. The few studies of this design in the literature demonstrate that high clean air delivery rates (CADRs) can be realized; note that CADR is a common metric used to define the volume of clean air provided by an air cleaner [27–29]. While other DIY air cleaner designs have emerged in recent years—most notably designs that are similar in concept, but use 1 or 2 MERV-13 filters affixed to a box fan or computer fans—the CR Box is among the most ubiquitous, due to its relatively low cost and ease of assembly.

Though governmental organizations such as the United States Center for Disease Control and Prevention (CDC) have acknowledged, made assembly instructions available, and experimentally verified the effectiveness of the CR Box, construction and performance variability remains a concern. In a 2023 blog post addressing DIY air filtration, the CDC stated that “there are no standards for constructing DIY units, which has led to several variations in designs that can significantly influence their effectiveness” and that “potential problems with construction quality such as leaks and gaps could substantially affect the performance of DIY air filtration units” [24]. Additionally, assembling a CR Box typically necessitates the use of fresh HVAC furnace filters and large quantities of plastic adhesive tape; both the former [30–32] and latter [33] have been found to emit volatile organic compounds (VOCs). While exposure to VOCs at high concentrations is associated with adverse health impacts in humans [34–36], to our knowledge, there has been no comprehensive assessment of exposure levels and persistence due to off-gassing during and immediately following DIY air cleaner construction.

This work evaluates the variability inherent in the construction and performance of DIY air cleaners by tasking a group of seven subjects, all unfamiliar with DIY air cleaning, to build CR Boxes using the same instructions, materials, and location of assembly. The devices were placed in an environmentally controlled chamber and VOC emission rates were measured, after which CADR testing was employed to compare each build’s ability to remove PM_{2.5} when challenged with simulated wildfire smoke emissions. While DIY air cleaners are an effective and accessible alternative to commercial PACs during a wildfire event, this study aims to characterize the impact of variability in assembly procedure during their construction (which to our knowledge, has not been previously quantified), as well as address the potential for exposure to VOCs emitted from newly-constructed CR Boxes.

2. Materials and methods

2.1. Materials/build description

Seven college-aged students, all part of a selective, multidisciplinary climate and aerosol research summer cohort, were tasked with building a CR Box using a one-page instruction sheet (Figure A.1) [37]; participants confirmed that they had no prior experience building DIY air cleaners. All sessions took place in a small university conference room and began with the same short oral presentation describing the practical applications of CR Boxes. While participants were asked to follow the given instructions, they were permitted to use outside resources as needed, as the goal was to simulate a comfortable, real-world scenario, comparable to one they might experience assembling a DIY air cleaner at home. Each participant was provided with a 0.5 × 0.5 m box fan (Air King, Model 9723), four new MERV 13 filters (0.5 × 0.5 × 0.05 m, Tex-Air), two 0.5 × 0.5 m cardboard squares, scissors, a box cutter, pencil, tape measure, cutting surface, and roll of duct tape (Lockport, 2.3 × 0.05 m); to account for the amount of the duct tape used during assembly, the roll’s mass was recorded before and after each build. Build time was recorded using a stopwatch by the experimenter. As a point of comparison, an eighth session was carried out under the same

conditions, where the study’s head experimenter—who was present at all prior sessions and had experience building DIY air cleaners—constructed a “control” CR Box that followed instructions explicitly. Figure A.2 in Appendix A.1 presents images of the control device.

A point system was developed to quantify the number of qualitative mistakes made by each participant, weighted to account for the impact the mistake may have had upon device performance. Mistakes recorded included: a) leaving unsealed gaps in the cube of filters (1 point), b) leaving openings on the sides of the box fan uncovered (1 point), c) arranging filters backwards or sideways, rather than in the direction of airflow recommended by the manufacturer (1 point for four filters and 0.5 points for two filters arranged incorrectly), d) orienting the filters to form a rectangle, rather than a cube (1 point), and e) cutting the cardboard shroud opening at the incorrect diameter (1 point for diameters > 43.2 or < 35.6 cm).

2.2. Testing chamber and instrumentation

All experiments were conducted in an insulated, 3.6 × 2.4 × 2.6 m stainless steel chamber (with an interior volume of 17.8 m³), outfitted with supply and exhaust fans (TD-150S, Soler & Palau, USA) to ventilate the chamber at the conclusion of each experiment. To facilitate air mixing, two 2.2 m tall stands were placed on opposite sides of the chamber with three 0.12 × 0.12 m axial fans (MEC0251V3-000 U-A99, Sunon Fans) affixed to each, approximately 0.89 m apart and facing in different directions. Multi-point CO₂ tests confirmed well-mixed conditions; CO₂ concentrations throughout the chamber varied < 10 %. During both CADR and VOC off-gassing experiments, air cleaners were placed atop a wire rack against the rear-center wall of the chamber, ~1 m from its floor. When the CR Box was engaged during CADR testing, outlet air flowed toward the chamber ceiling where a supply register was located. While the register was closed during testing, CR Box operation caused a small increase in the chamber’s air exchange rate (AER) compared to when the CR Box was off; air exchange was therefore systematically accounted for. Appendix A.2 provides a detailed description of the testing chamber and Fig. 1a presents a 3D model of its interior and exterior.

For CADR testing, PM_{2.5} concentrations were monitored with an optical particle sizer (TSI, Model 3330), which measured particles with diameters from 0.3 to 10 µm in 16 adjustable size bins, and a condensation particle counter (TSI, PTrak Model 8525), which measured particles with diameters from 0.02 to 1 µm; both instruments recorded in one second intervals. PM_{2.5} concentrations were calculated as the sum of particles (#/cm³) from 0.02–2.5 µm, with overlapping measurements in the 0.3–1 µm diameter range removed from the optical particle sizer’s dataset. To measure VOC concentrations during off-gassing experiments, on-line VOC sampling was conducted via proton transfer reaction – time of flight – mass spectrometry instrumentation (PTR-ToF-MS, Ionicon Analytik GmbH, Innsbruck, Austria, PTR1000); the principle of the PTR-ToF-MS has been well described in the literature [38–40]. The instrument’s inlet was connected to a switching valve system that sampled from the testing chamber and laboratory in five-minute intervals, recording measurements each minute. PTR-ToF-MS operating condition, calibration, and data processing details are provided in Appendix A.2.

