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Assessment of low-cost air quality sensor systems when used to evaluate DIY air cleaner performance

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ABSTRACT

Do-it-yourself (DIY) air cleaners can be a temporary, low-cost ventilation strategy for improving indoor air quality by reducing airborne particulate contaminants. However, to our knowledge, no comprehensive assessment of multiple low-cost sensor systems (LCSs) for evaluating DIY air cleaner performance has yet been conducted. In this study, we investigated seven LCSs when used to evaluate the air cleaning performance of DIY air cleaners. Three portable high efficiency particulate air (HEPA) air cleaners (HACs) and three different DIY air cleaners, namely the single filter, Ford Scrappy, and Corsi-Rosenthal (CR) Box designs, were evaluated. All air cleaners were challenged with a NaCl aerosol, and their clean air delivery rate (CADR) was calculated from $PM_{2.5}$ mass concentrations measured by the LCSs and a reference particulate matter (PM) monitor. The published Dust CADR ratings of the HACs and the CADRs calculated from the reference PM monitor were used to determine the mean absolute percent error (MAPE) in the CADRs calculated from the LCSs. The LCSs' MAPE in CADR among all air cleaners tested ranged from 1.6–44.2%. Three of the seven LCSs had a MAPE $\leq$10%. No correlations between LCS performance in our study and their published performance evaluations were identified. However, we found that the correction factor of PM sensors from one manufacturer, found in four of the LCSs evaluated, impacted performance. We also suspect the transient test conditions created by operating mixing fans and air cleaners during experiments, the LCS housing design, and the calibration of the LCS may be driving factors impacting LCS performance in our study. Overall, we demonstrated that certain LCSs can be a viable option for evaluating the air cleaning performance of DIY air cleaners.

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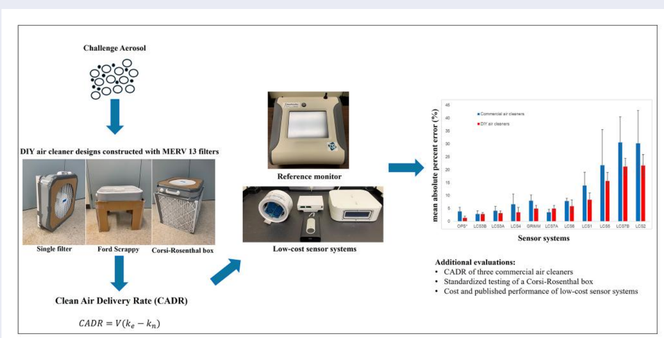

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1. Introduction

The use of certified commercial air cleaners is one indoor air quality improvement strategy that has seen increased usage in recent emergency responses, including recent wildfire smoke events and the COVID-19 pandemic. However, a Centers for Disease Control and Prevention (CDC) Morbidity and Mortality Weekly Report (MMWR) article found that these devices can cost more than $500 per unit (CDC 2022). Sporadic availability of these air cleaners during events impacting indoor air quality is sometimes also an obstacle. Do-it-yourself (DIY) air cleaners are a low-cost ventilation improvement strategy that can be used to improve indoor air quality. They typically consist of a box fan, one or more heating, ventilation, and air conditioning (HVAC) filters, tape, and cardboard, and can cost less than $100 to build. The components are often readily available for purchase from local hardware stores or through online retailers. A common measure of air cleaner performance is the clean air delivery rate (CADR), which represents the volume of contaminant-free air delivered, within a given particle size range. A higher CADR indicates greater air cleaning efficiency. This metric helps end users determine the number of units needed to sufficiently clean the air in their built environment. Some commercial portable air cleaners undergo standardized test procedures at independent laboratories to evaluate their performance and establish an official CADR that can be marketed to the public. DIY air cleaners can be evaluated using the same procedures; however, standardized testing can cost upwards of $5000 to perform. Additionally, government agencies such as the CDC and Environmental Protection Agency (EPA), and Association of Home Appliance Manufacturers (AHAM), a standards development organization, advise caution when using them. These organizations all highlight how DIY air cleaners can be useful in emergencies, for short-term use, or when commercially available air cleaners are inaccessible. However, they are not recommended as a permanent or long-term solution for indoor air cleaning. Whenever possible, commercially available portable air cleaners with high-efficiency particulate air (HEPA) filters are preferred, because they are tested for performance and rated with a CADR. Participating manufacturers have their products independently tested and certified to ensure they meet their stated performance claims. For more information, see the *EPA Guide to Air Cleaners in the Home* (EPA 2018).

Low-cost sensor systems (LCSs), defined by the EPA Air Sensor Toolbox as costing less than $2500, are increasingly available in the consumer market for monitoring air quality in both outdoor and indoor environments. A "sensor system" refers to an integrated package of sensors and components that measure particulate matter (PM) concentrations in one or more particle size bins (e.g., PM_1, $PM_{2.5}$, PM_{10}) and may also measure other parameters such as temperature, relative humidity (RH), or total volatile organic compounds (TVOCs). Additional features may include data logging/storage, network connectivity, and a graphical user interface, and some have even been integrated into ventilation equipment (e.g., HVAC systems and commercial air cleaners) to provide real-time monitoring of pollutants indoors. These devices provide end users with a straightforward way to track pollutant levels and environmental conditions and may help guide timely actions to improve indoor air quality (Demanega et al. 2021; EPA 2024). Despite these benefits, the use of LCSs also presents challenges. LCSs generally do not meet the strict performance criteria for regulatory air monitoring applications such as the EPA's designated federal reference method (FRM) and federal equivalent method (FEM). They also encompass a wide variety of technologies that are not subject to certification and may suffer from significant biases and drifts in their measurements over long periods of operation (Tryner et al. 2020; UNECE 2024). This concern aligns with findings from the Government Accountability Office (GAO), which reported that some manufacturers are not transparent about how they test or report the performance of their LCSs (GAO 2024). However, some entities, such as the EPA and the Air Quality Sensor Performance Evaluation Center (AQ-SPEC), have conducted and published performance evaluations to increase transparency (AQ-SPEC n.d.a; EPA 2025). The GAO (2024) also identified broader challenges with implementing LCSs, including limited technical expertise for proper setup and data interpretation, insufficient data quality for decision-making, and competing priorities between decision-makers and end users that can hinder effective responses to air quality concerns. Nonetheless, LCSs have proven useful in evaluating the performance of DIY air cleaners.

Recent studies have shown that DIY air cleaners can deliver clean air in volumes equivalent to commercial air cleaners, but at a fraction of the cost (May et al. 2021; Zeng et al. 2021; Dal Porto et al. 2022; Holder et al. 2022; Li et al. 2022; Srikrishna 2022 and 2023; Derk et al. 2023; Myers et al. 2023; Jehn et al. 2024; Pistochini et al. 2024). Most of these studies used reference PM monitors to measure the decay slope of a challenge aerosol in a test room, with and without the DIY air cleaner operating, to determine a size-dependent CADR. Notably, Dal Porto et al. 2022 collocated an LCS with a reference PM monitor but did not quantify the variation in CADR between the two instruments. Pistochini et al. (2024) calibrated two LCSs used to evaluate DIY air cleaner performance by applying empirical correlations to convert LCS-measured particle concentrations to equivalent concentrations measured by a reference instrument. In contrast, May et al. (2021) and Srikrishna (2023) relied exclusively on LCSs to quantify DIY air cleaner performance. May et al. (2021) conducted a case study in a residence affected by a wildfire smoke event in Seattle, WA, monitoring indoor and outdoor air quality using LCSs. They found that indoor $PM_{2.5}$ concentrations decreased by up to 99% after operating DIY air cleaner using MERV 13 filters, although reductions were largely dependent on room size and duration of operation. Srikrishna (2023) performed periodic field checks of DIY air cleaners deployed in an elementary school, using an LCS to measure ambient aerosol concentrations at the intake and exhaust of each unit to monitor filter efficiency at 0.3 µm (the most penetrating particle size). Results across these studies varied depending on methodology employed, but all emphasized that design and component choices (e.g., box fan, filters) were critical to DIY air cleaner performance. However, we found no studies that assessed multiple LCSs of different makes, models, and $PM_{2.5}$ sensor technologies collocated with a reference PM monitor to compare and validate performance evaluations of DIY air cleaners.

To address this gap, the objective of this study was to evaluate the effectiveness of multiple LCSs for estimating the CADR of DIY air cleaners using procedures modeled after AHAM Standard AC-1 2020. A reference PM monitor was used in parallel to the LCSs during experiments to validate our results. It is important to note that this study does not, and is not intended to, certify the performance of either commercial or DIY air cleaners. Furthermore, it does not serve as an alternate to standardized test methods used to certify the performance of commercial air cleaners such as the AHAM AC-1–2020. The results of this study may help end users appropriately size, scale, and deploy DIY air cleaners within their built environment to meet indoor ventilation recommendations from entities such as the CDC or AHAM, particularly where other ventilation improvement strategies are not feasible or available.

2. Materials and methods

To determine the feasibility of using LCSs to assess DIY air cleaner performance in a simplified and low-cost field test, we tested seven LCSs' ability to accurately determine the CADR of three commercial HEPA air cleaners and three DIY air cleaner designs in a laboratory.

2.1. Low-cost air quality sensor systems

To be included in this study, candidate LCSs had to: 1) cost less than about \$300; 2) be capable of measuring $PM_{2.5}$ mass concentration; and 3) be capable of logging data for later retrieval and analysis. The selection criteria to identify candidate LCSs was obtained from the performance evaluations available in the academic and grey literature. $PM_{2.5}$ mass concentrations were used as a selection criterion because nearly all the LCSs we surveyed during our market research, priced at approximately \$300 or less, reported data only in this format. Although $PM_{2.5}$ sensors commonly estimate mass concentrations from number concentrations, few LCS manufacturers at this price point provide the option to output number concentrations directly. Performance testing of LCSs has been done using various methods and challenge aerosols (Singer and Delp 2018; Li et al. 2020; Tryner et al. 2020; Vercellino et al. 2018; Wang et al. 2020; Demanega et al. 2021; Zou et al. 2021). However, the South Coast Air Quality Management District's (South Coast AQMD), Air Quality Sensor Performance Evaluation Center (AQ-SPEC) provided the largest publicly available quantity of LCS performance evaluation reports using a peer-reviewed, standard methodology (AQ-SPEC 2017; Papapostolou et al. 2017). AQ-SPEC also took part in the development of ASTM-D840105-21 Standard Test Method for Evaluating $PM_{2.5}$ Sensors or Sensors Systems Used in Indoor Air Applications (ASTM 2021). For these reasons, we chose the performance selection criteria

Table 1. Qualitative and quantitative performance specifications required for low-cost air quality sensor systems. All metrics evaluated by AQ-SPEC.

Performance metric	Acceptable value
Field R^2	≥0.75
Lab R^2	≥0.9
Precision	High[a]
Intra-model variability	Low[a]
Data Recovery	≥90%

[a]According to AQ-SPEC, the "high" value for Precision means that the variation around the mean of the repeated measurements of the same pollutant concentration under identical or similar experimental conditions is >90%. The "low" value for intra-model variability means the measurements from three units of the same sensor type are <20%.

shown in Table 1 based on the quantitative and qualitive performance metrics AQ-SPEC provided in their sensor evaluations. The specifications of five LCSs which met our requirements and were evaluated in this study are listed in Table 2 as LCS2 – LCS6. We did not have the resources to evaluate all LCSs on the market that met our requirements, so we chose representative samples based on the various PM sensors that can be found in LCSs. LCS3 includes two $PM_{2.5}$ sensors and the results for each are reported separately as LCS3A and LCS3B throughout.

To assess the validity of our LCS performance selection criteria, two additional LCSs that either did not meet our selection criteria or have not been evaluated by AQ-SPEC were also evaluated and are anonymized in Table 2. LCS1 has been evaluated by other researchers, including AQ-SPEC, and did not meet our selection criteria. It should be noted that LCS1 reports particle number concentration in two size fractions. An empirical formula to estimate $PM_{0.5-2.5}$ mass concentration was provided by the manufacturer and was used in this study. LCS7 has not been evaluated by AQ-SPEC. LCS7 reported two $PM_{2.5}$ outputs corresponding to two different correction factors implemented by the sensor. The uncorrected output and the output corrected using a proprietary algorithm and calibration to estimate atmospheric aerosol mass concentrations are labeled LCS7A and LCS7B throughout, respectively (Tryner et al. 2020; Rueda et al. 2023). The performance metrics reported by AQ-SPEC, corresponding to our performance selection criteria, for each LCS evaluated in this study are summarized in Table S1 (AQ-SPEC n.d.a). Two reference PM monitors were also used in tandem during the LCS evaluations: Optical Particle Sizer (OPS) (Model: 3330, TSI Inc., Shoreview, MN, USA) and GRIMM portable aerosol spectrometer (Model: 11D, DURAG Group, Hamburg, Germany). For the OPS, $PM_{2.5}$ mass concentration was calculated from 10 mass differentiated size bins ranging from 0.3 to 2.685 µm which were evenly spaced in the logscale.