Eleven VOCs for which calibration factors were experimentally determined were putatively identified and selected for emission rate analysis: methanol, acetonitrile, acetaldehyde, acrylonitrile, acetone, isoprene, benzene, toluene, ethylbenzene, xylenes, naphthalene, and monoterpenes. BTEX compounds (benzene, toluene, ethylbenzene, and xylenes) were chosen for further analysis and presentation here due to their prevalence in wildfire smoke emissions [41,42], the adverse health effects associated with prolonged exposure to them [43,44], and the relative strength of their emission rates during testing. Note that because the PTR-ToF-MS was unable to differentiate between constitutional isomers, ethylbenzene and xylenes were grouped together as

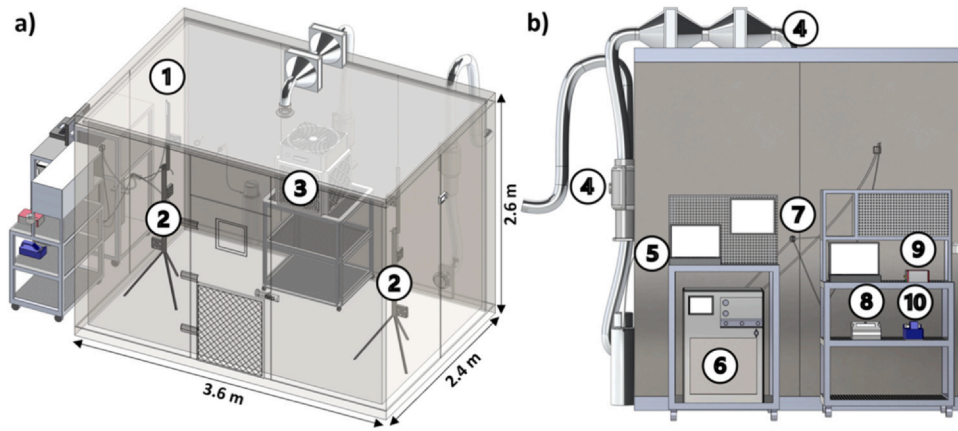


Fig. 1. 3D model of testing chamber at a) isometric and b) left side views. Numeric icons correspond to chamber features and instrumentation: 1) temperature and relative humidity sensor, 2) mixing fans, 3) CR Box, 4) ventilation system, 5) injection ports, 6) PTR-ToF-MS, 7) sampling line port, 8) optical particle sizer, 9) CO₂ monitor, and 10) condensation particle counter.

C8 aromatics.

To account for air exchange and environmental conditions within and around the chamber, a CO₂ monitor (Licor LI-820) and temperature and relative humidity sensor (HygroVUE 10, Campbell Scientific) measured continuously throughout both CADR and VOC off-gassing experiments. Fig. 1b presents a 3D model of the chamber that emphasizes relevant instrumentation.

CR Box sound and power draw levels were recorded immediately after construction using a noise metering application (Decibel X, iPhone) and portable power wattage meter (Watts Up? PRO, Model 99333), respectively. Air cleaners were challenged with smoke generated by the combustion of 0.25 g of pine needles sourced locally from Portland, Oregon, U.S.A., burned via a food smoking gun (Breville, Model BSM600SIL).

2.3. Experimental procedure

Prior to each triplicate CADR experiment, the moisture content of the pine needles was calculated as the difference in mass of a subsample of pine needles pre- and post-oven drying [45]. The “pull-down” method [46,47] was employed inside of the chamber to evaluate CADRs. Briefly, background particulate matter and CO₂ concentrations were measured for five minutes outside and ten minutes inside of the chamber. The challenge aerosol and CO₂ were then injected simultaneously for five seconds and allowed to decay for thirty minutes; this period was used to account for air exchange and PM_{2.5} losses to the chamber while the air cleaner was off. After exhausting the chamber until PM_{2.5} and CO₂ concentrations had returned to background levels, the CR Box was engaged at its highest fan speed setting and the injection and decay process was repeated. With the air cleaner operational, PM_{2.5} concentrations returned to steady-state levels in approximately ten minutes, after which concentrations were recorded for an additional ten minutes.

Three of the eight devices that underwent CADR testing were also evaluated for VOC emissions. Prior to these off-gassing experiments, background VOC and CO₂ concentrations were recorded inside and outside of the chamber. Twenty minutes after CR boxes were constructed, they were placed inside of the sealed chamber and CO₂ was injected. Measurements for two of the devices were collected across 24-hour periods and a third device was allowed to off-gas for 72 hours. Note that triplicate, 24-hour experiments were conducted without an air cleaner present to account for VOC emissions from the chamber itself; baseline emission rates were subtracted from CR Box emission rates.

Sound levels were averaged over thirty seconds in a quiet university office at a distance of 0.91 m. Power draw was recorded once the reading on the portable wattage meter became stable for a minimum of ten seconds.

2.4. Analysis of air cleaner testing data

Using Eq. 1, a linear regression was performed for portions of the experiment where the air cleaner was non-operational, and again when it was operational, in order to determine total loss rates ($\lambda + \beta$) as the regression coefficient. The chamber’s AER (λ), determined using a similar regression method with CO₂ concentrations, was subtracted from this value to arrive at PM_{2.5} loss rate constants:

$$-\ln \frac{C_{i,t} - C_{bg}}{C_{i,t=0} - C_{bg}} = (\lambda + \beta)t \quad (1)$$

where $C_{i,t}$ is the PM_{2.5} or CO₂ concentration at time t (#/cm³ or ppm), $C_{i,t=0}$ is the PM_{2.5} or CO₂ concentration at time $t=0$ (#/cm³ or ppm), C_{bg} is the average steady-state, background PM_{2.5} or CO₂ concentration (#/cm³ or ppm), λ is the chamber’s AER (h⁻¹), β is the chamber’s PM_{2.5} loss rate (h⁻¹), and t is time (seconds).