2.2. Air cleaner performance evaluation procedure

The CADR of an air cleaner is the volume of contaminant-free air delivered, within a given particle size range, and is defined as CADR $= V(k_e - k_n)$, where V is the volume of the test room. k_n is the natural decay rate and results from removal of particles through settling and diffusional deposition, as well as exfiltration *via* ventilation (e.g., air circulating fan) from the test room. k_e is the operational decay rate and results from both the natural decay and air cleaner operation. A higher CADR corresponds to greater air cleaning efficiency. Each air cleaner evaluation consisted of two nearly identical measurements. In the first measurement, the air cleaner under evaluation is off and the natural decay rate is determined. In the second measurement, the air cleaner under evaluation is turned on and the operational decay rate is determined. When the particles are well-mixed throughout the test room, decay rates can be estimated by a linear regression of log-transformed $PM_{2.5}$ (or $PM_{0.5-2.5}$ in the case of LCS1) mass concentrations measured throughout the duration of the measurement (see Appendix A of the Supplemental Information (SI) file for details).

Air cleaner performance evaluations were conducted using lab-based methods similar to those applied in previous studies assessing DIY air cleaner performance (Zeng et al. 2021; Dal Porto et al. 2022; Holder et al. 2022; Derk et al. 2023; Myers et al. 2023; Pistochini et al. 2024). Tests were performed in a $45.8\,m^3$ ($1617\,ft^3$) enclosed room with an air change rate (ACH) of $0.555\,h^{-1}$ with no room HVAC running and one air circulating fan operating as described below (Figure 1). Tracer gas decay was used to determine the ACH of the room. Details of the methods used can be found in Appendix B of the SI file. The air cleaner under evaluation was placed on the floor at the center of the room. The LCSs and reference PM monitors were placed around the perimeter of the test room on carts at heights of 74–79 cm. Location-dependent variation in sensor response was not a concern, as independent mixing assessments, including tracer gas, decay comparison using the challenge aerosol mentioned below, and fog visualization test) verified uniform air distribution under test conditions. One large air circulating pedestal fan (Model: NSC-243, AirKing America LLC, West Chester, PA, USA) was operated at 4980 cfm to provide mixing throughout the test room during the evaluations. Room temperature and relative humidity (RH) was monitored throughout each test trial using a hand-held RH and temperature meter (Model: HM40, Viasala Inc., Vantaa, Finland). A dehumidifier (Model: UD501KOG5, LG Electronics USA, Inc., Englewood Cliff, NJ, USA) was used when necessary for maintaining the desired environmental conditions as outlined in the next paragraph. To minimize disruptions to the room environmental conditions, room entry only occurred to power on or off the test equipment, as needed, during the evaluations.

Before starting any measurements, the room's environmental conditions were adjusted to base conditions

Table 2. Technical specifications of selected low-cost air quality sensor systems.

Low-Cost Air Quality Sensor System	Manufacturer	Model	Optical Particle Sensor	Pollutant	Concentration range	Time Resolution (s)	Battery	Data Logging	Data Retrieval	Cost (USD)
LCS1	Redacted	Redacted	proprietary sensor	$PM_{0.5-2.5}$	$\leq$1,000,000 #/ft^3	60	Optional	Internal or PC	*via* RS232 (software required)	$261
LCS2	Wicked Device LLC	Air Quality Egg (2022 Model)	Two Plantower PMS5003	$PM_{2.5}$	$\leq$1000 µg/m^3	60	No	Internal	*via* Wi-Fi or USB (software required)	$306
LCS3	Purple Air Ltd	PA-II SD	Two Plantower PMS5003	$PM_{2.5}$	$\leq$1000 μg/m^3	Stock: 120; Adjusted: $\geq$8	No	Internal *via* removable SD card; Cloud storage *via* Wi-Fi	SD card; Download from Purple Air Cloud (must register device)	$259
LCS4	Atmotech Inc.	Atmotube Pro	Sensirion SPS30	$PM_{2.5}$	$\leq$1000 μg/m^3	60	Yes	Internal; Mobile device *via* Bluetooth	Exported to mobile device as .csv file *via* Bluetooth (app required)	$189
LCS5	Davis Instruments Corp.	AirLink	Plantower PMSA003	$PM_{2.5}$	$\leq$1000 μg/m^3	60	No	Cloud storage *via* Wi-Fi	Download from Weatherlink dashboard (subscription required)	$215
LCS6	IQAir	AirVisual Pro Indoor	proprietary sensor	$PM_{2.5}$	$\leq$1000 μg/m^3	10	Yes	Internal	*via* Wi-Fi	$299
LCS7	Redacted	Redacted	Plantower PMS5003	$PM_{2.5}$	$\leq$2048 µg/m^3	$\geq$1	No	Internal or PC	*via* USB (software required)	$53

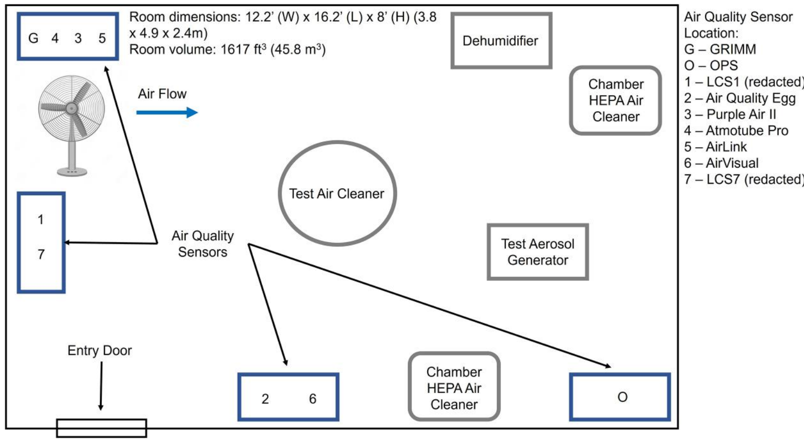

Figure 1. Test room experimental setup.