For PM_{2.5}, the C_{bg} term present in Eq. 1 was determined by averaging steady-state concentrations inside of the chamber. For periods when the air cleaner was off, this averaging occurred just before injection, while for periods when the air cleaner was on, averaging occurred once particle concentrations returned to steady-state levels. For CO₂, the C_{bg} term present in Eq. 1 was determined by averaging steady-state concentrations outside of the chamber just before both injections. The difference between PM_{2.5} loss rate constants when the air cleaner was on versus off was multiplied by the chamber’s volume to arrive at the air cleaner’s CADR [48].

Eq. 2 is a discretized mass balance equation that describes the time-varying emission rate of a VOC within the chamber:

$$E^t = \left(\frac{C^{t+\Delta t} - C^t}{\Delta t} - \lambda C_o^t + \lambda C^t \right) \cdot V \quad (2)$$

where E^t is the VOC emission rate at the current time step (ppb m³/h), $C^{t+\Delta t}$ and C^t are the VOC concentration inside of the chamber at the subsequent and current time step, respectively (ppb), Δt is the duration of the time step (minutes), C_o^t is the VOC concentration outside of the chamber at the current time step (ppb), V is the volume of the chamber (m³), and all other terms are defined previously.

A discretized model that employed Eq. 2 was necessary due to the time varying VOC emission rates from recently constructed CR Boxes. The first, fifth, sixth, and tenth minute of each switching cycle—which included measurements inside and outside of the chamber—were excluded from the dataset to account for sampling line delays, and the remaining data points were averaged in ten-minute intervals so that measurements from both locations aligned at each time step. AERs were assumed to be constant over the course of an experiment.

2.5. Modeling assumptions and parameters

Using the average CR Box CADR calculated as part of this study ($352 \text{ m}^3/\text{h}$), a numerical model was developed to evaluate indoor $\text{PM}_{2.5}$ and total BTEX concentrations during a hypothetical wildfire smoke event. During such an event, the United States Environmental Protection Agency (U.S. EPA) recommends setting up a “clean room” in one’s home [49], ideally a bedroom with a door that can remain closed for extended periods of time. Thus, the hypothetical space had a floor area of 13.9 m^2 with 2.4 m tall ceilings (assumed dimensions from the U.S. EPA’s *Cleaner Indoor Air During Wildfires* Challenge [50]) and a $\text{PM}_{2.5}$ penetration factor (0.7) [51] and $\text{PM}_{2.5}$ deposition loss rate (0.4 h^{-1}) [52] typical of residential buildings was assumed. Four AERs were modeled (0.1, 0.2, 0.5 (which is typical for a residential building [53]), and 1 h^{-1}) to demonstrate the tradeoff between maintaining an airtight space and facilitating outdoor ventilation during a wildfire smoke event. VOC off-gassing from the CR Box was the only indoor source of VOCs considered.

A hypothetical one-hour period was modeled for $\text{PM}_{2.5}$ and hypothetical 12-hour periods were modeled for benzene, toluene, and C8 aromatics; appropriate time intervals were chosen based on expected rates of $\text{PM}_{2.5}$ removal and VOC off-gassing. Prior to initializing the model (at time < 0), the indoor space was assumed to have come to steady state with outdoor $\text{PM}_{2.5}$ ($167.5 \mu\text{g}/\text{m}^3$) [50] and benzene, toluene, and C8 aromatics (6.1 , 29.8 , and $0.36 \mu\text{g}/\text{m}^3$, respectively) [54,55] levels observed in wildfire smoke. Accounting for $\text{PM}_{2.5}$ penetration and deposition, steady state indoor $\text{PM}_{2.5}$ concentrations of 24, 29, 65, and 84 were calculated at AERs of 0.1, 0.2, 0.5, and 1 h^{-1} , respectively, and used to initialize the model. Once initialized (at time $= 0$), a newly constructed CR Box was assumed to have been engaged.

Eq. 3, which describes the time-varying concentration of indoor $\text{PM}_{2.5}$ when accounting for source and loss mechanisms to and from the hypothetical space, was discretized:

$$\frac{dC_i}{dt} = P\lambda C_o - \left(\lambda + L + \frac{\text{CADR}}{V} \right) C_i \quad (3)$$

where $\frac{dC_i}{dt}$ is the time-varying indoor concentration of $\text{PM}_{2.5}$ ($\mu\text{g m}^{-3} \text{ h}^{-1}$), P is the $\text{PM}_{2.5}$ penetration factor (0.7), λ is the modeled AER ($0.1\text{--}1 \text{ h}^{-1}$), C_o is the modeled outdoor $\text{PM}_{2.5}$ concentration ($167.5 \mu\text{g}/\text{m}^3$), L is the $\text{PM}_{2.5}$ deposition loss rate (0.4 h^{-1}), CADR is the average, experimentally determined CADR of the CR Box ($352 \text{ m}^3/\text{h}$), and V is the hypothetical space’s volume (33.4 m^3).

Air cleaner effectiveness (ϵ), or the ability of the air cleaner to remove air pollution from the space, was determined using equations in Shaughnessy and Sextro [56]. To model indoor VOC concentrations, Eq. 2 was solved for $C^{t+\Delta t}$. Experimentally determined, time-varying emission rates for benzene, toluene, and C8 aromatics were used as inputs for E^t , outdoor VOC concentrations were assumed to be constant,

and AERs were varied from $0.1\text{--}1 \text{ h}^{-1}$.

3. Results and discussion

3.1. CR box CADR variability: Impact of individual builder

Table 1 presents the average ($\pm$ standard deviation) $\text{PM}_{2.5}$ CADR, build time, amount of duct tape used, power draw, sound level, and number of mistakes associated with each of the CR Boxes. Note that though the point system is weighted according to potential impact on device performance, we recognize that it is inherently subjective. Table B.1 in Appendix B presents the point values assigned to each mistake and the number of them made by each participant.

Average ($\pm$ standard deviation) CR Box CADR range from $313 \pm 19\text{--}396 \pm 40 \text{ m}^3/\text{h}$, with an overall average ($\pm$ standard deviation) and median of 352 ± 27 and $354 \text{ m}^3/\text{h}$, respectively. Results of a Kolmogorov-Smirnov test at a significance level of 0.05 indicate that the data is normally distributed ($D(8) = 0.18$, $p = 0.905$); this implies the observed variability in CADR is reflective of random effects, rather than a consistent bias. Fig. 2a illustrates CADR variability across the eight CR Boxes via a box plot. While CADR are modestly variable (relative standard deviation = 7.6%), the range of CADR from CR Boxes evaluated as part of this study would result in appreciable reductions in indoor $\text{PM}_{2.5}$ when deployed in appropriate-sized zones of a building.

Fig. 2b demonstrates that there is a moderate correlation ($R^2 = 0.64$) between average CADR and the number of mistakes made during CR Box construction; builds with 3–4 versus 0–2 mistakes produce average CADR $\sim 12\%$ lower; this implies that subjective evaluation of CR Box builds may help to correct common mistakes, thus improving CADR. Fig. 2c demonstrates that there is no correlation ($R^2 = 0.005$) between average CADR and amount of duct tape used. We initially hypothesized that the use of more duct tape would result in a higher CADR, as it could potentially indicate a more thorough sealing of gaps and the participant’s general attention to detail. While it could also be argued that the use of more duct tape would result in a lower CADR—the implication being that the participant struggled to assemble the device—a low coefficient of determination proves that this variable ultimately had no effect on the dataset. Fig. 2d demonstrates that there is a weak correlation ($R^2 = 0.24$) between average CADR and build time. Following a similar line of reasoning, we hypothesized that a longer build time would result in a higher CADR, as it could be an indicator of the participant’s general attention to detail. Though the correlation is weak, the opposite trend emerges, perhaps suggesting that a longer build time can be associated with the participant struggling to assemble the DIY air cleaner.

Table 1

$\text{PM}_{2.5}$ clean air delivery rate (CADR) (average $\pm$ standard deviation), build time (mm:ss), amount of duct tape used during construction (g), power draw (W), sound level (dB), and mistakes made during construction.

Participant	$\text{PM}_{2.5}$ CADR (m^3/h)			Build Time (mm:ss)	Tape Used (g)	Power Draw (W)	Sound Level (dB)	Total Mistakes Made*
1	396	$\pm$	40	25:11	132.8	ND**	ND	0
2	353	$\pm$	14	31:28	111.8	96.3	64.7	1.5
3	314	$\pm$	19	35:31	129.9	94.3	64.3	4
4	331	$\pm$	10	20:10	119.7	96.2	64.4	4
5	332	$\pm$	10	31:18	106.7	96.2	65.1	3
6	379	$\pm$	11	19:00	105.4	97.6	64.4	2
7	357	$\pm$	17	22:13	161.1	96.3	64.2	1.5
8***	356	$\pm$	11	32:00	122.1	96.1	64.9	0
Average $\pm$ St. Dev	352	$\pm$	27	27:06 $\pm$ 06:15	123.7 $\pm$ 18.1	96.1 $\pm$ 1.0	64.6 $\pm$ 0.3	2 $\pm$ 1.6

* See Table B.1 for more information on mistakes made

** No data

*** This participant was an experienced DIY air cleaner builder

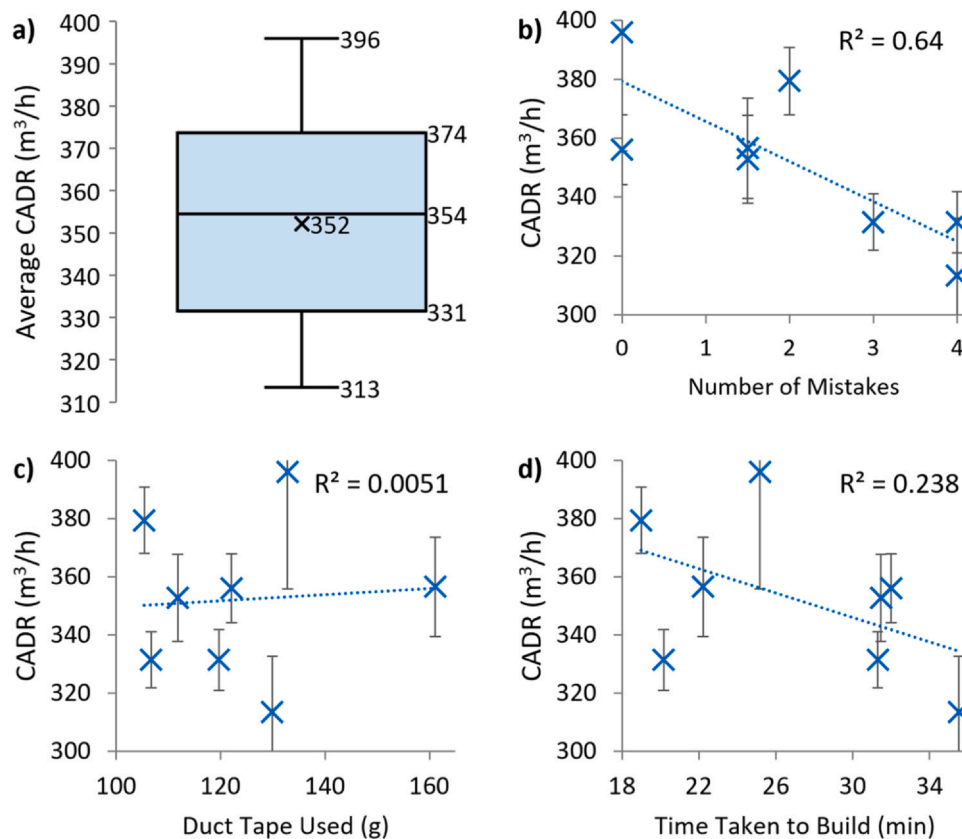


Fig. 2. a) CADR variability box plot and regression analyses of b) CADR vs. number of mistakes c) CADR vs. amount of duct tape used, and d) CADR vs. time taken to build.