(room temperature of 70 ± 5 °F and RH below 40%), if necessary. Maintaining stable conditions was necessary, as high RH can cause hygroscopic growth of some particles, particularly hygroscopic salts such as sodium chloride (NaCl), thereby altering particle size distribution (Papapostolou et al. 2017; Badura et al. 2018). Excess moisture can also interfere with internal electrical components of optical PM sensors, degrading their performance (Badura et al. 2018). Additionally, fluctuations in temperature or RH may increase relative error of LCSs when compared to a reference PM monitor (Mui et al. 2023). Once conditions were stabilized, the room's HVAC system was turned off and the supply diffusers were sealed. All LCSs, except LCS3(A&B) were programmed to log PM mass concentration in 1 min intervals. LCS3(A&B) were programmed to log in 56 s intervals, as it was only capable of logging at 8 s increments. The OPS was programmed to log every second while the GRIMM was programmed to log every 6 s. Next, two commercial HACs with a combined Dust CADR of 640 cfm were operated to reduce the background mass concentration in the test room to less than 1 µg/m^3, as measured by the OPS.

After acceptable environmental conditions and background particle concentrations were achieved, a test aerosol was generated inside the room by aerosolizing a 0.4 g/L NaCl aqueous solution from one or two low-cost (less than $50) commercially available ultrasonic humidifiers (Model: AO-101, Aqua Oasis, Monsey, NY, USA). The NaCl solution was prepared by dissolving 1/4 tsp of commercially available pickling salt (~1.5 g) (Morton Salt, Inc., Chicago, IL, USA) in one gallon (3785 mL) of distilled water (BlueTriton Brands, Arrowhead Distilled Water, Stamford Connecticut, USA). During aerosolization, the room relative humidity (RH) was kept below the efflorescence RH (40%) of NaCl (Martin 2000) to ensure complete drying of the test aerosol. The peak particle size of the test aerosol (0.18 µm) was within specified range (0.1 to 0.2 µm) for count median diameter for inorganic $PM_{2.5}$ in the ASTM-D8405-21 Standard Test Method for Evaluation of $PM_{2.5}$ Sensors or Sensor Systems Used in Indoor Air Applications (ASTM 2021). A detailed representation of the test aerosol particle size distribution can be found in Figure S1 of the SI file. Ultrasonic humidifiers were operated on a cart 74 cm above the floor near the center of the room. The operating time and number of humidifiers operated were dependent on the CADR rating of the air cleaner being evaluated. Higher CADR air cleaners required a longer dosing period to ensure an adequate number of data points for the decay rate regression. The dosing period was determined by trial and error, but ranged approximately from 3 to 12 min. The test aerosol was then allowed to mix in the room for at least 1 min.

After the test aerosol was allowed to mix, the procedures for the natural and operational decay measurements diverged, with the air circulating fan remaining in operation. For the natural decay measurement, the sampling period began 2 min after the mixing period. For the operational decay measurement, the air cleaner was powered on and the sampling period began 2 min after. For both measurements, the sampling period was up to 20 min. Six trials (each consisting of a natural and operational decay measurement) were conducted for each air cleaner evaluated.

To analyze sensor performance, we calculated the absolute percentage error (APE) of the CADR of air cleaner i as measured by sensor j in trial k as $APE_{i,j,k} = \left|1 - CADR_{i,j,k}/CADR_{\mathrm{ref}\,i}\right| \times 100\%$, where the reference CADR value for air cleaner i, $CADR_{\mathrm{ref}\,i}$,

Table 3. AHAM verified suggested room size and certified CADRs for each selected HAC.

HEPA Air Cleaner	Room Size (ft^3)	Cigarette Smoke CADR (cfm)	Dust CADR (cfm)	Pollen CADR (cfm)
HAC 1	153	99	107	116
HAC 2	259	167	177	178
HAC 3	465	300	320	300

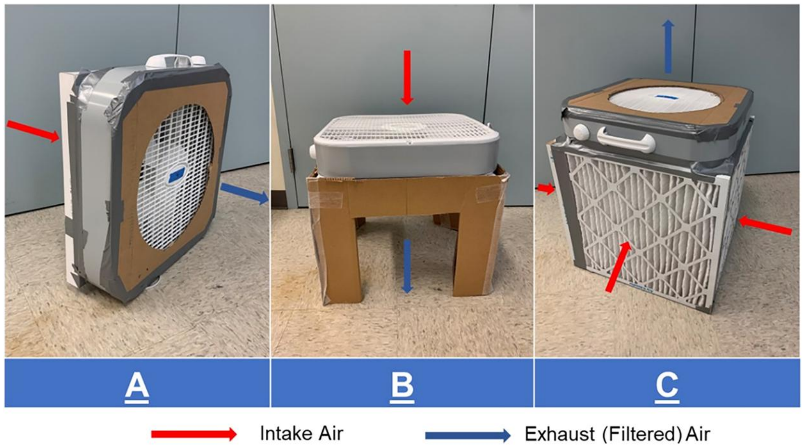

Figure 2. DIY air cleaner designs evaluated in our study: (a) Single Filter, (b) Ford Scrappy, and (c) Four Filter Corsi-Rosenthal Box.

was taken to be the published AHAM verified Dust CADR for all HACs and the mean CADR as measured by the OPS for all DIY air cleaners. The OPS was selected as the reference because it had a lower mean absolute percentage error (MAPE) [3.24%] than the GRIMM [8.07%] in preliminary tests, using the same methods described in this section, of the three HACs evaluated in this study. MAPE and the standard deviation of the absolute percentage error was then calculated for each air cleaner and sensor combination. A MAPE less than or equal to 10% was chosen to be the target performance benchmark for whether a sensor adequately estimated air cleaner performance. This benchmark was chosen based on the 10% allowable variation in CADR when evaluating air cleaners in the smoke and dust categories per Annex J of the AHAM AC-1 2020 standard (AHAM 2020).

For external validation of our test procedure, we sent a DIY air cleaner constructed and operated identically as used in this study to an independent test lab accredited to perform the AHAM AC-1 standardized test (SGS IBR Laboratories, Grass Lake, MI). Three replicates each were performed to determine the Cigarette Smoke CADR and Dust CADR. In addition, the $PM_{2.5}$ CADR was determined following Annex I of AHAM AC-1 (2020). Furthermore, three replicates of a modified AHAM AC-1 test were performed where a NaCl test aerosol was generated using the methodology outlined in this study and $PM_{2.5}$ number concentrations were measured by a similarly configured OPS.

2.3. Commercial portable HEPA and DIY air cleaners

Three commercially available, AHAM verified, HACs were selected for evaluation based on market search and to represent a range in cigarette smoke CADR spanning from approximately 100–300 cfm. AHAM verified air cleaners can be found on AHAM's website through their searchable directory, which organizes certified air cleaners by CADR rating, suggested room size use, manufacturer, and brand name (AHAM n.d.b). Table 3 lists the AHAM verified suggested room size and CADR for cigarette smoke, dust, and pollen pollutants for the selected HACs when operated at their highest flow settings. All HACs evaluated in this study were operated at their highest flow setting.

Three DIY air cleaner designs were selected for evaluation: single filter, Ford Scrappy, and Corsi-Rosenthal (CR) Box. These designs have been investigated and their air cleaning performance characterized in other recently published studies (Dal Porto et al. 2022; Holder et al. 2022; Srikrishna 2022; Derk et al. 2023; Myers et al. 2023; Jehn et al. 2024; Pistochini et al. 2024). The single filter DIY configuration was constructed by placing the HVAC filter on the intake side of the fan with the filter flow indicator pointing toward the fan. Tape was then applied on the edges of the filter to secure and seal it to the box fan (Figure 2a). The Ford Scrappy (Figure 2b) design was built per the instructions listed on Ford Motor Company's website (Ford Motor Company 2021). The CR box (Figure 2c) incorporated

Table 4. Average CADR calculated using PM2.5 mass concentrations, with standard deviation of CADR in parentheses, for each sensor system among all commercial HEPA air cleaners and DIY air cleaners.

	Average CADR (standard deviation of CADR) (cfm)													
Sensor system	HAC 1		HAC 2		HAC 3		Ford scrappy		Single filter (Low)		Single filter (high)		CR box	
LCS1[a]	86	(11)	155.6	(6.6)	288.2	(8.1)	171.3	(8.2)	207.5	(8.9)	347	(15)	666	(27)
LCS2	59.8	(5.7)	128.9	(5.9)	257.9	(7.7)	138.6	(4.5)	168	(13)	310	(21)	604	(15)
LCS3A	101.8	(6.3)	180.0	(4.5)	330.9	(8.8)	195.9	(4.8)	224.9	(6.3)	389.5	(9.0)	755	(32)
LCS3B	103.9	(2.5)	179.0	(2.9)	332.6	(6.0)	194.8	(6.0)	222.1	(5.7)	390.1	(5.5)	756	(12)
LCS4	95.0	(6.6)	170.4	(5.3)	305.4	(5.7)	182.6	(6.8)	212.4	(4.2)	380	(27)	749	(12)
LCS5	66.9	(3.6)	148.2	(5.5)	283	(14)	153.4	(9.5)	182.0	(8.6)	322	(14)	651	(11)
LCS6	100	(10)	189	(12)	303	(22)	200.6	(7.6)	220	(13)	412	(25)	717	(44)
LCS7A	102.0	(4.3)	174.2	(5.4)	322	(13)	192	(11)	227.0	(8.5)	399	(23)	753	(34)
LCS7B	62.2	(5.1)	129.6	(6.7)	246	(10)	142.3	(8.8)	170.3	(5.8)	305	(22)	605	(32)
GRIMM	96.0	(1.5)	163.4	(1.4)	300.5	(5.6)	178.5	(6.7)	205.5	(4.4)	363.8	(1.5)	712	(16)
OPS[b]	101.5	(2.4)	169.4	(2.2)	313.4	(2.6)	190.9	(5.3)	216.2	(3.8)	381.5	(6.5)	736.8	(5.0)

[a]The $PM_{2.5}$ mass concentration for LC1 was calculated by using an empirical formula provided by the manufacturer to estimate $PM_{0.5–2.5}$ mass concentration. [b]The $PM_{2.5}$ mass concentrations for the OPS was calculated from 10 mass differentiated size bins ranging from 0.3 to 2.685 μm.

Table 5. Mean absolute percentage error in CADR, with standard deviation of absolute percentage error in parentheses, for each sensor system among all commercial HEPA air cleaners and DIY air cleaners.

	Mean absolute percentage error (standard deviation of absolute percentage error) (%)													
Sensor system	HAC 1		HAC 2		HAC 3		Ford scrappy		Single filter (low)		Single filter (high)		CR box	
LCS1	20	(10)	12.1	(3.7)	10.0	(2.5)	10.3	(4.3)	4.5	(3.4)	9.1	(4.0)	9.7	(3.7)
LCS2	44.2	(5.3)	27.2	(3.3)	19.4	(2.4)	27.4	(2.4)	22.2	(6.1)	18.9	(5.6)	18.0	(2.0)
LCS3A	6.0	(4.5)	2.7	(1.1)	3.7	(2.3)	2.9	(2.1)	4.1	(2.9)	2.2	(2.1)	3.6	(3.1)
LCS3B	3.2	(1.8)	1.6	(1.2)	3.9	(1.9)	3.1	(1.7)	3.6	(1.1)	2.1	(1.5)	2.6	(1.6)
LCS4	11.3	(6.1)	3.9	(2.7)	4.5	(1.8)	4.8	(3.0)	2.1	(1.3)	5.6	(3.5)	1.7	(1.4)
LCS5	37.5	(3.3)	16.3	(3.1)	11.5	(4.4)	19.7	(5.0)	15.7	(4.0)	15.6	(3.6)	11.7	(1.5)
LCS6	8.5	(7.2)	8.5	(4.0)	6.6	(5.5)	5.3	(3.7)	4.6	(3.9)	9.4	(3.4)	4.2	(4.8)
LCS7A	4.8	(3.8)	2.6	(2.1)	3.2	(2.3)	4.4	(3.1)	5.4	(3.4)	6.4	(3.5)	3.7	(3.3)
LCS7B	41.8	(4.7)	26.8	(3.8)	23.2	(3.2)	25.5	(4.6)	21.2	(2.7)	20.2	(5.8)	17.9	(4.3)
GRIMM	10.3	(1.4)	7.7	(0.78)	6.1	(1.7)	6.6	(3.5)	4.9	(2.0)	4.78	(0.40)	3.4	(2.1)
OPS*	5.2	(2.2)	4.3	(1.3)	2.06	(0.81)	2.3	(1.2)	1.37	(0.95)	1.2	(1.1)	0.55	(0.31)

*The calculation for the aggregated mean absolute percentage error of the OPS for DIY air cleaners compares the CADRs measured from each individual experiment (six in total) to the mean CADR of all experiments.

four HVAC filters and was built per the instructions listed on University of California: Davis College of Engineering's website (UC Davis College of Engineering 2024). One 20″ box fan (Model: 3773, Lasko Products LLC, West Chester, PA, USA) was used for each configuration. Air Handler MERV 13 HVAC filters (W.W. Grainger Inc., Lake Forest, IL, USA) were the only filters used for each configuration. The filter dimensions used for the CR box and single filter configurations were 20″ × 20″ × 2″ (50.8 × 50.8 × 5.1 cm) and 20″ × 20″ × 4″ (50.8 × 50.8 × 10.2 cm) for the Ford Scrappy. A fan shroud was constructed from a cardboard cutout the shape of the box fan grill with a centered 14.5″ (36.8 cm) diameter circular opening and was sealed to the top of the fan (exhaust side) with duct tape for the single filter and CR Box designs. This shroud prevents backflow of air created from negative pressure along the corners of the fan while operating and improves airflow efficiency (Rosenthal 2020). No fan shroud was used on the Ford Scrappy, as we wanted to evaluate the performance of its original design.