3.2. DIY air cleaner variability: Comparison across studies in the literature

Though interest around DIY air cleaners has increased in recent years, a limited body of experimental research quantifying their efficacy exists. Excluding this study, there have been (to our knowledge) eight peer-reviewed journal articles and measurement reports published since 2021 that evaluate CR Box CADRs. Differences in air cleaner construction protocol, test method, challenge aerosol, and particle diameter range analyzed have resulted in a wide range of experimentally determined particulate matter CADRs across these studies: 285–1448 m³/h. Fig. 3 presents average ($\pm$ standard deviation when applicable) CADRs in increasing order for each of the studies assessed, as well as number of filters used, test method, challenge aerosol, and particle diameter range. Note that because the focus of the present study is air cleaner performance under wildfire conditions, for studies that report CADRs at various particle diameter ranges, we choose (in Fig. 3) to present the range most closely aligned with our testing protocol, that is, particles $< 2.5 \mu\text{m}$.

In terms of materials and air cleaner construction, we expect that range of fan speeds, method of affixing filters to the box fan, the inclusion of a cardboard shroud, number of filters used, and filter dimensions are all factors that could have an impact on CR Box efficacy. To make a comparison between studies, all those reviewed here assess the CR Box operated at its highest fan speed setting and with duct tape as the method of affixation. All but one study (Weingartner et al. [57]) tests the device with a cardboard shroud; while (as they state in their report) their construction protocol is inspired by the design of the CR Box, they attach two filters to the inlet side of the box fan to form a triangular geometry. The majority of the other designs employ four $0.5 \times 0.5 \times 0.05 \text{ m}$ MERV 13 filters arranged as a cube with a cardboard base (similar to the present study), with two experiments (Zeng et al. [58] and Dal Porto et al. [59]) testing a five-filter design with top,

bottom, and front filters of the same dimensions and two side filters that are slightly smaller ($0.4 \times 0.5 \times 0.05 \text{ m}$). Myers et al. [60] conduct experiments with four 2.5 cm thick MERV 13 filters, while all other studies use filters with a thickness of 5 cm.

CADR is the product of flowrate and removal efficiency, and these parameters are not independent; two CR Boxes constructed with the same number of the same type of filters will produce different CADRs if constructed with box fans with different fan curves. Though Pistochini et al. [61] and Srikrishna [62]—the two studies that predict CADRs as the product of measured air cleaner flowrate and MERV 13 filter removal efficiency (rather than employing the pull-down method, as described in Section 2.3)—follow the same construction protocol, there is an 82 % difference between predicted CR Box CADRs across the two studies. Not only do they employ different box fans with different air flowrates (753 m³/h and 1446 m³/h, respectively), they determine CADRs using different MERV 13 removal efficiencies (54 % and 67 %, respectively), which are determined at different particle diameters (the average at $0.3\text{--}1 \mu\text{m}$ and $0.3 \mu\text{m}$, respectively). The interplay of box fan flowrate and filter removal efficiency is one likely explanation for the wide divergence in CADRs reported across studies.

Though no clear relationship appears to exist between experimental method and CR Box efficacy from the reviewed studies, the challenge aerosols deployed across studies that use the pull-down method produce particulate matter in different diameter ranges, potentially driving CADR variability. MERV 13 filters are rated as having removal efficiencies $> 90 \%$ for particles $3\text{--}10 \mu\text{m}$, $> 85 \%$ for particles $1\text{--}3 \mu\text{m}$, and $> 50 \%$ for particles $0.3\text{--}1 \mu\text{m}$ [63], and though they are not rated for particles $< 0.3 \mu\text{m}$, Dols et al. [64] show that removal efficiency decreases from $\sim 96 \%$ to $\sim 36 \%$ between $0.01\text{--}0.2 \mu\text{m}$ and is $\sim 42 \%$ at $0.3 \mu\text{m}$, the most penetrating particle diameter. Thus, it is expected that the magnitude of CR Box (a device that employs MERV 13 filters) CADR is closely related to both the challenge aerosol and range of