3. Results

3.1. Performance of low-cost air quality sensor systems with commercial portable HEPA air cleaners

We evaluated the CADR of three AHAM Verified commercially available HACs with published Dust CADR ratings. The HACs were evaluated first to validate our results. We found that the CADRs measured by the OPS, our reference PM monitor, had mean absolute percent error (MAPE) ≤5.2% from the published Dust CADR rating for all three HACs (MAPE ≤2.3% for all DIY air cleaner). Therefore, the results reported in this section and beyond will focus on the LCSs and GRIMM. LCS MAPE ranged from 1.6 to 44% from the published Dust CADR of HAC 1–3. Table 4 lists the measured CADR from all LCSs and reference PM monitors for HAC 1–3.

Table 5 lists the MAPE in CADR for each LCS among all HAC and DIY air cleaners evaluated. For commercial HAC 1, which has a published Dust CADR of 107 cfm, the MAPE in CADR obtained

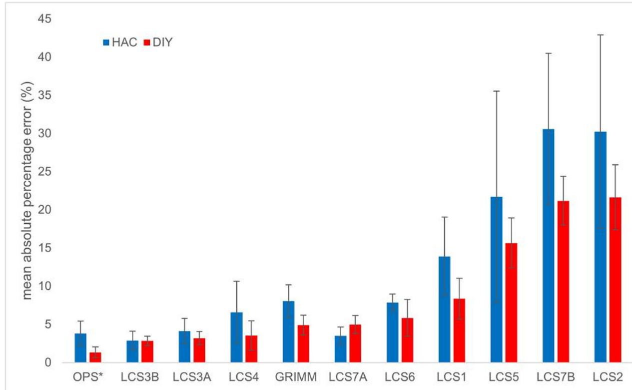

Figure 3. Aggregated mean absolute percentage error in CADR for each sensor system by air cleaner type. Error bars represent one standard deviation.
*The calculation for the aggregated mean absolute percentage error of the OPS for DIY air cleaners compares the CADRs measured from each individual experiment (six in total) to the mean CADR of all experiments.

from the LCSs and GRIMM compared to the published Dust CADR ranged from 3.2 to 44%. The aggregated MAPE from HAC 1 for all LCSs had the highest standard deviation ($\sigma = 16\%$) of the three HACs evaluated. LCS3A, LCS3B, LCS6, and LCS7A met our benchmark having MAPEs of 6.0%, 3.2%, 8.5%, and 4.8%, respectively. All other LCSs and the GRIMM did not meet the benchmark. LCS2 had the highest MAPE (44.2%).

The MAPE between the published Dust CADR (177 cfm) of HAC 2 and the CADR obtained from the LCSs and GRIMM ranged from 1.6 to 27%, and had the second highest standard deviation in aggregated MAPE for all LCSs ($\sigma = 9.6\%$) among the three HACs. LCS3A, LCS3B, LCS4, LCS6, LCS7A, and GRIMM all met the performance benchmark having MAPEs of 2.7%, 1.6%, 3.9%, 8.5%, 2.6%, and 7.7%, respectively. LCS1, LCS2, LCS5, and LCS7B did not meet the performance benchmark. Again, LCS2 had the highest MAPE (27.2%).

For HAC 3, the MAPE between the published Dust CADR (320 cfm) and the LCSs and GRIMM CADRs ranged from 3.2 to 23%. HAC 3 had the lowest standard deviation ($\sigma = 7.0\%$) in aggregated MAPE among the three HACs for all LCSs. All LCSs and GRIMM, except LCS2, LCS5, and LCS7B, met our target performance benchmark for HAC 3. LCS7B had the highest MAPE (23.2%) for HAC 3. Among the three HACs evaluated, we saw a trend of decreasing MAPE as the value of the published Dust CADR increased. LCS3A, LCS3B, LCS6, and LCS7A met our target performance benchmark for every HAC. LCS4 and the GRIMM hit the benchmark for two of the three HACs having higher CADR values. This finding aligns with the trend of decreased relative error in CADR obtained from LCSs as the published Dust CADR of the HAC increased.

3.2. Performance of low-cost air quality sensor systems with DIY air cleaners

Three DIY air cleaner designs (single filter, Ford Scrappy, and CR Box) were also evaluated. Since there are no published CADR values for these configurations using a standardized test method, the CADR value obtained from the OPS was deemed to be the reference value when calculating MAPE. The mean CADRs as measured by our reference monitor were found to be 216 cfm for the single filter design operated at low fan speed, 382 cfm for the single filter design operated at high fan speed, 191 cfm for the Ford Scrappy, and 737 cfm for the CR Box (Table 4). We also compared the CADR of the CR Box as measured by our reference monitor to that found by an independent test laboratory. The independent test lab following AHAM AC-1–2020 found the CR Box had a mean Cigarette Smoke CADR of 542 cfm, a mean Dust CADR of 746 cfm, and a mean PM2.5 CADR of 636 cfm. When they used a NaCl test aerosol generated and counted using the methodology outlined in this study, the mean CADR, using $PM_{2.5}$ number concentrations, for the CR Box was 757 cfm and showed good agreement (error = 2.7%) with what we measured with our reference monitor. It is important to note that the CADR evaluated by the test lab used particle number concentrations, while particle mass concentrations were used in this study. The laboratory test results can be found in Appendix C of the SI file. The CADRs as measured by the LCSs, GRIMM, and reference PM monitor (i.e., OPS) for the Ford

Scrappy, the single filter design operated at two fan speeds, and CR Box are listed in Table 4.

Similar to our evaluation of the three HACs, our target benchmark for LCS MAPE was ≤10% of the average CADR measured by the OPS for the DIY air cleaners evaluated. The MAPE in CADR among the LCSs and GRIMM were widespread and ranged from 1.7 to 27.4% (Table 5). The MAPE in CADR among the four DIY air cleaner configurations evaluated ranged from 2.9 to 27.4% for the Ford Scrappy, 2.1 to 20.2% for the single filter high fan speed configuration, 2.1 to 22.2% for the single filter low fan speed configuration, and 1.7 to 18% for the CR Box. For both single filter configurations, at low and high fan speeds, all LCSs except LCS2, LCS5, and LCS7B were within our target performance benchmark of ≤10% MAPE. LCS4 had the lowest MAPE in CADR for the single filter configuration operated at low speed, 2.1%, and LCS3B had the lowest when operated at high speed, 2.1%. LCS2 and LCS7B had the highest MAPE in CADR for the low-speed configuration, 22.2% and 21.2%, respectively, and high-speed configuration, 18.9% and 20.2%, respectively. For the Ford Scrappy, LCS3A, LCS3B, LCS4, LCS6, LCS7A, and the GRIMM all met the performance benchmark. LCS3A showed the lowest MAPE (2.9%), while LCS2 and LCS7B showed the highest at 27.4% and 25.5%, respectively. For the CR Box, all LCSs, except LCS5 and LCS7B, met our target performance benchmark. The MAPE in LCS-measured CADR displayed a similar trend of decreasing as the reference CADR value of the air cleaner increased, as seen in our results for the three HACs. We suspect this occurred because air cleaners with higher CADR values increased room mixing, which reduced variance in NaCl particle concentrations throughout the test room during experiments. All LCSs that met the target performance benchmark for all HAC and DIY air cleaners had an error between 1.6 and 9.4% and a standard deviation of $\sigma = 2.0\%$ for the aggregated MAPE among all LCSs. Figure 3 summarizes the aggregated MAPE in CADR for each sensor system by air cleaner type.

3.4. Discussion

In this study, we demonstrated that some LCSs can be a viable option to evaluate the CADR of DIY air cleaners under laboratory conditions. Of the seven LCSs evaluated, two (LCS3(A&B) and LCS6) met our target performance benchmark for all seven air cleaners tested; one (LCS4) met our target benchmark for all air cleaners except HAC 1, which had lowest CADR; one (LCS1) met our target benchmark for 4 of the 7 air cleaners; and two (LCS2 and LCS5) did not meet our target benchmark for any of the air cleaners tested. For LCS7, LCS7A met our benchmark target for all air cleaners tested, whereas LCS7B did not meet the benchmark for any. We found no clear correlations between the performance metrics reported by AQ-SPEC for each LCS (Table S1) and their MAPE in CADR for all air cleaners evaluated in this study. Such correlations might aid an end user in selecting an LCS suitable for DIY air cleaner evaluations. It is important to note that the performance of LCSs is impacted by several factors, which can include: measurement principles, laser power and wavelength, optical-scattering angle, sensor calibration procedure (if any), calibrant aerosol, sensor age, composition and size range of sampled PM, sampling method, flow path design, temperature, relative humidity, sensor housing design, product quality control, and algorithmic post processing of raw data (Singer and Delp 2018; Tryner et al. 2020; Wang et al. 2020; Mui et al. 2023).

One possible explanation for the variability in performance among the LCSs tested is that the LCSs may respond differently in transient conditions. All LCS testing protocols/standards for indoor applications we reviewed (Papapostolou et al. 2017; RESET 2018; ASTM 2021; EPA 2021) evaluate LCSs at steady state PM concentrations. We could not find any published LCS evaluation protocol/standard that evaluates rapidly changing PM concentrations. We suspect that the design of the LCS housing is a key driver to its performance in transient conditions, as it can affect particle flow paths and internal mixing. The installation instructions provided by manufacturers for several PM sensors found in the LCSs evaluated in this study may represent efforts to alleviate the effects of transience in the LCSs' measurements. These recommendations include positioning the sensor near the housing's outer shell, incorporating large openings and/or tightly sealed partitions between the inlet and outlet of the sampling mechanism to ensure airflow is not restricted nor increased (Sensirion 2019; AQ-SPEC 2016). LCS2, LCS3(A&B), LCS4, LCS5, and LCS7(A&B) appeared to consider these recommendations; however, variations in housing geometry, internal volume, PM sensor(s) placement within the housing, and the number and size of perforations (if any) on the outer shell of the housing impacted airflow through the PM sensor's sampling mechanism and, consequently, its performance. LCS1 and LCS6 use a proprietary PM sensor without published installation guidance. However, LCS6 seemed to conform to the installation recommendations provided by other PM sensor manufacturers, whereas LCS1 did not. In LCS1, the PM sensor was located near the center of the housing and further from the inlet and outlet of the sampling mechanism compared to the other LCSs evaluated. It also was the only LCS without an internal housing for the PM sensor inside its outer shell. More research could help explain how LCS housing design can impact its performance in transient conditions.

The PM sensor used in each LCS was another area we analyzed to identify potential correlations with performance in this study. LCS1 and LCS6 use manufacturer specific proprietary PM sensors where calibration method (if any) and technical specifications are unknown. LCS1 systematically underestimated reference CADR values by approximately 10% in all tests (see Figure S2a), while LCS6 showed excellent agreement with reference CADR values (Figure S2g). LCS4 incorporates the Sensirion SPS30 PM sensor, which is factory-calibrated using atomized potassium chloride (KCl) for $PM_{2.5}$ mass concentration measurements (Sensirion 2023). This calibration method may explain the excellent agreement observed between LCS4 and reference CADR values (Figure S2e), since KCl and NaCl, the challenge aerosol used in this study, have similar optical properties (Eldridge and Palik 1997; Palik 1997) and produce similarly shaped particles when aerosolized from a solution (Zelenyuk et al. 2006; Wang et al. 2022).

LCS2, LCS3(A&B), and LCS7(A&B) all use the Plantower PMS5003 low-cost PM sensor which is commonly found in LCSs in the market (Rueda et al. 2023). The performance of these sensors has been studied by many researchers in laboratory and indoor environments (Papapostolou et al. 2017; Singer and Delp 2018; Li et al. 2020; Wang et al. 2020; Demanega et al. 2021; Zou et al. 2021; Ouimette et al. 2023). The PMS5003 reports mass concentrations using two proprietary algorithms: an uncorrected output ("CF = 1") and one with a correction factor for atmospheric monitoring ("ATM") (Tryner et al. 2020). LCS3(A&B) and LCS7A use "CF = 1" and performed nearly identically with good agreement with reference CADR values (Figures S2c, d and S2h, respectively). LCS2 and LCS7B, both use the "ATM" correction factor, performed similarly and systematically underestimated reference CADR values by approximately 20% (Figures S2b and S2i). Figure S3 compares the mass concentrations (response), measured during natural and operational decays in experiments, between the reference sensor (OPS) and each LCS. Generally, across all comparisons, varying degrees of nonlinearity were observed. For LCS2 and LCS7B, we believe their systematic underestimation of the reference CADR is a result of the nonlinear response of correction factor "ATM." This can be seen when comparing their $PM_{2.5}$ mass concentrations with the OPS (see Figures S3b and S3i). Wallace (2023) reported that the "ATM" correction factor will be equal to "CF = 1" for "ATM" concentrations less than about 28 μg m^{-3} and will then asymptotically increase to approximately 1.5 times that of "CF = 1" at "ATM" concentrations greater than 52 μg m^{-3}. These concentrations correspond with the nonlinearities observed in Figures S3b and S3i.