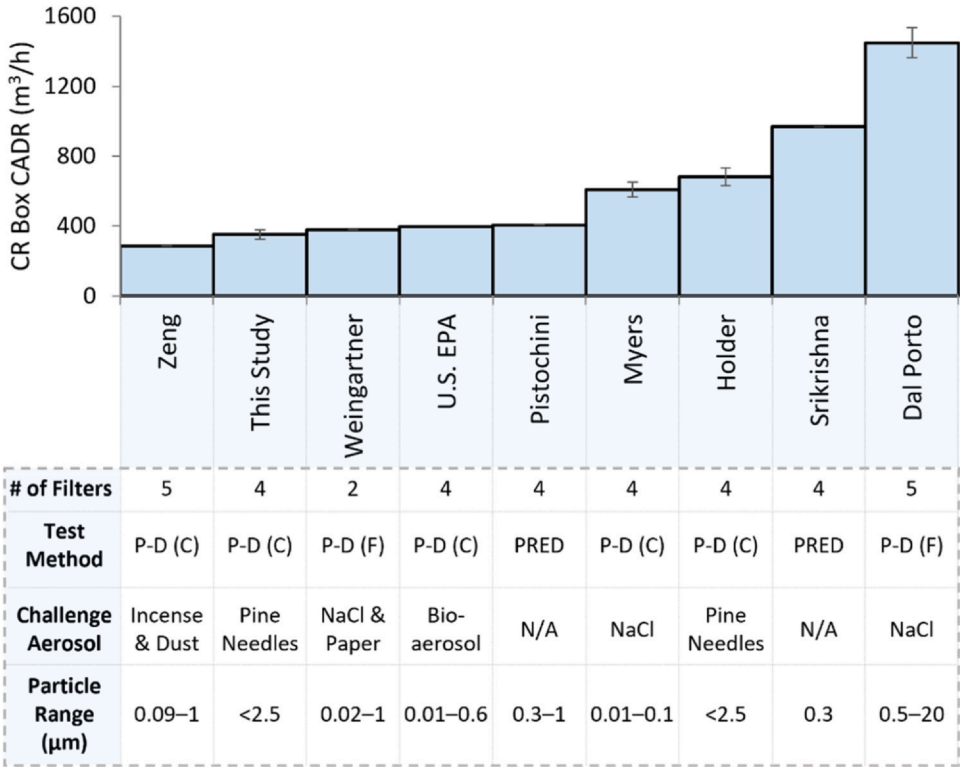


Fig. 3. Average (± standard deviation when applicable) clean air delivery rate (CADR) (m³/h), number of filters used, test method (where “P-D (C)” and “P-D (F)” refer to the pull-down method in a chamber or in the field, respectively, and “PRED” refers to predicted CADR testing via independent single-pass removal efficiency and air flowrate analyses), challenge aerosol, and particle diameter range for nine studies that have evaluated CR Box effectiveness.

particle diameters being analyzed.

Zeng et al. [58], which uses a combination of challenge aerosols, provides size-resolved CADRs that demonstrate the trend between particle size and CADR clearly; in the three particle size bins evaluated as part of the ANSI-AHAM AC-1 protocol [65], CADRs increase with increasing particle diameter. Myers et al. [60]—one of three studies that use NaCl as a challenge aerosol—plot CADR on a particle number basis as a function of diameter, showing that CADRs remain relatively consistent from 0.01–0.3 µm, after which they increase steadily until ~6 µm, where the maximum CADR occurs (~1087 m³/h). Furthermore, a size distribution plot of nebulized NaCl shows that the majority of particles generated are ~0.01–0.3 µm in diameter, with a maximum at ~0.1 µm. Though less larger particles are being generated, a higher PM_{2.5} CADR (761 m³/h) is realized when analyzing the data on a particle mass basis (versus particle number basis), again demonstrating the ability of MERV 13 filters to remove larger particles more efficiently. Employing NaCl as part of a field study, Dal Porto et al. [59] measure average (± standard deviation) CADRs of 1448 ± 85 m³/h on a particle number basis and 1543 ± 83 m³/h on a mass basis, a result that also demonstrates this phenomenon. The high CADRs found as a part of

their study could be explained by the size distribution of the challenge aerosol and the range of diameters analyzed; a particle sizer that measures particles with diameter 0.5–20 µm was employed.

Combustion processes, such as the burning of pine needles, primarily generate particles in the 0.02–0.05 µm size range [66]. In an effort to assess the efficacy of CR Boxes under simulated wildfire smoke conditions, Holder et al. [67] challenge their device with pine needle smoke emissions in an environmentally controlled chamber (similar to the present study). Measuring an average (± standard deviation) PM_{2.5} CADR of 681 ± 52 m³/h, there is a 64 % difference between the average CADR realized as part of the present study and theirs. This difference is likely a result of Holder et al. [67] using gravimetric particulate matter measurements to determine CADRs, an approach that emphasizes the influence of larger particles, which contribute strongly to mass and are more efficiently removed by MERV 13 filters. Similar to the particle size distribution of pine needle smoke emissions, studies have shown that aerosolized bacteriophage MS2 generates particles primarily in the 0.04–0.07 µm range with a maximum at 0.05 µm [68]. Using a particle sizer that measure particles from 0.01–0.6 µm, U.S. EPA [69] determine a CADR of 398 m³/h when challenging their

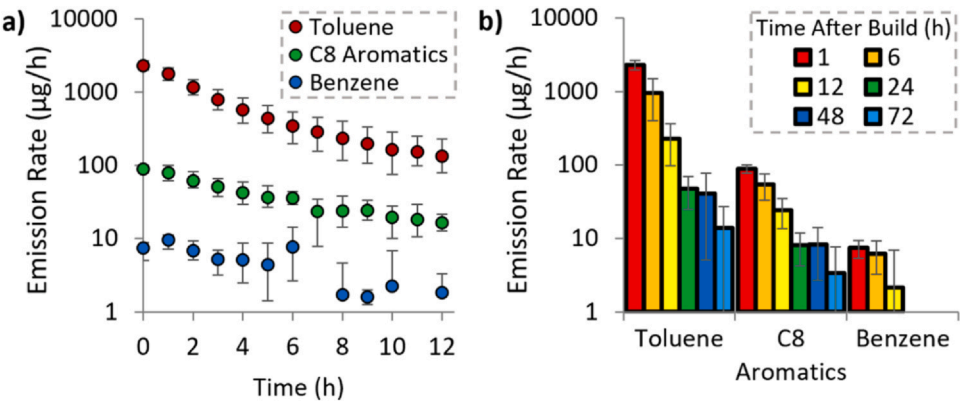


Fig. 4. a) Log-scale average emission rates (± minimum and maximum) for m79.054 (benzene), m93.087 (toluene), and m107.097 (C8 aromatics) over the course of 12 hours and b) average emission rates (± standard deviation) 1, 6, 12, 24, 48, and 72 hours after build. Note that after 12 hours, benzene emissions were indistinguishable from chamber background.

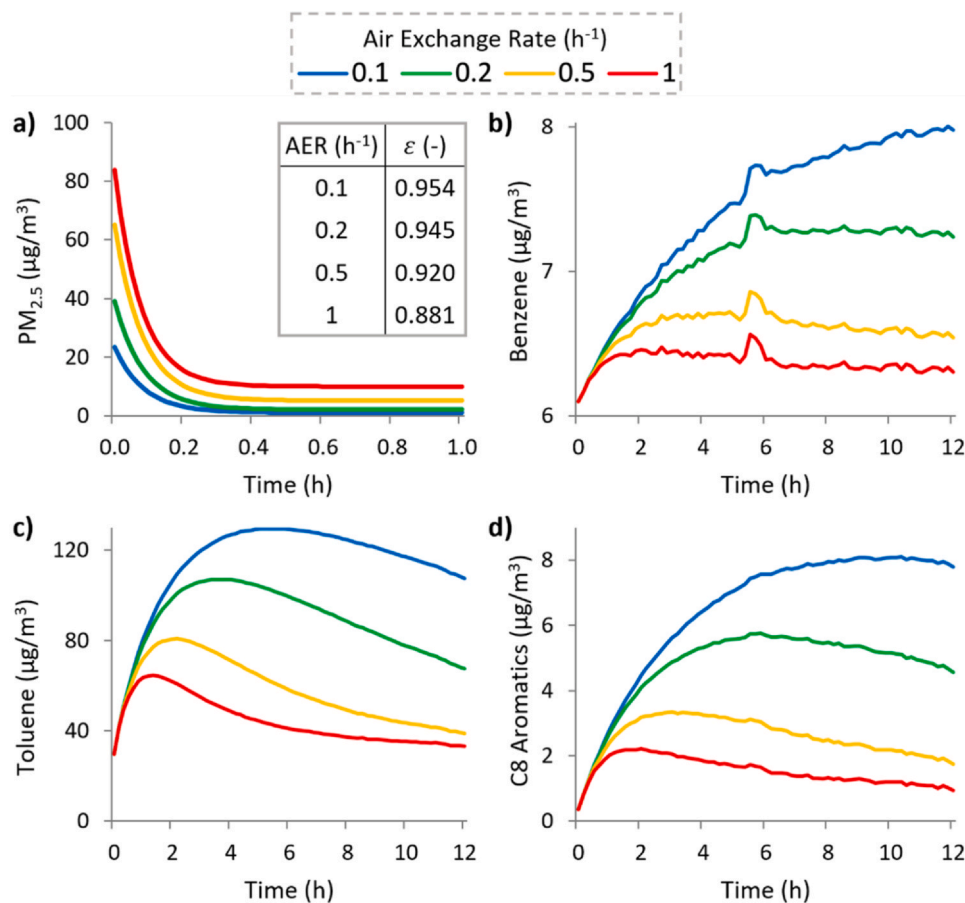


Fig. 5. a) Modeled indoor PM_{2.5} concentration vs. time plot at four AERs over one hour (inset shows steady state air cleaner effectiveness (ε)) and modeled b) benzene, c) toluene, and d) C8 aromatics indoor concentration vs. time plots at four AERs over 12 hours. At $t = 0$, steady state indoor PM_{2.5} concentrations are 24, 39, 65, and 85 μg/m³ at AERs of 0.1, 0.2, 0.5, and 1 h⁻¹, respectively, and indoor benzene, toluene, and C8 aromatics concentrations are 6.1, 29.8, and 0.36 μg/m³, respectively. The CR Box is assumed to be placed in the space and turned on at $t = 0$. Note that fluctuations in modeled VOC concentrations reflect variability in measured VOC emission rates.

CR Box with bacteriophage MS2. While making a direct comparison between their study and others is difficult due to the nature of the aerosol, MERV 13 filter efficiency trends upward from 0.07 to 0.04 μm, ranging from ~56 % to ~76 %, according to Dols et al. The similarity in size distribution of the challenge aerosol could explain the smaller (12 %) percent difference between CADRs determined as a part of the present study and theirs.

Though a variety of air cleaner construction protocols, test methods, challenge aerosols, and analyzed particle diameter ranges result in a wide range of CADRs, it is worth acknowledging that in all reviewed studies, CR Box CADRs are produced that are competitive with or greater than those produced by many commercial air cleaners [47].

3.3. VOC off-gassing

Fig. 4a presents hourly average (± minimum and maximum) benzene, toluene, and C8 aromatics emission rates for three of the CR Boxes over a 12-hour period. Fig. 4b presents emission rates for the same compounds over a 72-hour timeframe, but with hourly emission rates averaged for all trials and error bars representing standard deviation. Note that only one of three devices was allowed to off-gas beyond 24 hours.

Examining Fig. 4a, toluene and C8 aromatics emission rates are initially 2289 and 89 μg/h, respectively, but decrease by 94 % and 82 % after 12 hours. While benzene emission rates fluctuate during the first six hours, initial concentrations are relatively low and average emission rates are reduced by ~75 % after 12 hours. Examining Fig. 4b, toluene

and C8 aromatics emissions continue to decrease between hour 12 and 24 of the study, reaching average emission rates of 42 and 9 μg/h, respectively, after 24 hours. In the subsequent 48 hours, toluene and C8 aromatics emission rates (for the single device tested over a 72-hour period) continue to decrease, albeit at a slower rate; once reaching zero—at hour 40 for toluene and hour 44 for C8 aromatics—emission rates fluctuate ± ~20 μg/h and ± ~10 μg/h, respectively, for the remainder of the experiment.

Of the other 8 VOCs tested, methanol, acetonitrile, acrylonitrile, acetaldehyde, acetone, and naphthalene all produce near-zero or slightly negative average emission rates for the entirety of the experiment, indicating that they are not off-gassing from the CR Box. Average isoprene and monoterpenes emission rates are initially 37 and 67 μg/h, but decrease by ~90 % after four and fifteen hours, respectively. A separate 24-hour off-gassing experiment in which four MERV 13 filters were arranged to form a cube around the box fan, but were not affixed to it with duct tape, was conducted. Emission rates for BTEX compounds, isoprene, and monoterpenes remained slightly negative for the entirety of the experiment, indicating that the use of duct tape is likely the sole contributor to VOC off-gassing from CR Boxes themselves. Yeng et al., 2020 found that VOC emissions from plastic tape are dominated by aromatic VOCs such as toluene, ethyl acetate, xylenes, and ethylbenzene [33]. Isoprene and monoterpenes emissions (which are often associated with human activity [70]) may be the result of desorption from air cleaner materials; compounds may have adsorbed to filters, duct tape, and the box fan following close contact with the participant for ~20–35 minutes during construction.