LCS5 uses the Plantower PMSA003 PM sensor, an older generation of the Plantower PMS5003 sensor mentioned above, and employed the "ATM" correction factor, as verified by the manufacturer. The CADR values reported by LCS5 systematically underestimated the reference CADR values by about 13% (Figure S2f) and exhibited nonlinear behavior similar to that observed for LCS2 and LCS7B (see Figure S3f). AQ-SPEC reported similar bias trends, where LCS2 and LCS5 similarly overestimated $PM_{2.5}$ mass concentrations at low and high levels (AQ-SPEC n.d.b, c.). These findings demonstrate that the make and model of the PM sensor, calibration (if any), and/or correction factor may be driving factors for LCS performance in our study, consistent with prior studies evaluating LCS response to a variety of indoor PM sources, including dust, cooking emissions, incense, sea salt, candles, and wood smoke (Singer and Delp 2018; Vercellino et al. 2018; Li et al. 2020; Tyner et al. 2020; Wang et al. 2020; Demanega et al. 2021; Zou et al. 2021). We believe the same variation in LCS response would apply for our study.

Consideration to ensure that sufficient mechanical power is input into the test room *via* mixing fans to satisfy that the mixing time of the test aerosol is significantly less than the effective ventilation time (the inverse of the effective air change rate) (Drescher et al. 1995) is important when evaluating DIY air cleaners. Furthermore, future work to develop correlations between ultrasonic humidifier specifications and test aerosol generation rates might guide end users on the number of humidifiers and/or the duration of test aerosol generation required to sufficiently dose the room. For environments with RH between 40–59% (Martin 2000) a test aerosol generated from an aqueous solution of pure KCl powder supplement might be a more robust low-cost alternative. Additionally, the procedures used in this study could benefit from being evaluated in different room sizes that represent communal sized spaces. Some studies have characterized the performance of DIY air cleaners in the following conditions: a mock classroom (Derk et al. 2023), mock office space (Li et al. 2022), residential rooms (May et al. 2021), and occupied classrooms (Srikrishna 2022, 2023; Jehn et al. 2024). Collecting end users feedback in these settings could also provide insight into practicality, limitations, and user experience of operating DIY air cleaners.

4. Limitations

We acknowledge that our study has limitations. First, we were not able to evaluate the full spectrum of LCSs available on the market. Those included in our study were a representative sample of various PM sensors found in LCSs that have been evaluated, for their intended purpose, using published methods (AQ-SPEC 2017; Papapostolou et al. 2017). There may be other LCSs available on the market that can meet our performance benchmark (≤10% MAPE) when evaluating HACs and DIY air cleaners using the methods described in this study. We demonstrated that there were LCSs that met our selection criteria as well as our performance benchmark for all air cleaners evaluated (LCS3(A&B) and LCS6), and one LCS (LCS7A) with no published performance evaluation to reference that also met our benchmark.

Second, the LCSs in this study were used outside their intended purpose, which is to detect, monitor, and report on specific air pollutants (e.g. particulate matter, carbon dioxide, VOCs) and/or environmental conditions such as temperature and relative humidity (EPA 2024). Instead, we used them to evaluate the air cleaning performance of HACs and DIY air cleaners. Our findings are not indicative of how the LCSs evaluated in our study may perform when used as intended. The results represent how effective LCSs could be when evaluating the air cleaning performance of HAC and DIY air cleaners.

Finally, the methods presented in this study do not serve as a replacement for test standards (e.g., AHAM AC-1) that can evaluate and certify the performance of air cleaners. These methods are intended to be a tool to help end users evaluate the performance of DIY air cleaners which may be used on a temporary basis to improve indoor air quality when other ventilation improvement strategies are not feasible or accessible. Quantifying the performance of air cleaners can be helpful for sizing and scaling purposes for the built environment(s) they are operated in.

5. Conclusion

In our study, we evaluated the feasibility of using an LCS, along with commercially available and low-cost equipment and supplies, to characterize the CADR of HACs and DIY air cleaners in a laboratory setting. Of the seven LCSs we evaluated, three (LCS3(A&B), LCS4, LCS6, and LCS7A) met our target performance benchmark (MAPE ≤10%) for all air cleaners tested, apart from LCS4 for HAC 1 (11% MAPE). The remaining LCSs were inconsistent (LCS1) or failed to meet the benchmark (LCS2, LCS5, LCS7B) for any air cleaner. Generally, we found that LCSs which measure $PM_{2.5}$ mass concentrations and meet our performance selection criteria (provided they don't use Plantower PMSX003 sensors with an "ATM" corrected output, which exhibits nonlinear behavior) can be useful in evaluating the CADR of DIY air cleaners using our study methods. Future studies could investigate how low-cost sensors will perform at evaluating DIY air cleaners in field conditions, which can help reveal additional insights on the LCS applications. More specifically, built environments of varying size where mechanical ventilation is in operation at varying ventilation rates (including nonexistent mechanical ventilation), when environmental conditions (i.e., temperature and humidity) cannot be easily controlled, and/or when furniture is present, may be of interest. Summarizing the findings from these studies could lead to consistent messaging and use of DIY air cleaners. This messaging can assist DIY air cleaner end users in identifying approaches to mitigate exposures to airborne contaminants such as respiratory aerosols that contain viruses or bacteria that can lead to infectious disease transmission and wildfire smoke.

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Disclaimers

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

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CRediT: **Chris Barnes**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing; **Drew Thompson**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing; **Amelia Chen**: Data curation, Formal analysis, Investigation, Validation, Writing – original draft, Writing – review & editing; **Huiling Amy Feng**: Data curation, Formal analysis, Validation; **Mirle Pena**: Investigation, Writing – review & editing; **Duane Hammond**: Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability

The authors confirm that the data supporting the findings of this study are available within Appendix C of supplemental information file.

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