While VOC emission rates calculated as part of this study are not of acute health concern, in the case of toluene, odor thresholds for sensitive individuals (160 ppb [71]) may be approached or exceeded in small, airtight zones with a newly constructed CR Box deployed; subsequent modeling (Section 3.4) demonstrates this. The combination of VOCs emitted may also contribute to noticeable odors below the stated thresholds, again, especially when the device is deployed immediately into a small, airtight space. If possible, an off-gassing period of ~6–12 hours outdoors may be appropriate following CR Box construction.

3.4. Pollutant modeling

Fig. 5 presents $PM_{2.5}$ concentration during the first hour and BTEX concentrations during the first 12 hours of the same hypothetical wildfire smoke event (described in Section 2.5) at four AERs. In a small (34 m^3) residential room, a newly constructed CR Box with a CADR of $352\text{ m}^3/\text{h}$ (the experimental average determined as part of this study) is engaged at time $t = 0$ and operated continuously. Experimentally determined, average VOC emission rates are used to model indoor BTEX concentrations in ten-minute intervals over the same time period. Note that prior to initializing the model, it is assumed that both indoor $PM_{2.5}$ (which has an initial concentration that varies with AER) and BTEX concentrations have come to steady state with outdoor concentrations representative of a wildfire smoke event.

Four AERs are modeled ($0.1\text{--}1\text{ h}^{-1}$) to demonstrate the tradeoff between maintaining an airtight space, which reduces the rate of infiltration of outdoor smoke, and facilitating outdoor ventilation. In this case, outdoor air ventilation serves to dilute the VOC emissions from off-gassing of the CR Box. Examining Fig. 5a, CR Box effectiveness ranges from 0.881 to 0.954, bringing the room's $PM_{2.5}$ concentration to steady state in < 30 minutes at all modeled AERs. Though there are currently no indoor $PM_{2.5}$ health-based standards in the United States, the U.S. EPA recently proposed adjusting their national outdoor ambient air quality standards for $PM_{2.5}$, lowering the primary annual limit to $9\text{--}10\text{ }\mu\text{g}/\text{m}^3$ and maintaining a 24-hour limit of $35\text{ }\mu\text{g}/\text{m}^3$ [72]. CR Boxes bring the modeled bedroom's $PM_{2.5}$ concentration below the 24-hour threshold in < 5 minutes at all AERs and below the annual limit ($9\text{--}10\text{ }\mu\text{g}/\text{m}^3$) in < 13 minutes at all but the maximum AER (1 h^{-1}). At 1 h^{-1} , $PM_{2.5}$ comes to steady state at the upper limit of the annual standard; if an individual sensitive to odors produced by the CR Box fails to adequately seal their building envelope (thus increasing AER) during a wildfire event, they may be exposed to $PM_{2.5}$ concentrations in excess of the national annual standard, potentially for a sustained period of time.

Examining Figs. 5b, 5c, and 5d, indoor BTEX concentrations follow the opposite trend, increasing as AER decreases. The U.S. Occupational Safety and Health Administration (OSHA) has set permissible exposure limits (PELs) for each BTEX compound. Benzene and toluene have eight-hour time weighted average PELs of $\sim 32\text{ }\mu\text{g}/\text{m}^3$ and $\sim 750\text{ mg}/\text{m}^3$, respectively, while C8 aromatics (both ethylbenzene and xylene) have generalized regulatory limits of $\sim 435\text{ mg}/\text{m}^3$ [73]. Even when the room is most airtight (0.1 h^{-1}) and benzene, toluene, and C8 aromatics have reached their maximum concentrations (~ 8 , ~ 130 , and $\sim 8\text{ }\mu\text{g}/\text{m}^3$, respectively), levels are still several orders of magnitude below OSHA's exposure limits. Fig. 5 demonstrates that BTEX concentrations from CR Boxes are dominated by toluene; after ~6 hours when maximum indoor concentrations are reached, toluene remains far below OSHA's eight-hour PEL. However, as discussed previously, levels of toluene approach odor thresholds for sensitive individuals under the most airtight (0.1 h^{-1}) condition. While an airing out period of a newly constructed CR Box may be considered for comfort and an overabundance of caution, the net benefits associated with the modeled level of $PM_{2.5}$ reductions during an extreme smoke event are expected to far outweigh any adverse impact from short-term emissions of aromatic VOCs.

3.5. Conclusion

This study tasked seven participants (with no prior DIY air cleaner experience) with constructing CR Boxes using the same directions, materials, and location of assembly. While the CDC cites DIY air cleaner construction and performance variability as a concern, CADRs measured as a part of this study are modestly variable (relative standard deviation = 7%) when following consistent build instructions and using similar materials. Notably, the range of CADRs across all DIY air cleaners constructed here would result in appreciable reductions in indoor particulate matter when deployed in appropriate-sized zones of a building. However, our review of the literature indicates that there is large variability in reported CADR, which likely contributes to confusion on the topic of DIY air cleaner reliability. Our analysis of the reviewed literature indicates that the large range of reported CADRs from CR Boxes ($285\text{--}1448\text{ m}^3/\text{h}$) is likely the result of differences in materials used, challenge aerosols tested, and evaluation protocol.

The use of duct tape during air cleaner assembly generated measurable concentrations of VOCs, namely BTEX compounds. Observed emission rates imply that an off-gassing period of ~6–12 hours outdoors would avoid episodic emission of VOCs at rates that may cause accumulation in excess of the lower-limit of odor threshold estimates. In an emergency situation where an off-gassing period is not possible, numerical modeling demonstrates that total BTEX concentrations from CR Boxes—which are dominated by toluene—remain well below eight-hour PELs set by OSHA, even at maximum concentrations. Our study investigated these emissions with one type of tape; future studies could evaluate the range of emissions from different types of tape to understand how tape selection may affect transient VOC emission rates from DIY air cleaners.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Elliott Gall reports a relationship with Multnomah County that includes: paid expert testimony. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.indenv.2024.100023](https://doi.org/10.1016/j.indenv.2024.100023).

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